AN-NAJAH NATIONAL UNIVERSITY

FACULTY OF ENGINEERING

TELECOMMUNICATION ENGINEERING DEPARTMENT

Advanced Communications Lab

10646529

Student Manual

Last Revised by:

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2018/2019

An-Najah National University
Faculty of Engineering and IT

جامعة النجاح الوطنية
كلية الهندسة وتكنولوجيا المعلومات

Department Name : Telecommunication Engineering
Course Name: Advanced Communications lab Number:10646529
Report Grading Sheet

Instructor Name:	Experiment #:
Academic Year: 2018/2019	Performed on:
Semester: 9	Submitted on:
Experiment Name:	
Students:	
1-	2-
3-	4-
5-	6-

Report's Outcomes

ILO _1_ =(37) %	ILO _2_ =(21) %	ILO _3_ =(42) %	ILO __ =( ) %	ILO __ =( ) %

Evaluation Criterion	Grade	Points
Abstract answers of the questions: "What did you do? How did you do it? What did you find?"		
Introduction Sufficient,Clear and complete statement of objectives.	2	
Theory Presents sufficiently the theoretical basis.		
Apparatus/ Procedure Apparatus sufficiently described to enable another experimenter to identify the equipment needed to conduct the experiment. Procedure sufficiently described.		
Experimental Results and Calculations Results analyzed correctly. Experimental findings adequately and specifically summarized, in graphical, tabular, and/or written form.	5	
Discussion Crisp explanation of experimental results. Comparison of theoretical predictions to experimental results, including discussion of accuracy and error analysis in some cases.	2	
Conclusions and Recommendations Conclusions summarize the major findings from the experimental results with adequate specificity. Recommendations appropriate in light of conclusions. Correct grammar.	1	
References Complete and consistent bibliographic information that would enable the reader to find the reference of interest.		
Appendices Appropriate information, organized and annotated. Includes all calculations and raw data Sheet.		
Appearance Title page is complete, page numbers applied, content is well organized, correct spelling, fonts are consistent, good visual appeal.		
Total	10	

Table of Contents

Department of Telecommunication Engineering	
Advanced Communication Lab. (10646529)	
Total Credits	**1**
major compulsory	
Prerequisites	P1: Antennas (10646470) P2: Microwaves (10646561)

Course Contents

Experimentation with wire antennas; Horn antennas; Helical antennas; Microstrip Antennas and Antenna arrays.
Experimentation with Fiber cables; Optical sources and detectors; Audio and video transmission through optical systems.
Experimentation with microwave gun oscillator; rectangular waveguides; Microwave attenuators; Directional couplers and magic tees; SWR measurements; impedance measurement and impedance matching.
Experimentation with Transmission lines; Delays on TL's; Standing waves; Transformer Matching and Time Domain Reflectometry.

	Intended Learning Outcomes (ILO's)	Student Outcomes (SO's)	Contribution
1	An ability to design and conduct Fiber, Microwave, Antennas, and TL's based experiments, as well as to analyze and interpret data.	B	50 %
2	Ability to design a system, component, or process to meet desired needs, within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.	C	25 %
3	Ability to function on multi-disciplinary teams	D	25 %

Textbook and/ or References

LABVOLT books and manuals; Elletronica Venetta Lab manuals;

Assessment Criteria	Percent (%)
Laboratory Work	60 %
Final Exam	40 %

Course Plan

Week	Topic
1	Introduction to the Lab.
2	Introduction to the Transmission Line Trainer, Attenuation, Delay and Matching Using a Pulse Input.
3	Familiarization with Microwave Equipment, Calibration of the Variable Attenuator, The Gunn Oscillator characteristics.
4	Radiation Pattern of a $\lambda/2$, λ and $3\lambda/2$ Dipoles at 1 GHz.
5	Matching and Frequency Response, Standing Waves in Transmission Lines.
6	Standing Waves in Waveguides, The Directional Coupler.
7	Circular Polarization and Helical Antennas, Parasitic Array (Yagi-Uda) Antennas.

8	Transformer Matching, Time Domain Reflectometry.
9	Hybrid Tees.
10	Microstrip Technology: The Rectangular Patch Antenna, Microstrip Planar Array Antennas.
11	Impedance Measurement and Impedance Matching
12	Half-Wave Folded Dipole Antennas, Loop Antennas and Monopole Antennas
13	Characterization of the Optical Cables, Optical Sources and Detectors, Audio and video transmission through Optical Systems.
14	Final Exam

Lab Safety Guidelines

1) Be familiar with the electrical hazards associated with your workplace.

2) You may enter the laboratory only when authorized to do so and only during authorized hours of operation.

3) Be as careful for the safety of others as for yourself. Think before you act, be tidy and systematic.

4) Avoid bulky, loose or trailing clothes. Avoid long loose hair.

5) Food, beverages and other substances are strictly prohibited in the laboratory at all times. Avoid working with wet hands and clothing.

6) Use extension cords only when necessary and only on a temporary basis.

7) Request new outlets if your work requires equipment in an area without an outlet.

8) Discard damaged cords, cords that become hot, or cords with exposed wiring.

9) Before equipment is energized ensure, (1) circuit connections and layout have been checked by a laboratory technician and (2) all colleagues in your group give their assent.

10) Know the correct handling, storage and disposal procedures for batteries, cells, capacitors, inductors and other high energy-storage devices.

11) Experiments left unattended should be isolated from the power supplies. If for a special reason, it must be left on, a barrier and a warning notice are required.

12) Equipment found to be faulty in any way should be reported to the laboratory technician immediately and taken out of service until inspected and declared safe.

13) Never make any changes to circuits or mechanical layout without first isolating the circuit by switching off and removing connections to power supplies.

14) Know what you must do in an emergency, i.e. Emergency Power Off

15) For microwave and antenna trainer:

   a. You should, whenever possible, remove the power from the gun oscillator before placing yourself in front of transmitting antenna.
   b. For your safety, do not look directly into the waveguides or horn antennas while power is being supplied by the gun oscillator. Because, although the microwave is invisible, it can be dangerous at high levels or long exposure times.

16) For fiber optics trainer:

   a. Do not look inside the connector of the Optical Sources when these are operating. Although nothing can be seen, as the emitted wavelength should be out of the visible range, it can be dangerous for your sight.

b. Do not bend the optical cables with too narrow curves, as the fiber inside should cut off or damage. The minimum curving ray is around 2 cm;

c. Sometimes clean the connectors' head with a cotton wad soaked with alcohol;

Electrical Emergency Response

The following instructions provide guidelines for handling two types of electrical emergencies:

1. ***Electric Shock***:

When someone suffers serious electrical shock, he or she may be knocked unconscious. If the victim is still in contact with the electrical current, immediately turn off the electrical power source. If you cannot disconnect the power source, depress the Emergency Power Off switch.

IMPORTANT:

Do not touch a victim that is still in contact with a live power source; you could be electrocuted.

Have someone call for emergency medical assistance immediately. Administer first-aid, as appropriate.

2. ***Electrical Fire:***

If an electrical fire occurs, try to disconnect the electrical power source, if possible. If the fire is small and you are not in immediate danger; and you have been properly trained in fighting fires, use the correct type of fire extinguisher to extinguish the fire. When in doubt, push in the Emergency Power Off button.

NEVER use water to extinguish an electrical fire.

Lab Report Format

Following the completion of each laboratory exercise, a report must be written and submitted for grading. The purpose of the report is to completely document the activities of the design and demonstration in the laboratory. Reports should be complete in the sense that all information required to reproduce the experiment is contained within. Writing useful reports is a very essential part of becoming an engineer. In both academic and industrial environments, reports are the primary means of communication between engineers.

There is no one best format for all technical reports but there are a few simple rules concerning technical presentations which should be followed. Adapted to this laboratory they may be summarized in the following recommended report format:

- ABET Cover Page
- Title page
- Introduction
- Experimental Procedure
- Experimental Data
- Discussion
- Conclusions

Detailed descriptions of these items are given below.

Title Page:

The title page should contain the following information

- Your name
- ID
- Experiment number and title
- Date submitted
- Instructors Name

Introduction:

It should contain a brief statement in which you state the objectives, or goals of the experiment. It should also help guide the reader through the report by stating, for example, that experiments were done with three different circuits or consisted of two parts etc. Or that additional calculations or data sheets can be found in the appendix, or at the end of the report.

The Procedure

It describes the experimental setup and how the measurements were made. Include here circuit schematics with the values of components. Mention instruments used and describe any special measurement procedure that was used.

Results/Questions:

This section of the report should be used to answer any questions presented in the lab hand-out. Any tables and /or circuit diagrams representing results of the experiment should be referred to and discussed / explained with detail. All questions should be answered very clearly in paragraph form. Any unanswered questions from the lab hand-out will result in loss of points on the report.

The best form of presentation of some of the data is graphical. In engineering presentations a figure is often worth more than a thousand words. Some simple rules concerning graphs and figures which should always be followed. If there is more than one figure in the report, the figures should be numbered. Each figure must have a caption following the number. For example, *"Figure 1.1:DSB-SC "* In addition, it will greatly help you to learn how to use headers and figures in MS Word.

The Discussion

It is a critical part of the report which testifies to the student's understanding of the experiments and its purpose. In this part of the report you should compare the expected outcome of the experiment, such as derived from theory or computer simulation, with the measured value. Before you can make such comparison you may have to do some data analysis or manipulation.

When comparing experimental data with numbers obtained from theory or simulation, make very clear which is which. It does not necessarily mean that your experiment was a failure. The results will be accepted, provided that you can account for the discrepancy. Your ability to read the scales may be one limitation. The value of some circuit components may not be well known and a nominal value given by the manufacturer does not always correspond to reality. Very often, however, the reason for the difference between the expected and measured values lies in the experimental procedure or in not taking into account all factors that enter into analysis.

Conclusion:

A brief conclusion summarizing the work done, theory applied, and the results of the completed work should be included here. Data and analyses are not appropriate for the conclusion.

Notes

Typed Reports are required. Any drawings done by hand must be done with neatness, using a straightedge and drawing guides wherever possible.
Freehand drawings will not be accepted.

Experiment Groups

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Week 1	Introduction to Lab Devices & Safety Instructions							
Week 2	Exp 1	Exp 1	Exp 2	Exp 2	Exp 3	Exp 3	Exp 4	Exp 4
Week 3	Exp 2	Exp 2	Exp 3	Exp 3	Exp 4	Exp 4	Exp 1	Exp 1
Week 4	Exp 3	Exp 3	Exp 4	Exp 4	Exp 1	Exp 1	Exp 2	Exp 2
Week 5	Exp 4	Exp 4	Exp 1	Exp 1	Exp 2	Exp 2	Exp 3	Exp 3
Week 6	Exp 5	Exp 5	Exp 6	Exp 6	Exp 7	Exp 7	Exp 8	Exp 8
Week 7	Exp 6	Exp 6	Exp 7	Exp 7	Exp 8	Exp 8	Exp 5	Exp 5
Week 8	Exp 7	Exp 7	Exp 8	Exp 8	Exp 5	Exp 5	Exp 6	Exp 6
Week 9	Exp 8	Exp 8	Exp 5	Exp 5	Exp 6	Exp 6	Exp 7	Exp 7
Week 10	Exp 9	Exp 9	Exp 10	Exp 10	Exp 11	Exp 11	Exp 12	Exp 12
Week 11	Exp 10	Exp 10	Exp 11	Exp 11	Exp 12	Exp 12	Exp 9	Exp 9
Week 12	Exp 11	Exp 11	Exp 12	Exp 12	Exp 9	Exp 9	Exp 10	Exp 10
Week 13	Exp 12	Exp 12	Exp 9	Exp 9	Exp 10	Exp 10	Exp 11	Exp 11
Week 14	Review & Discussion							
Week 15	Final Practical Exam							

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 1 Introduction to Transmission Line

Part 1
Introduction to the Transmission Line Trainer

Objectives of this Part	**Having completed this part you will be able to:** ■ Recognize the function of each block of the Transmission Line Trainer. ■ Explain the operation of the switches and controls in the various blocks of the Transmission Line Trainer.
Equipment Required for this Part	• CT30 Transmission Line Trainer. • Power Supply.

1.1 Layout Diagram of Transmission Line Trainer

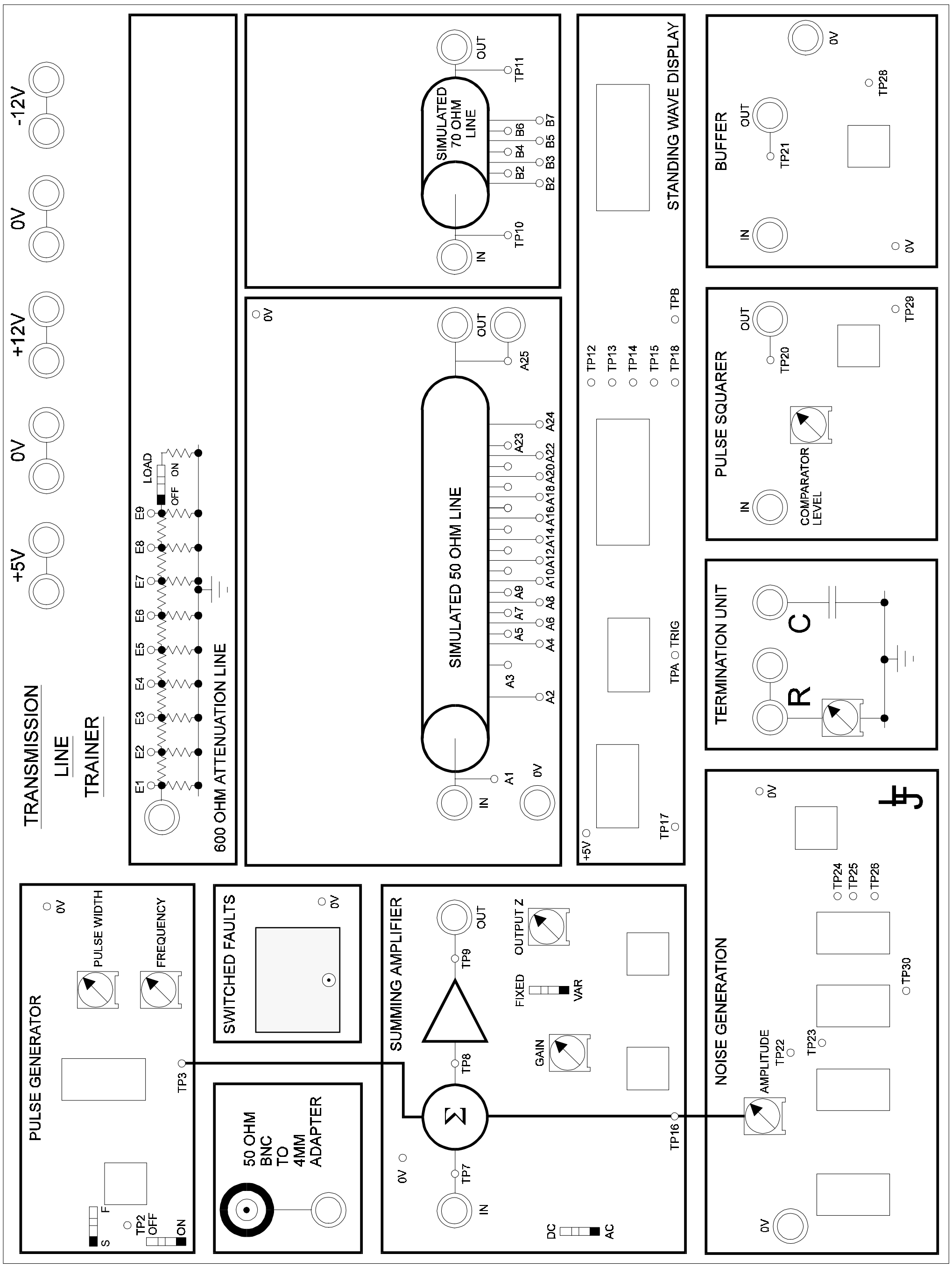


Figure 1

1.2 The Transmission Line Trainer Blocks

The **Transmission Line Trainer** can be considered as thirteen separate blocks:

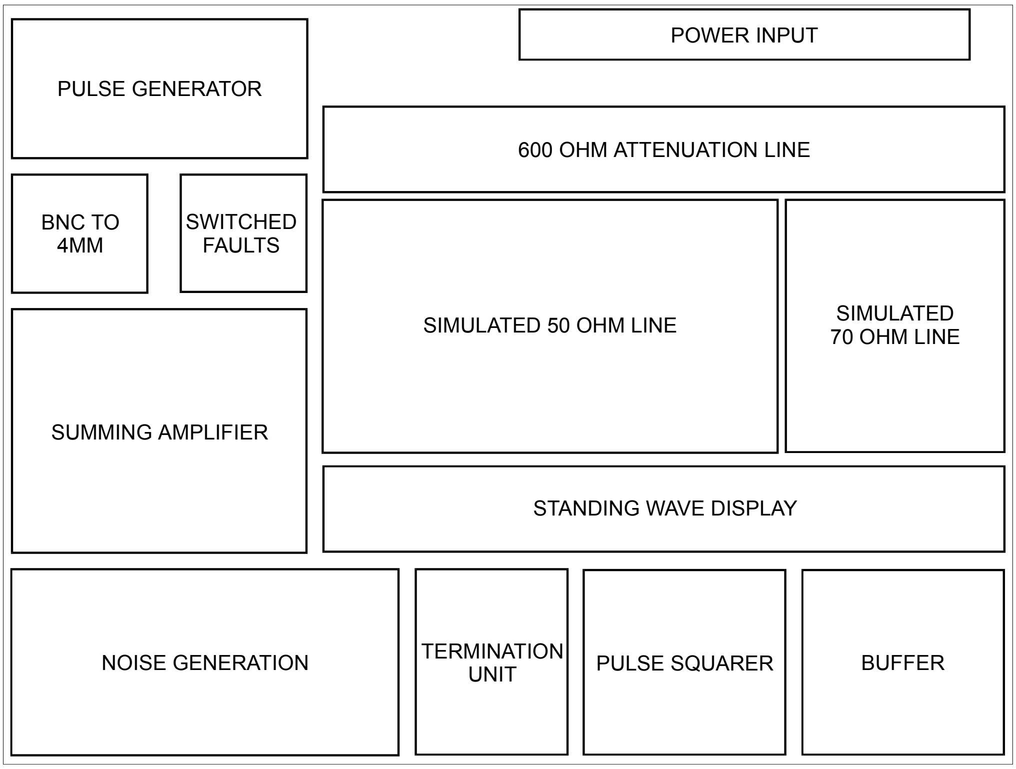


Figure 2

The function of each block will now be explained.

Power input

These are the electrical input connections necessary to power the module. The LJ Technical Systems "IC Power 60" or "System Power 90" are the recommended power supplies.

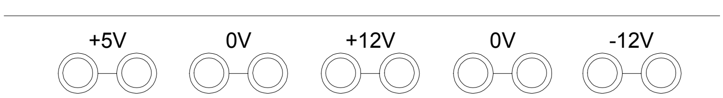
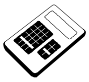


Figure 3



1.2a In addition to the 0 volt connection, the Transmission Line Trainer requires:

a only a -5 volt supply.

b only +5 volt and +12 volt supplies.

c +5 volt, -5 volt, +12 volt and -12 volt supplies.

d +5 volt, +12 volt and -12 volt supplies.

The 600 Ohm Attenuation Line

This simple circuit is designed to introduce the idea of uniform attenuation along a transmission line. It does this by simulating the series resistance of the wire and the parallel resistance between the signal carrying conductor and the ground or return wire. This parallel resistance is normally expressed in units of conductance to make the mathematics easier.

A switch allows a matched 600 ohm load to be connected to the end of the attenuation line.

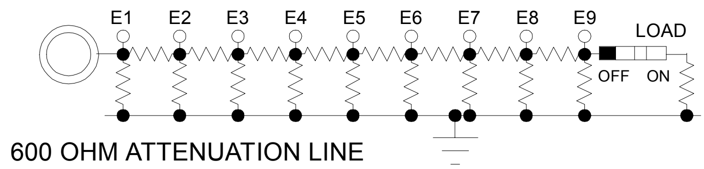


Figure 4

Simulated 50 Ohm Line

This block simulates a transmission line with a characteristic impedance of 50 ohms, using a network of inductors and capacitors (10µH and 3.3nF respectively). The simulated line is divided into 24 sections, in order to allow you to monitor signals at various points along its length. It is this simulated transmission line that you will use for most of the practical experimentation in this Laboratory Manual.

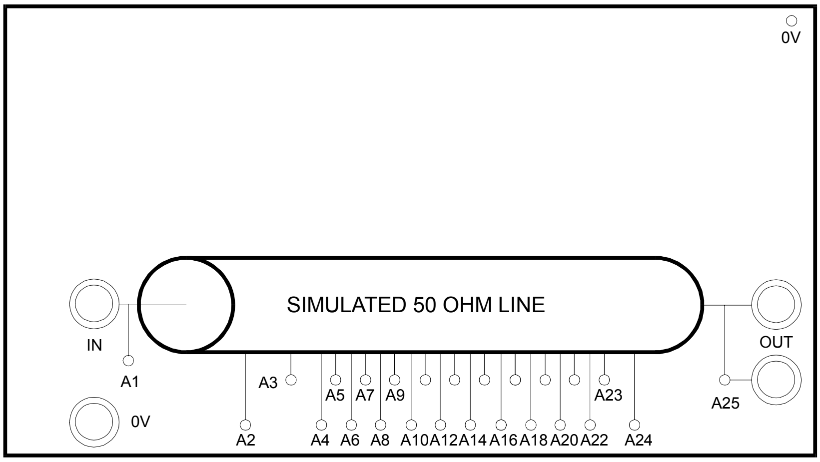


Figure 5

Simulated 70 Ohm Line

This part of the board simulates a transmission line with a characteristic impedance of 70 ohms, using a network of inductors and capacitors (10μH and 2nF respectively). The simulated line is divided into 8 sections, and is designed to illustrate the use of a transmission line for impedance matching purposes.

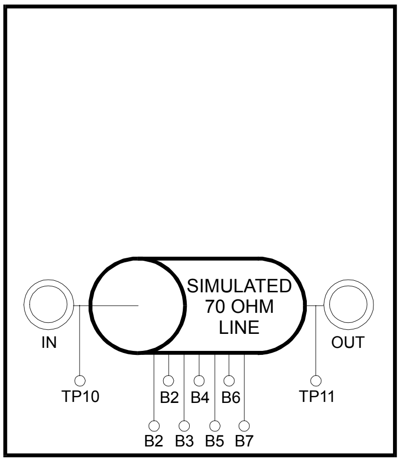


Figure 6

Standing Wave Display

The Standing Wave Display circuit allows you to display any 'standing' waves that may be present on the 50 ohm and 70 ohm lines, using your oscilloscope.

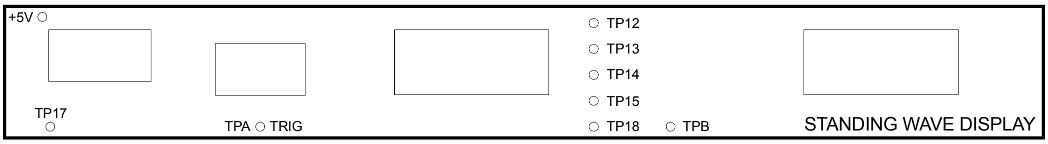


Figure 7

Termination Unit

This block provides a 100 ohm variable resistor and a capacitor to allow you to experiment with different termination conditions at the end of the transmission line.

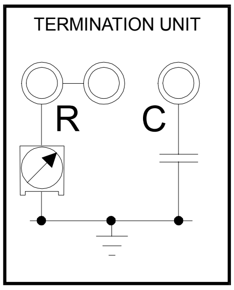


Figure 8

Pulse Generator

The Pulse Generator circuit generates a digital pulse train for transmission over the transmission line. The frequency and pulse width of the pulse train may be varied by means of the FREQUENCY and PULSE WIDTH controls. A Slow/Fast (S/F) switch allows one of two operating frequency ranges to be selected.

The Pulse Generator output is connected directly to one of the inputs of the Summing Amplifier. An ON/OFF switch allows the circuit output to be disconnected from the Summing Amplifier when the Pulse Generator is not required.

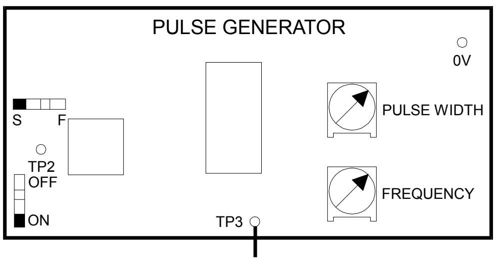


Figure 9

Noise Generation

This block can be used to show how electrical noise can affect signals received over a transmission line. The circuit generates wide-band electrical noise, whose amplitude may be adjusted by means of the AMPLITUDE control.

The output from the Noise Generation circuit is directly connected to one of the inputs of the Summing Amplifier. When the AMPLITUDE control is set to the fully counter-clockwise (minimum) position, no noise is fed to the Summing Amplifier.

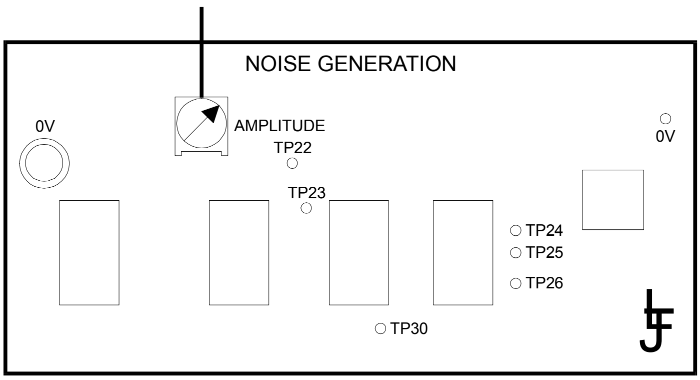


Figure10

Summing Amplifier

The Summing Amplifier adds the voltage applied to its IN socket to the signals from the Pulse Generator and Noise Generation circuits. The resulting voltage is then amplified by the Summing Amplifier, whose gain may be adjusted from +1 to approximately +9 by means of the GAIN control. The final output voltage appears at the OUT socket, and is used to drive the transmission line.

The output impedance of the Summing Amplifier can either be fixed at 50 ohms, or varied in the range of 0-100 ohms, depending on the setting of the FIXED/VAR switch. When the switch is in the VAR position, the output impedance of the Summing Amplifier is controlled by the OUTPUT Z control.

When the DC/AC switch is in the DC position, any DC components that are present at the inputs of the Summing Amplifier will be amplified and will appear at the OUT socket. If this switch is in the AC position, any DC component will be removed from the output of the Summing Amplifier.

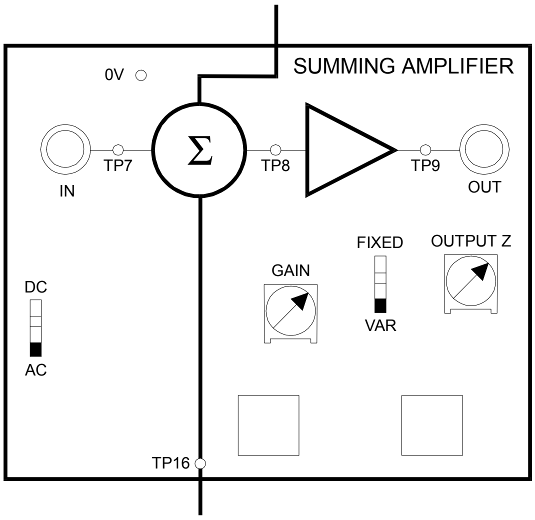


Figure 11

Pulse Squarer

This block is used to 'square up' the edges of digital pulses that have been distorted by their passage over the transmission line.

The block compares the voltage appearing at the IN socket with an adjustable DC voltage level, which is set by the COMPARATOR LEVEL control. A logic '1' voltage (+5V) is generated at the OUT socket if the voltage at the IN socket is higher than the voltage level set by the potentiometer. Otherwise, a logic '0' voltage (0V) appears at the OUT socket.

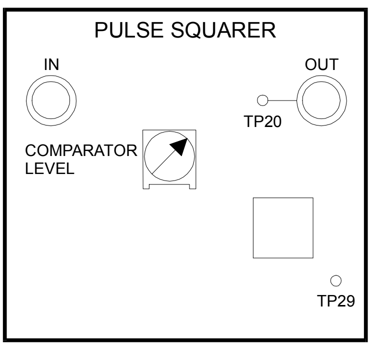
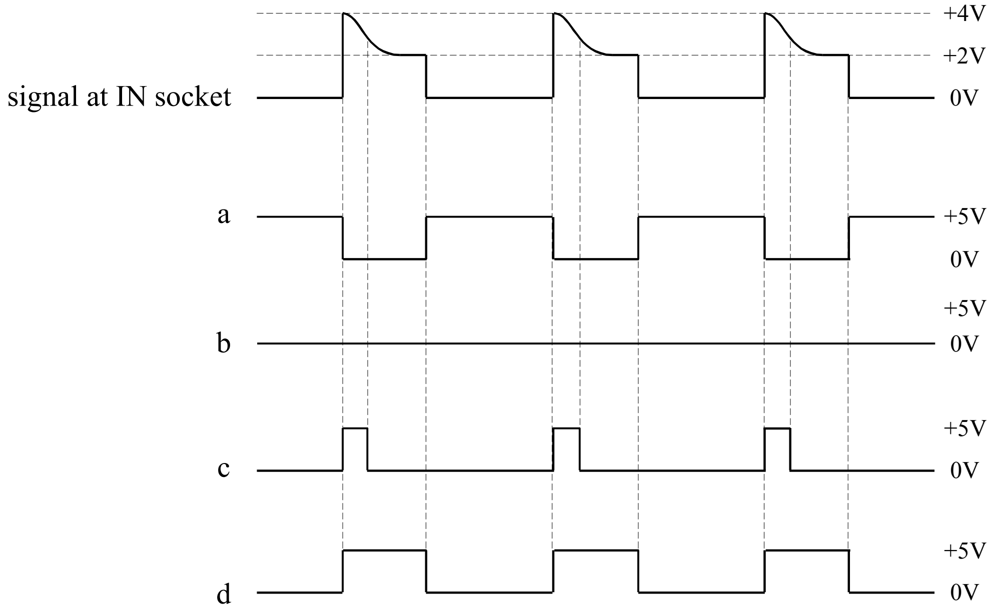


Figure 12

1.2b The signal below appears at the IN socket of the Pulse Squarer circuit. If the DC voltage set by the COMPARATOR LEVEL control is +1.5V, which of the options best illustrates the signal at the OUT socket?



- [a] a
- [b] b
- [c] c
- [d] d

1.2c For the input shown in Question 1.2b, if the DC voltage set by the COMPARATOR level control is now adjusted to +3V, which of the four options shown above best illustrates the new signal at the OUT socket?

- [a] a
- [b] b
- [c] c
- [d] d

Buffer

The Buffer is a unity-gain amplifier with a high input impedance and a low (50 ohm) output impedance. It is used to buffer analog signals arriving at the end of the transmission line.

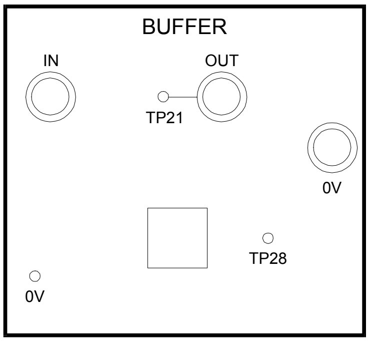


Figure 13

50 Ohm BNC to 4mm Adapter

This block allows a signal generator to be connected to the Transmission Line Trainer by means of a BNC-BNC cable. Once this connection has been made, the 4mm output socket allows the signal generator output to be patched through to the other circuits of the Transmission Line Trainer, via a standard 4mm lead.

Of course, if your signal generator lead is already terminated in 4mm plugs, then you will not need to use the BNC to 4mm Adapter, as you will be able to connect the signal generator directly to the individual circuits of the Transmission Line Trainer.

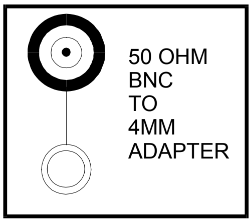


Figure 14

Switched Faults

Faults may be inserted into the circuits of the Transmission Line Trainer, by means of eight switches hidden under a lockable cover. Your instructor will be able to unlock the cover when faults are to be inserted.

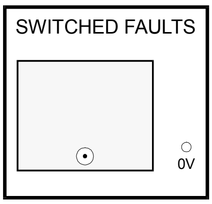


Figure 15

Student Assessment 1

1. **The simulated 50 ohm line on the Transmission Line Trainer is divided into how many sections?**

   a 8

   b 9

   c 16

   d 24

2. **The block that allows you to experiment with different line termination conditions is the:**

   a Pulse Squarer.

   b 50 ohm BNC to 4mm Adapter.

   c Termination Unit.

   d Noise Generation circuit.

3. **In order to remove any DC component that may be present at the output of the Summing Amplifier, the following switch setting must be made:**

   a FIXED/VAR switch set to FIXED.

   b DC/AC switch set to AC.

   c FIXED/VAR switch set to VAR.

   d DC/AC switch set to DC.

4. **In order to vary the output impedance of the Summing Amplifier between 0 and 100 ohms, the FIXED/VAR switch must be set to:**

   a FIXED and the OUTPUT Z control must be adjusted.

   b VAR and the GAIN control must be adjusted.

   c FIXED and the GAIN control must be adjusted.

   d VAR and the OUTPUT Z control must be adjusted.

5. The Summing Amplifier adds the voltage applied to its IN socket to the signals from the:

- [a] Pulse Generator and Noise Generation blocks.
- [b] Pulse Squarer and Noise Generation blocks.
- [c] Standing Wave Display and Pulse Squarer blocks.
- [d] Termination Unit and Pulse Generator blocks.

6. The purpose of the Standing Wave Display circuit is to allow you to:

- [a] Display standing waves on the 600 ohm attenuation line, using a digital multimeter.
- [b] Display standing waves on the 50 ohm and 70 ohm lines, using an oscilloscope.
- [c] Display standing waves on the 50 ohm line only, using an oscilloscope
- [d] Display standing waves on the 70 ohm line only, using an oscilloscope.

7. The circuit which can be used to buffer analog signals arriving at the end of the transmission line is the:

- [a] Summing Amplifier.
- [b] Termination Unit.
- [c] Buffer.
- [d] Pulse Squarer.

8. The 50 ohm BNC to 4mm Adapter:

- [a] Simulates a transmission line with a characteristic impedance of 50 ohms.
- [b] Allows a signal generator to be connected to the Transmission Line Trainer using a BNC-BNC cable.
- [c] Simulates inductance and capacitance in a BNC-BNC cable.
- [d] Is only required if your signal generator lead is terminated in 4mm plugs.

Part 2
Attenuation

Objectives of this Part

Having completed this part you will be able to:

- ■ Plot the relationship between distance and attenuation along a line using the 600 ohm Attenuation Line.
- ■ Predict the attenuation along a practical transmission line in logarithmic units of decibels and Nepers.
- ■ Describe what is meant by the characteristic impedance of a transmission line.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.
- Function Generator.
- Digital Multimeter.

2.1 Introduction

This chapter explores the concept of uniform attenuation through experiments on the 600 ohm attenuation line. This line differs from the 50 ohm and 70 ohm simulated lines in that it is purely resistive, while the other two contain reactive elements (inductors and capacitors).

DC and AC applied signals will be explored, and measurements taken along the length of the 600 ohm line to determine the attenuation characteristic of a transmission line.

Before carrying out any of the practical exercises in this Laboratory Manual, ensure that all of the electrical equipment involved is initially switched off.

■ A solid black block indicates actions to be carried out.

2.2 Practical Exercise

Our first exercise is to observe how a DC voltage is attenuated along the 600 ohm line.

- Connect the power supply to the Transmission Line Trainer in accordance with the interconnection diagram (Figure 16).

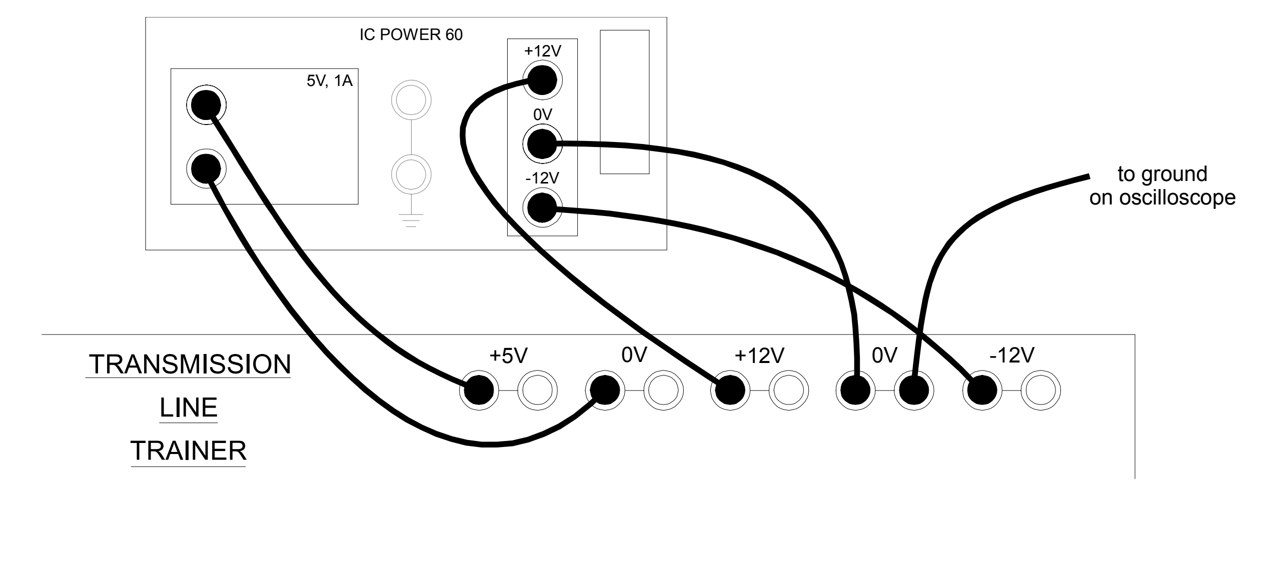


Figure 16

- Connect the ground of the oscilloscope to 0V on the Transmission Line Trainer.
- Switch on the Power Supply.
- Connect the input of the 600 ohm attenuation line to +5V.

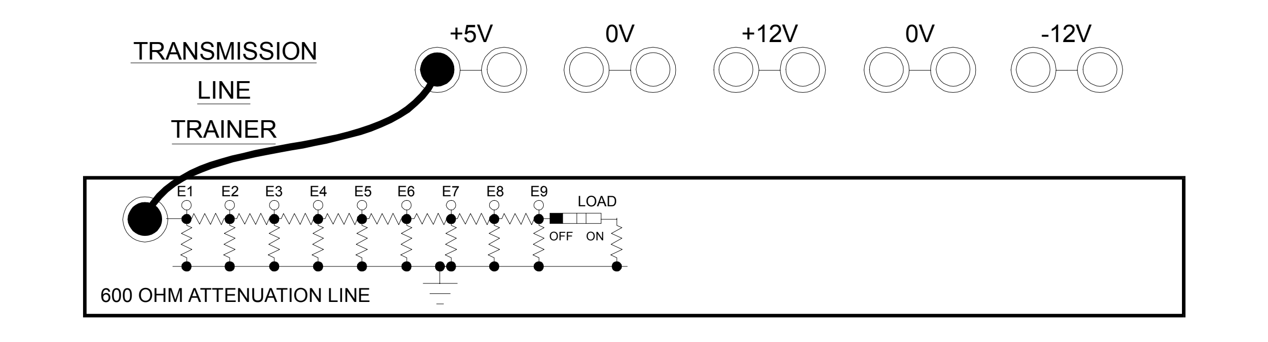


Figure 17

- Make sure the LOAD switch is switched to ON.
- Measure the voltage along the line with a voltmeter at test points E1 to E9, recording your results your workbook in Table 2.1.

Test Point	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**
Voltage									

Table 2.1

- Plot the results on the grid of Figure 18 in your workbook.

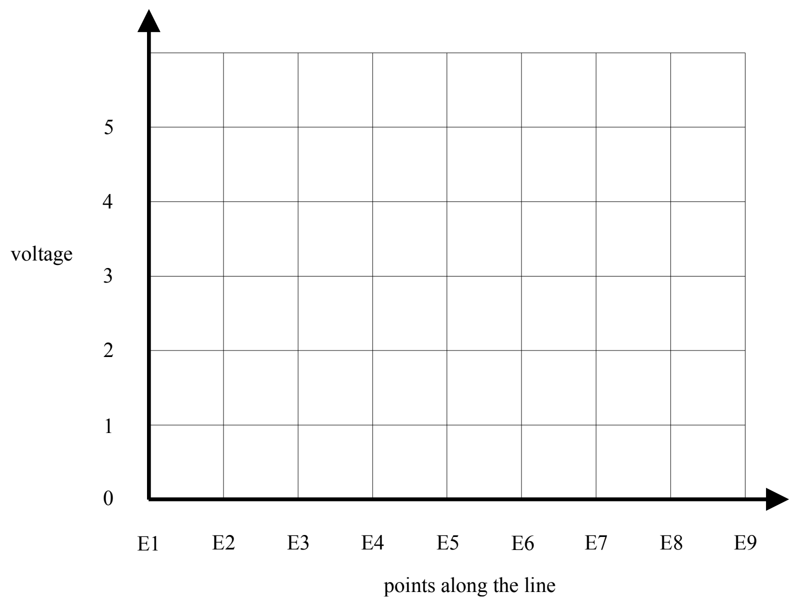


Figure 18 - Attenuation Characteristic for a DC Input Voltage

- Describe the shape of your graph in your workbook. This shape is the result of **uniform attenuation** along the line.

2.2a Which of these statements most closely describes the shape of your graph?

[a] A linear rise.

[b] A linear decay.

[c] An exponential rise.

[d] An exponential decay.

- Switch the power supply off.

2.3 Attenuation

Attenuation is sometimes expressed in Nepers. To convert the voltage ratio $\frac{V_{in}}{V_{out}}$ into Nepers (α), use the following formula:

$$\alpha = \ln\left(\frac{V_{in}}{V_{out}}\right)$$

Where 1n is a 'natural log'.

Note that attenuation can also be expressed in decibels (dB):

$$dB = 20\log_{10}\left(\frac{V_{in}}{V_{out}}\right)$$

Where V_{out} is the output voltage and V_{in} is the input voltage. Note that this formula is the same as gain expressed in decibels except that the voltage ratio is turned the other way up (reciprocated).

Multiply Nepers by 8.68 to convert to decibels.

Both Nepers and decibels are **logarithmic units**. Using logarithmic units is often a more convenient way of expressing attenuation. This is because the attenuation of a transmission line can be calculated by adding logarithmic units, rather than by the multiplication necessary when using linear units. So if a length of cable had an attenuation of 0.1 Nepers per 100m, then 200m of this cable would have an attenuation of 0.2 Nepers and 300m would have an attenuation of 0.3 Nepers.

2.3a From the measurements taken in Practical Exercise 2.2, calculate and enter the attenuation between test points E3 and E4 in Nepers.

2.3b From the measurements taken in Practical Exercise 2.2, calculate and enter the attenuation between test points E7 and E8 in Nepers.

2.3c If a cable has an attenuation of 0.02 Nepers per 10m, how much attenuation would 1km of this cable have?

- a 0.2 Nepers.
- b 2 Nepers.
- c 200 Nepers.
- d 20 Nepers.

2.3d Calculate and enter the decibel equivalent of 0.7 Nepers.

2.4 Practical Exercise

In Practical Exercise 2.2 we observed how a DC voltage was attenuated along the line. As the attenuation line is made up of resistors it is not reactive, so the experiment can be repeated using a signal generator in place of the +5V supply and measuring the signal with an oscilloscope.

- Connect the power supply as in Practical Exercise 2.2.
- Switch on the power supply.
- Connect the signal generator output to the input of the 600 ohm attenuation line.
- Use an oscilloscope to set up the input (at test point 1) to be a sinewave with a peak-to-peak amplitude of 5 volts and a frequency of 1kHz.
- Use the oscilloscope to measure the signals at test points E1 to E9 recording your results in Table 2.2 of your workbook.

Test Point	E1	E2	E3	E4	E5	E6	E7	E8	E9
Voltage									

Table 2.2

- Plot the results in your workbook on the grid of Figure 19.

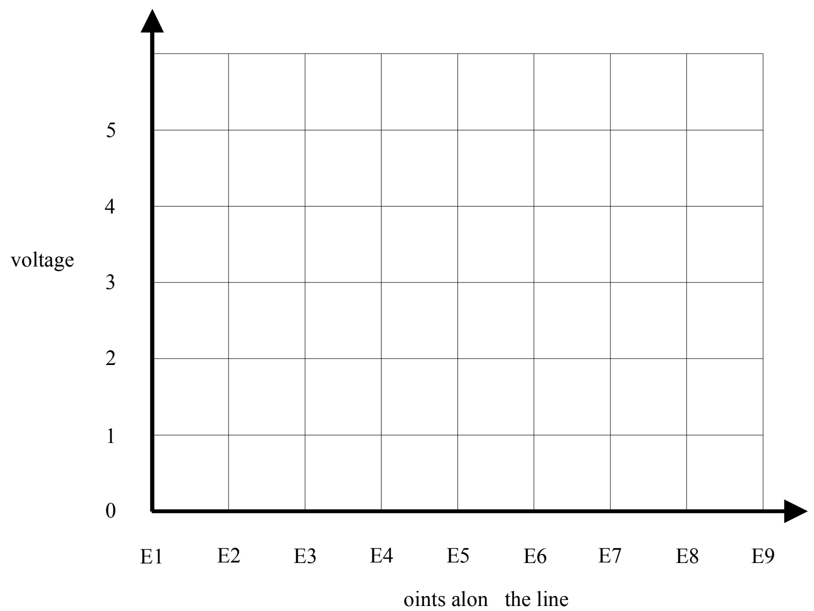


Figure 19 - Attenuation Characteristic for an AC Input Signal

You should notice that the graphs for Figure 18 and Figure 19 are very similar. If you choose a different frequency there should be no difference in the shape of the graph plotted.

- Switch the power supply off.

2.5 Introduction to Characteristic Impedance

So far nothing has been mentioned about why this line is a **600 ohm** attenuation line. The reason this is a 600 ohm line is that it has an impedance that characterizes this line. This impedance is called its **Characteristic Impedance**. All transmission lines have a characteristic impedance. Note that as this line is made up of resistors this could be termed 'characteristic resistance' but for the sake of uniformity the term characteristic impedance will be used.

One of the concepts of the characteristic impedance, is the impedance of an infinitely long line. This concept will be explored in the following practical exercise.

2.6 Practical Exercise

- Disconnect any input from the 600 ohm attenuation line.

- Connect a digital multimeter, set to measure resistance, between the input of the 600 ohm attenuation line and 0V. Measure the input resistance of the line with the LOAD switched to ON, recording this value in your workbook.

2.6a Enter your measured value of input resistance with the load connected.

2.7 Summary of Practical Exercises

These exercises have shown how a signal is attenuated along a transmission line.

i) The signal amplitude falls exponentially along the line with distance.

ii) The attenuations for the individual sections of the line are approximately equal.

iii) In the case of this resistive line, the waveshape is unimportant. For example, it could be a DC level, sinewave or rectangular.

In a real transmission line, the attenuation along the line is mainly due to the series resistance of the wire and the parallel conductance between the signal carrying conductor and the ground or return wire. A line whose series resistance and parallel conductance are high will have high attenuation. Such a line is known as a **high loss** line. Conversely, a line with low series resistance/parallel conductance will have low attenuation. Such a line is referred to as a **low loss** line.

A real transmission line not only has resistive elements distributed along its length but also reactive elements (capacitance and inductance). The following chapters show what the effects of these reactive elements are.

The concept of Characteristic Impedance has been introduced.

Notes:

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Student Assessment 2

1. **The characteristic impedance of the attenuation line that has been used for the practical exercises of this chapter is:**
   - a 50 ohms.
   - b 70 ohms.
   - c 600 ohms.
   - d 1000 ohms.

2. **A practical transmission line would contain:**
   - a elements of resistance.
   - b elements of capacitance.
   - c elements of inductance.
   - d all of the above.

3. **Nepers are calculated by taking:**
   - a the natural log of a power ratio.
   - b the log (base 10) of a voltage ratio.
   - c the log (base 10) of a power ratio.
   - d the natural log of a voltage ratio.

4. **Three similar cables each have a known attenuation. The total attenuation of the three cables connected together in series can be calculated by:**
   - a adding together their individual attenuations in Nepers.
   - b adding together their individual attenuations expressed as voltage ratios.
   - c multiplying together their individual attenuations in Nepers.
   - d multiplying together their individual attenuations in decibels.

5. Attenuation can be expressed in decibels using the formula:

[a] $dB = 20\log_{10}\left(\frac{V_{out}}{V_{in}}\right)$

[b] $dB = 10\log_{10}\left(\frac{V_{out}}{V_{in}}\right)$

[c] $dB = 20\log_{10}\left(\frac{V_{in}}{V_{out}}\right)$

[d] $dB = 20\ln\left(\frac{V_{out}}{V_{in}}\right)$

6. A plot of voltage against distance for a transmission line gives an exponential decay. This is caused by:

[a] no attenuation along the line.

[b] uneven attenuation along the line.

[c] exponential attenuation along the line.

[d] uniform attenuation along the line.

7. To convert Nepers to decibels, multiply by:

[a] 2.68

[b] 4.68

[c] 8.68

[d] 12.68

8. All transmission lines have:

[a] a characteristic resistance.

[b] a characteristic impedance.

[c] a 600 ohm resistance.

[d] infinite length.

Part 3
Delay Using a Pulse Input

Objectives of this Part

Having completed this part you will be able to:

- Measure a delayed pulse using the simulated 50 ohm line on the Transmission Line Trainer.
- Predict the delay of a line when the primary line constants are known.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.

3.1 The Lumped Parameter Line

An ideal cable has no series resistance or series inductance and no parallel capacitance or parallel conductance. In a real cable, all of these are distributed continuously along the length of the cable.

Figure 20 shows the equivalent circuit of a short section of cable. If the cable is of length x, then dx represents a section of this cable. This equivalent circuit is known as the **lumped parameter model** as the inductance, capacitance and resistance of the section of line is shown as individual components 'lumped' together. All the elements in this circuit are per unit length.

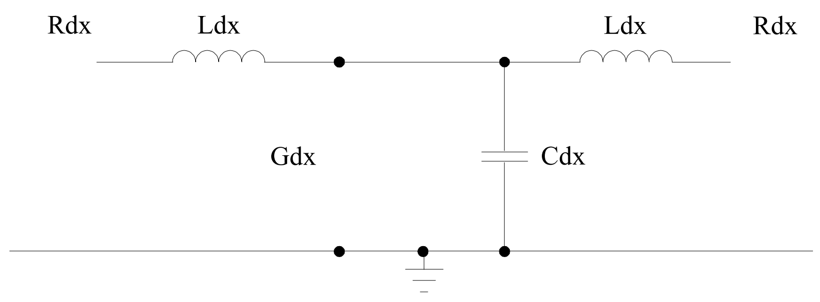


Figure 20

As dx $\rightarrow$ 0 the number of sections increases and the length represented by each section decreases. The model becomes a closer approximation to the real continuous transmission line. The four quantities R, L, G, and C in Figure 20 are called the **primary line constants**.

3.2 Propagation Velocity

Information sent in the form of an electrical signal along a transmission line will take a finite length of time to travel from one end to the other. The transmission or propagation velocity in a typical coaxial cable ranges from 2 x 10^8m/s to almost
3 x 10^8m/s (the speed of light in air is approximately 3 x 10^8m/s) so the delay ranges from 5ns/m to 3.33ns/m. The actual transmission velocity depends on the physical properties of the line. These physical properties of size and dimension of the cable determine the values of the primary line constants.

By using the lumped parameter model of a cable shown in Figure 20 the propagation velocity can be calculated as:

$$v = \frac{dx}{dt} = \frac{1}{\sqrt{CL}}$$

Where C and L are capacitance and inductance per unit length.

This can be expressed as a time delay per unit length:

$$D = \sqrt{CL}$$

giving D in seconds per unit length.

In the Transmission Line Trainer, capacitors and inductors are used to make the simulated 50 ohm line. One effect of this is to make the delay relatively long and so easier to measure.

3.2a What name is given to the components of inductance, capacitance and resistance that are distributed along a line?

[a] Distributed values.

[b] Primary line constants.

[c] Distributed line constants.

[d] Primary line components.

3.2b If a line has an inductance of 10μH per meter and a line capacitance of 3.3nF per meter, enter the delay in nano seconds per meter.

3.3 Practical Exercise

In this practical exercise we shall observe a pulse delayed by the simulated 50 ohm line.

- Connect the power supply to the Transmission Line Trainer as in Figure 16.
- Ensure all switched faults are off.
- Switch the Pulse Generator ON and set the speed to fast (F).

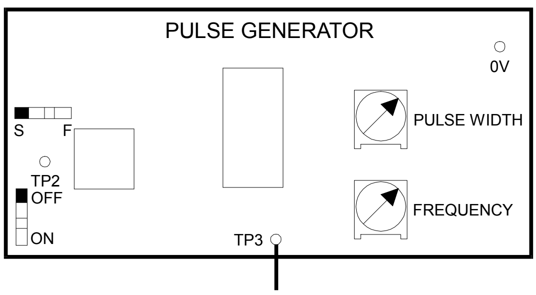


Figure 21

- Use a 4mm lead to connect the output of the Summing Amplifier to the input of the simulated 50 ohm line.

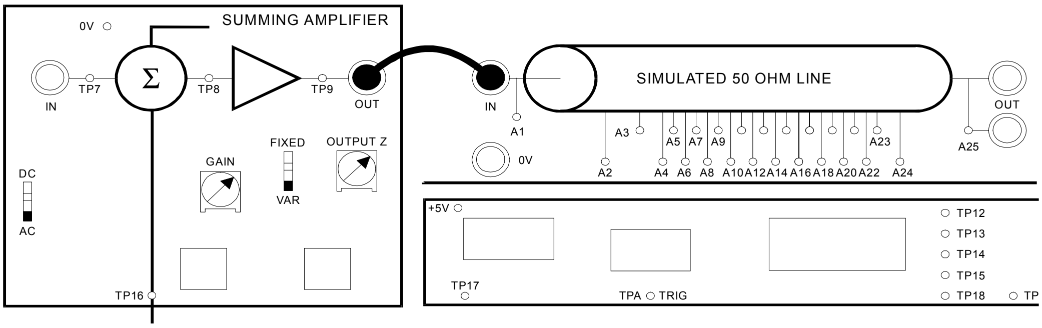


Figure 22

- Set the Summing Amplifier coupling to DC.
- Set the Summing Amplifier output impedance to FIXED.
- Set the Summing Amplifier gain to minimum (GAIN control turned fully counter-clockwise).
- Set the Noise Generator AMPLITUDE control to minimum (fully counter-clockwise).

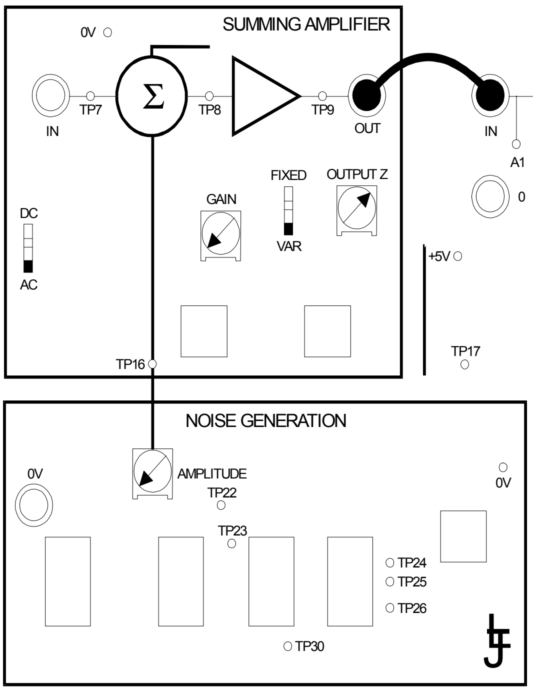


Figure 23

■ Use a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit. Set the variable resistor to its mid travel point (arrow pointing upwards).

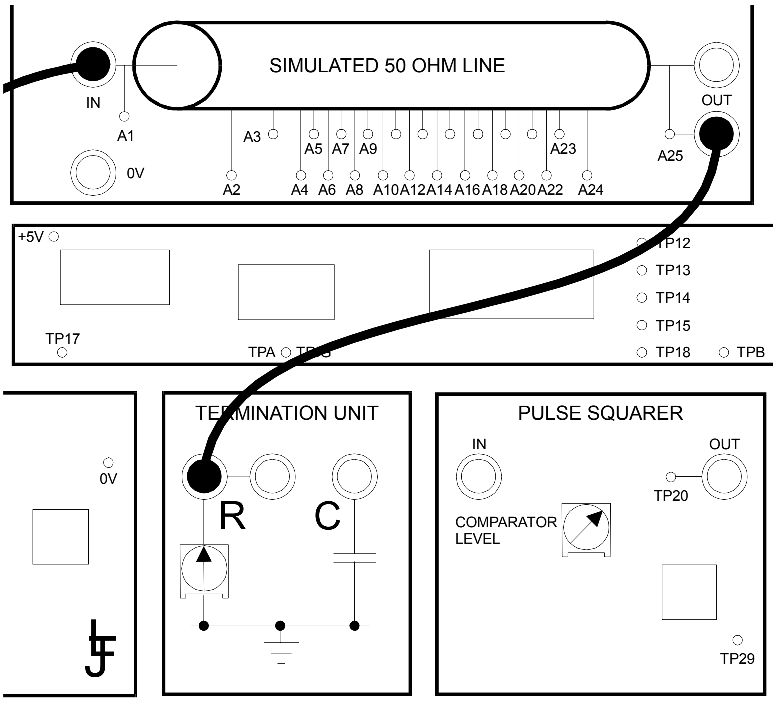


Figure 24

The input of the simulated 50 ohm line will be referred to as the transmitter end and the output of the simulated 50 ohm line will be referred to as the receiver end. Thus a pulse at the transmitter end is referred to as the transmitted pulse.

■ Switch on the power supply.

■ Connect channel 1 of the oscilloscope to examine the input of the simulated 50 ohm line at test point **A1**.

■ Connect channel 2 of the oscilloscope to examine the output of the simulated 50 ohm line at test point **A25**.

■ Connect your oscilloscope's external trigger to **TP2** (in the Pulse Generator block) and switch the oscilloscope to external triggering.

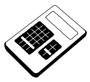
- Vary the PULSE WIDTH and the FREQUENCY controls to understand how the pulse is delayed. Set the PULSE WIDTH control to give a 3µs pulse at test point A1 and set the oscilloscope so that the delay between the transmitted and received pulses can be observed.

- Adjust the GAIN control of the Summing Amplifier to give a pulse amplitude of 2 volts at the input of the simulated 50 ohm line.

- In your workbook, sketch the two pulse waveforms in Waveform Sketch 3.1.

- Measure the delay between the rising edges of the pulses and record this value in your workbook.

3.3a Enter your measured delay (in µs) between the transmitted and received pulses on the simulated 50 ohm line.



3.3b Enter the peak amplitude (in volts) of the received pulse when connected to the simulated 50 ohm line.

- Switch off the power supply.

3.4 Pulse Degradation

You may have noticed that the received pulse looks less like a pulse than the transmitted pulse. One of the main reasons for this is that the capacitor and inductor network acts as a low pass filter (this will be explored in Chapter 11). To overcome this the Pulse Squarer circuit is used.

3.5 Practical Exercise

- Connect the simulated 50 ohm line as in Practical Exercise 3.3.

- Use a 4mm lead to connect the resistor in the Termination Unit to the input of the Pulse Squarer circuit.

- Switch on the power supply.

- Use the oscilloscope to observe the input of the simulated 50 ohm line at test point **A1** and the output of the Pulse Squarer circuit at **TP20**.

- Adjust the GAIN control on the Summing Amplifier to give a pulse amplitude of 2 volts at the input of the simulated 50 ohm line.

- Adjust the COMPARATOR LEVEL control so that the output pulse from the Pulse Squarer has the same width as the transmitted pulse.

  The output pulse from the Pulse Squarer circuit is now reconstituted. Note that the output pulse now has an amplitude of 5V. This is because the Pulse Squarer has output levels of +5V and 0V.

- Switch off the power supply.

3.6 Summary of Practical Exercises

These exercises have shown that a signal is delayed along a transmission line.

i) The signal is delayed according to the primary line constants.

ii) The primary line constants are determined by the physical construction of the cable.

In practical communications systems the delay of signals along a transmission line is not usually a problem, as timing information is sent along with the data. A more serious problem is the pulse degradation that occurs. In real cables there are repeater stations every 2km or so. This repeater station amplifies the signal and if the data is digital (a pulse), then a circuit similar to the Pulse Squarer circuit can be used to reconstitute the signal.

In the next chapter the importance of correct line matching will be explored.

Notes:

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Student Assessment 3

1. A real cable has distributed along its length:

- a series inductance and parallel conductance.
- b series capacitance and parallel inductance.
- c series resistance and parallel inductance.
- d all of the above.

2. A propagation velocity of a typical coaxial cable would range between:

- a 1×10^8m/s to 2×10^8m/s
- b 1.5×10^8m/s to 2.5×10^8m/s
- c 2×10^8m/s to 3×10^8m/s
- d 3×10^8m/s to 4×10^8m/s

3. The time that a signal takes to travel down a cable is dependent upon:

- a series inductance and parallel conductance.
- b its physical construction.
- c its length.
- d all of the above.

4. One effect of using capacitors and inductors to make a simulated line rather than using a length of real cable, is to:

- a increase the time delay so that it is easier to measure.
- b decrease the time delay so that it is harder to measure.
- c low pass filter the signal.
- d attenuate the signal.

5. The Pulse Generator provided on the Transmission Line Trainer has a variable control for adjusting the:

- a output amplitude.
- b output impedance.
- c output frequency.
- d gain.

Part 4
Matching Using a Pulse Input

Objectives of this Part

Having completed this part you will be able to:

- Recognize that a transmission line must be terminated with a resistor equal in value to its characteristic impedance to avoid reflections.
- Measure reflections using the simulated 50 ohm line.
- Predict the termination state from the reflected pulse.

Equipment Required for this Chapter

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.

4.1 Characteristic Impedance

In Chapter 2 we measured the characteristic ‘impedance’ of the 600 ohm attenuation line but in real life the characteristic impedance of a cable cannot be measured with an ohmmeter.

A cable which has a uniform construction and uniform conditions along its length will have uniform primary line constants (see Chapter 3, Section 3.1).

At any one frequency the cable will have an impedance. Mathematical analysis applied to Figure 20 in Chapter 3 can be used to give a formula to describe this impedance at any frequency.

It turns out that this formula is:

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Where R, L, G, and C are the primary line constants and ω is the angular frequency equal to $2\pi f$.

The term Z_o is known as the **characteristic impedance**.

From the above formula when $\omega = 0$ (at DC) the characteristic impedance becomes:

$$Z_o = \sqrt{\frac{R}{G}}$$

But at high frequencies where $j\omega L >> R$ and $j\omega C >> G$ it becomes:

$$Z_o = \sqrt{\frac{L}{C}}$$

It is this high frequency term that is usually quoted as the characteristic impedance for a cable. As Z_o is **not** a complex number, the characteristic impedance of the line will be resistive at high frequencies.

Note that if the R and G components can be ignored at the frequency that is being used, then the characteristic impedance can still be considered to be resistive. This is normally the case.

4.2 Reflections and Matching

A line correctly terminated with a resistor of value Z_o acts as an infinite length line, in that all power is dissipated in the termination (assuming a low loss line) and no reflections take place. This condition is known as **matched**. The termination is known as the **load**.

Where the line is not terminated with a resistor of value Z_o, the signal is reflected back down the line to the input. This condition is know as **mismatched**. Examples of the extreme cases of mismatch appear in Figure 25 and 26 below.

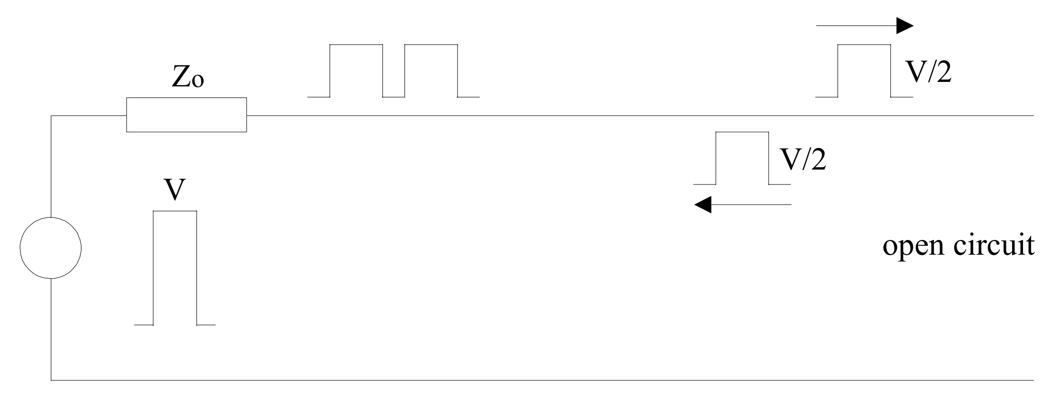

Figure 25

Figure 25 shows a pulse generator feeding an open circuit line. No power is absorbed by the load so all of the voltage is reflected back down the line. In Figure 25 the delay in the line is longer than the pulse width, so a double pulse will be seen at the pulse generator.

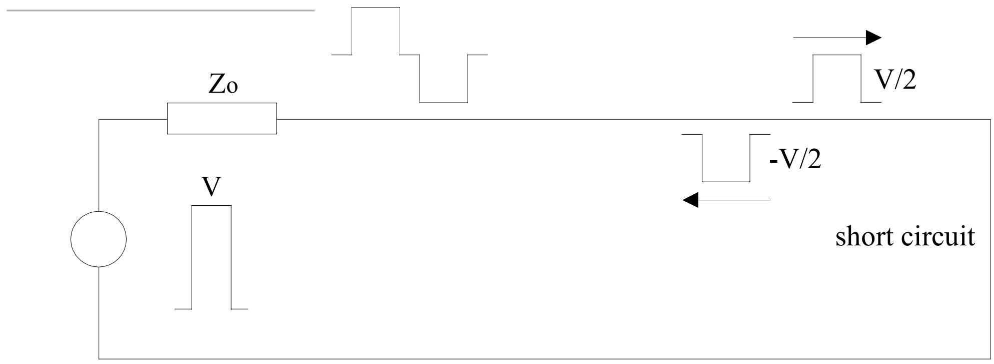

Figure 26

Figure 26 shows a similar example to Figure 25 except the line has a short circuit termination. This time an inverted pulse is reflected back down the line.

Note that in Figure 25 and Figure 26 the pulse generator is matched to the line, so the reflected wave is absorbed in the pulse generator.

The voltage ratio of the reflected wave to the transmitted wave is defined as the voltage reflection coefficient (the Greek letter gamma - Γ):

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

Where Z_L is the impedance of the load.

When the line is open circuit, $Z_L = \infty$ so $\Gamma = 1$ and the pulse is reflected back non-inverted.

When the line is short circuit, $Z_L = 0$ so $\Gamma = -1$ and the pulse is reflected back inverted.

When the line is matched, $Z_L = Z_o$ so $\Gamma = 0$ and no pulse is reflected.

The characteristic impedance may be thought of in one of the following ways:

i) The value which the load must take in order to avoid reflections.

ii) The impedance seen at the sending end of an infinitely long line.

iii) The impedance seen at any point of a matched line.

4.2a What is the condition that gives an inverted, reflected pulse?

- [a] Matched termination.
- [b] Open circuit termination.
- [c] Short circuit termination.
- [d] Open circuit generator.

4.2b Enter the value of resistor (in ohms) needed to correctly terminate a line with a characteristic impedance of 100 ohms.

4.3 Practical Exercise

In this exercise we shall observe reflected pulses using the simulated 50 ohm line.

- Connect the power supply to the Transmission Line Trainer as in Figure 16.
- Ensure all switched faults are off.
- Switch the Pulse Generator ON and set the speed to fast (F).
- Use a 4mm lead to connect the output of the Summing Amplifier to the input of the simulated 50 ohm line.
- Set the Summing Amplifier coupling to DC.
- Set the Summing Amplifier output impedance to FIXED.
- Set the Noise Generator AMPLITUDE control to minimum (fully counter-clockwise).
- Using a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit. Set the control of the variable resistor to its mid point.
- Switch on the power supply.

- Connect channel 1 of the oscilloscope to examine the input of the simulated 50 ohm line at test point **A1**.

- Connect channel 2 of the oscilloscope to examine the output of the simulated 50 ohm line at test point **A25**.

- Connect your oscilloscope's external trigger to **TP2** and switch the oscilloscope to external trigger.

- Set the PULSE WIDTH control to give a pulse of about 3μs duration and set the oscilloscope to view the transmitted and the received pulses on the display.

- Adjust the GAIN control on the Summing Amplifier to give a pulse amplitude of 2 volts at the input of the simulated 50 ohm line (the transmitted pulse).

- Align the 'space' part of the pulse waveform to a 0V reference line on the oscilloscope.

- Turn terminating resistor R to its minimum value (fully counter-clockwise) so giving the simulated 50 ohm line a **short circuit** termination.

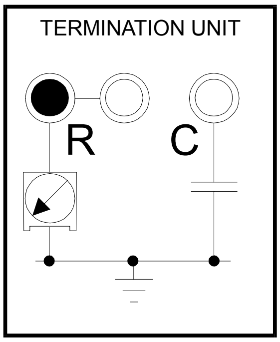

Figure 27

- View the reflected pulse. Sketch the input and output waveforms in your workbook (Waveform Sketch 4.1). Vary the PULSE WIDTH control of the pulse generator to see what happens as the pulse width changes.

4.3a Enter the amplitude of the *reflected* pulse (in V) at test point A1 when the line has a short circuit termination.

- Re-adjust the input signal's pulse width to 3μs.
- Disconnect the simulated 50 ohm line from variable resistor R to give the line an **open circuit** termination. Sketch the input and output waveforms in your workbook (Waveform Sketch 4.2).

4.3b Enter the amplitude of the *reflected* pulse (in V) at test point A1 when the line has an open circuit termination.

- Re-connect the simulated 50 ohm line to variable resistor R, ready for the next practical exercise.
- Switch off the power supply.

4.4 Using Reflections

Could this phenomenon that you have seen be of use? Imagine that you were at one end of a long cable and needed to know if the other end was connected correctly.

You do not want to walk to the other end and make sure that the cable was connected as it is a long way. So another way would be to use a pulse generator and an oscilloscope (and all the necessary leads) to set up an experiment similar to the one we have done. By observing if there are any reflections, the connection state can be determined. This will be covered in more detail in Chapter 13, which talks about **Time Domain Reflectometry** (TDR).

4.5 Avoiding Reflections

Computers are often connected together to form a network using coaxial cable. The information is transmitted along a single cable to each computer and this cable is terminated with a special terminating resistor. Each computer is sending and receiving information. If the cable is disconnected at any point, not only does it prevent certain computers from communicating, but it also stops the whole network as the cable is no longer matched and reflected pulses interfere with the real data.

So it is normal to connect computers to networks using ‘T’ pieces. This allows individual computers to be disconnected from the network while ensuring that the other computers remain connected to a matched network cable.

4.6 Practical Exercise

In the previous practical exercise the sending end was always matched and the terminating end was varied to see the effects of reflections. This meant that the pulse was reflected at the termination end and absorbed at the receiving end.

It is possible to vary the impedance of the sending end. If the sending end and the terminating ends are not matched to the transmission line, then a pulse can be reflected at the terminating end only to be reflected back by the sending end. This exercise investigates this.

■ Set up the Transmission Line Trainer as described in the first 15 steps of Practical Exercise 4.3. Each step is indicated by a ■.

■ Switch the output impedance of the Summing Amplifier to VAR.

■ Adjust the OUTPUT Z control on the Summing Amplifier and the R control on the Termination Unit, observing the effects of mismatching. Note that each control can be varied from zero ohms when turned fully counter-clockwise, to 100 ohms when fully clockwise.

■ Make notes in your workbook about the effects you have observed.

■ Switch off the power supply.

4.7 Summary of Practical Exercises

These exercises have shown reflections when a transmission line is mismatched.

i) The transmission line has a characteristic impedance.

ii) The transmission line is matched when terminated at each end with an impedance equal in value to the characteristic impedance. This is normally resistive.

iii) The signal is reflected according to the termination:

   a) If the line is matched then no reflections occur.

   b) If the line is terminated with a short circuit an inverted pulse is reflected.

   c) If the line is terminated with an open circuit a non-inverted pulse is reflected.

This chapter has shown the importance of correctly terminating or matching a transmission line. In practical systems, for example where data is sent down a cable, then mismatching the line is likely to result in errors.

In the next chapter the use of a reactive termination is explored.

Notes:

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Student Assessment 4

1. **The term used to represent characteristic impedance is:**
   - a C_i
   - b Z_i
   - c Z_o
   - d Z_c

2. **The characteristic impedance of a cable at high frequencies is:**
   - a resistive.
   - b reactive.
   - c dependent on C and G.
   - d dependent on R and L.

3. **A low loss line that is correctly terminated:**
   - a acts as an infinite length line.
   - b dissipates all power in the load.
   - c has no reflections.
   - d all of the above.

4. **The voltage ratio of the reflected wave to the transmitted wave is defined as the:**
   - a voltage refraction coefficient.
   - b voltage reflection coefficient.
   - c voltage matching coefficient.
   - d voltage termination coefficient.

Continued...

Student Assessment 4 Continued...

5. The condition that gives a non-inverted reflected pulse is:

- [a] a matched termination.
- [b] an open circuit termination.
- [c] a short circuit termination.
- [d] an open circuit generator.

6. To match the simulated 50 ohm line on the Transmission Line Trainer, the variable resistor in the Termination Unit has to be turned:

- [a] counter-clockwise.
- [b] one quarter turn from fully counter-clockwise.
- [c] to the midway position.
- [d] fully clockwise.

Notes:

Exercise 1

Calibration of the Variable Attenuator

EXERCISE OBJECTIVES

When you have completed this exercise, you will be familiar with the concepts of attenuation and insertion losses. You will be able to characterize a variable attenuator by plotting its attenuation-versus-blade position curve.

DISCUSSION

Guided Propagation of Microwaves

It is generally agreed that a microwave signal is a signal whose fundamental frequency is between 300 MHz and 300 GHz (1 GHz = 10^9 Hz). In terms of wavelength, a microwave signal has a wavelength between 0.1 cm and 100 cm.

A waveguide is a hollow mechanical structure that permits propagation of microwave signals from one point to another with the least possible loss. The most commonly used waveguides are those having a rectangular form. There are, however, a variety of rectangular waveguides, each being identified according to its internal dimensions.

Each type of waveguide allows microwave propagation within a particular frequency band. The waveguide you will use with the Lab-Volt Microwave Technology Training System is of the

- R-100 type, according to the IEC (International Electrotechnical Commission) standard;
- WR-90 type, according to the EIA (Electronic Industries Association) standard; or
- WG-16 type in the British system.

The internal dimensions of this type of waveguide are as follows: 10.16 mm x 22.86 mm (0.4 in x 0.9 in). The external dimensions are: 12.7 mm x 25.4 mm (0.5 in x 1 in). An R-100 waveguide will transmit microwave signals within the following frequency band: 8.2 to 12.4 GHz.

Basic Components of the Lab-Volt Microwave Technology Training System

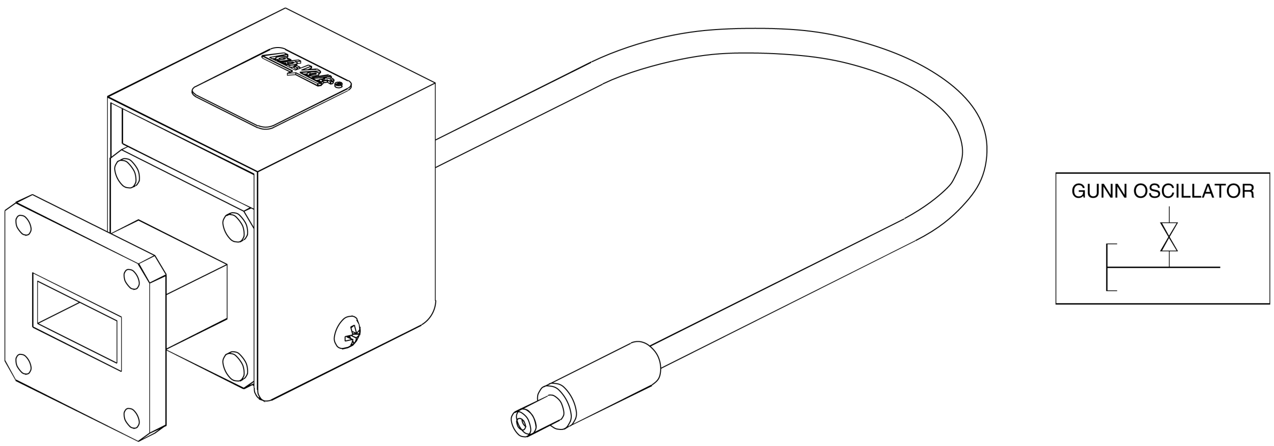
The Lab-Volt Gunn Oscillator

The microwave signal source you will use in this course is called a **Gunn oscillator**. Figure 1-1 shows the Lab-Volt Gunn Oscillator, Model 9510. This oscillator generates a microwave signal having a frequency of 10.525 GHz.

Calibration of the Variable Attenuator

The power of the microwave signal generated by the Gunn Oscillator can be varied by varying the voltage applied to this oscillator by the Lab-Volt Gunn Oscillator Power Supply.

The maximum power of the microwave signal, at 10.525 GHz, varies from one Gunn Oscillator to another: it ranges from 10 mW (minimum) to 25 mW (maximum) approximately.



(a) (b)

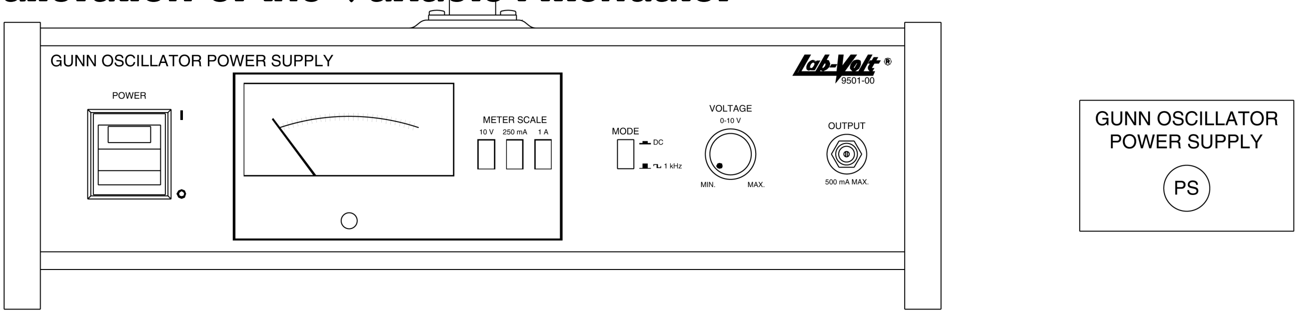
Figure 1-1. The Gunn Oscillator and its symbolic representation.

The Lab-Volt Gunn Oscillator Power Supply

The Lab-Volt Gunn Oscillator Power Supply, Model 9501, shown in Figure 1-2, is intended for use with the Gunn Oscillator. The OUTPUT of the Gunn Oscillator Power Supply connects to the Gunn Oscillator, via a power switch inside the Data Acquisition Interface.

The VOLTAGE control knob of the Gunn Oscillator Power Supply allows you to change the voltage applied to the Gunn Oscillator and, therefore, to vary the output power of the Gunn Oscillator's output signal. The frequency of this signal cannot be varied. It is fixed (10.5 GHz approximately).

The function of the MODE pushbutton switch of the Gunn Oscillator Power Supply will be discussed later in this manual.



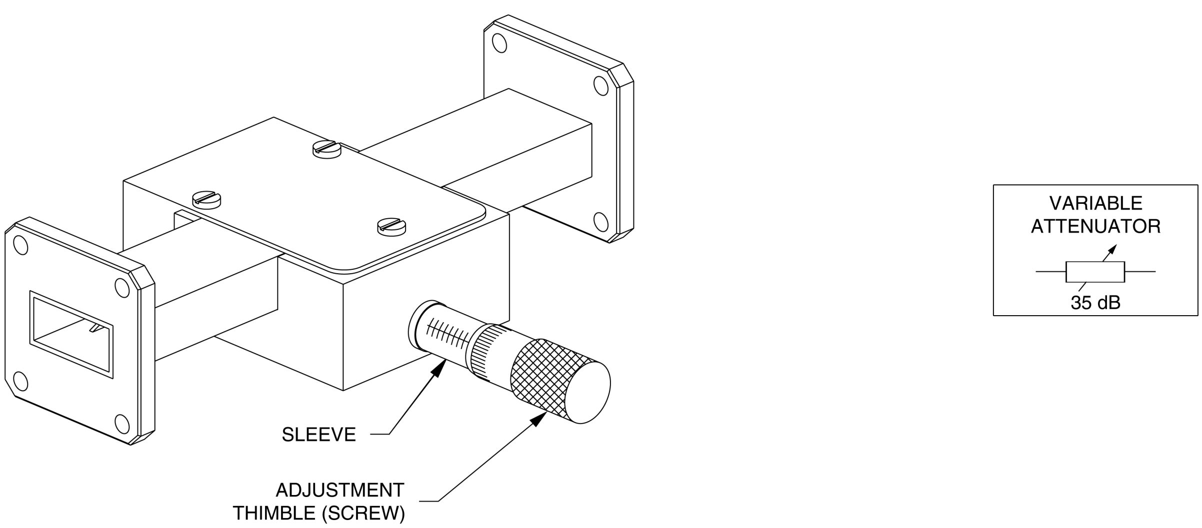
(a) (b)

Figure 1-2. The Gunn Oscillator Power Supply for the Gunn Oscillator and its symbolic representation.

The Lab-Volt Variable Attenuator

A microwave variable attenuator is a device used to reduce the power level at the input of microwave components. Two common types of variable attenuators are the rotary vane attenuator and the side vane attenuator.

Figure 1-3 shows the Lab-Volt Variable Attenuator, Model 9532. This attenuator is of the side vane type. A plastic fiberglass blade with a resistive coating is used to produce attenuation. The blade is inserted vertically into the waveguide, parallel to the short side walls.



(a) (b)

Figure 1-3. The Variable Attenuator and its symbolic representation.

The attenuation produced by the attenuator depends on the position of the blade in the waveguide. The blade position can be changed by using the attenuator's micrometer. The attenuation increases as the blade is moved towards the center of the waveguide.

The Variable Attenuator's micrometer is read by referring to the linear scale on the sleeve and the annular scale on the thimble (adjustment screw). The linear scale on the sleeve represents the variation range of the micrometer (e.g. 0 to 10 mm approximately). One full revolution of the thimble will move 0.5 mm on the linear scale of the sleeve. Read off the sleeve first, then add the fine adjustment from the thimble, taking off the reading at the intersection of the thimble's scale and the sleeve's scale.

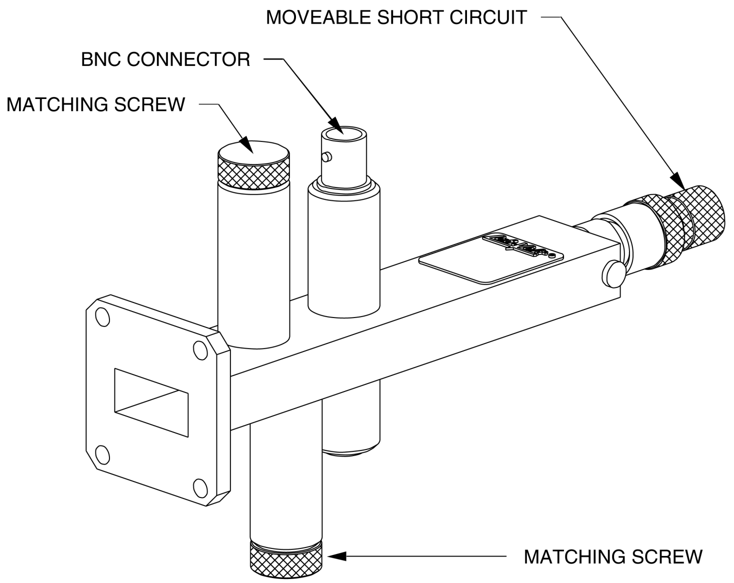
The attenuation characteristics differ from one attenuator to the other. Therefore, each attenuator must be characterized individually, by plotting its attenuation-versus-blade position curve. This will be performed in Exercise 4.

The Lab-Volt Thermistor Mount

A **thermistor** is a resistive element whose resistance is a function of its internal temperature. When a thermistor is placed in the path of a microwave signal, it absorbs energy from the signal, causing its internal temperature to increase. This increase in internal temperature causes the resistance of the thermistor to decrease.

This characteristic of the thermistor makes it useful to measure the power of a microwave signal propagating through a waveguide. The thermistor is inserted into the waveguide, and connected to one branch of a Wheatstone bridge located in the Data Acquisition Interface (this will be covered in detail in Exercise 2).

Figure 1-4 shows the Lab-Volt Thermistor Mount, Model 9521. This device consists of a thermistor permanently housed in a section of waveguide. Two **matching screws** and a moveable short circuit are used to maximize the microwave power that reaches the thermistor.



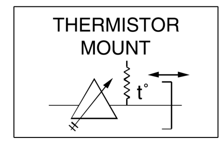


Figure 1-4. The Thermistor Mount.

Assembly of Components

The components of the Microwave Technology Training System must be connected so that there are no discontinuities at the waveguide junctions. To avoid faulty connections, the spacing of the holes in the waveguide flanges are not the same in both directions.

Figure 1-5 shows a permanent connection of two components, using four screws.

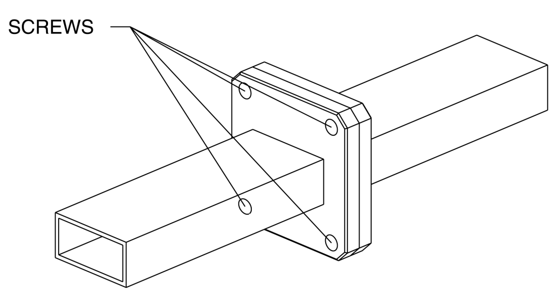


Figure 1-5. Connection of two microwave components with screws.

For short-term use, two screws or two quick-lock fasteners are sufficient to firmly connect two components together. Figure 1-6 shows the connection of two components, using the Lab-Volt quick-lock fasteners (included in your Cable and Accessories Kit, Model 9590). To connect two components together:

- First align the holes in the flanges of the components to be connected together.

- Then, insert the metal pin of a quick-lock into one hole, and the pin of a second quick-lock into the hole at the opposite corner, as Figures 1-6 (a) and 1-6 (b) show.

- Finally, push the plastic pieces against the flanges, as Figure 1-6 (c) shows. The components are now firmly connected together.

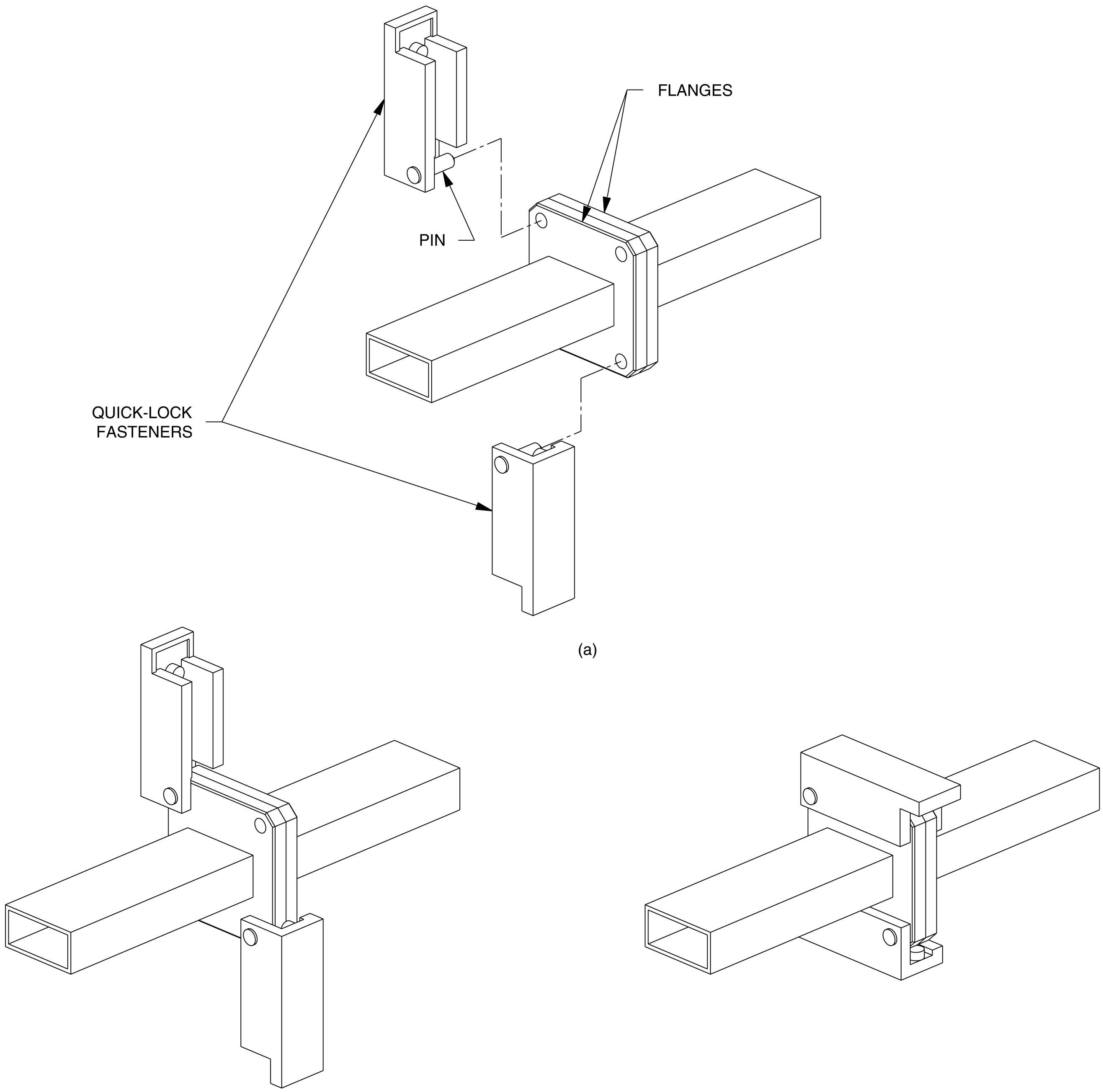


Figure 1-6. Connection of two microwave components by using the Lab-Volt quick-lock fasteners.

Calibration of the Variable Attenuator

To ensure the secure mounting of microwave setups at various heights, the accessories that come with the Microwave Technology Training System include Waveguide Supports. Each support consists of a base and adjustable height rod with setscrew, as Figure 1-7 shows.

Waveguides are inserted into the plastic bracket at the end of the support rod and gently pressed into place. The height of the setup can be adjusted by sliding the rods vertically, and securing the setscrews.

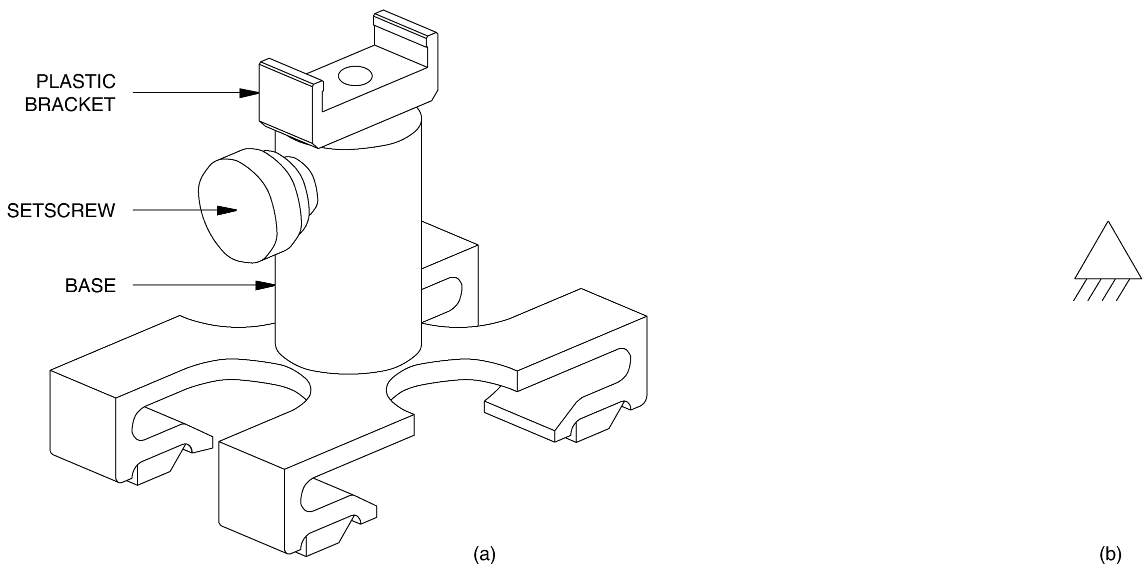


Figure 1-7. Waveguide Support and its symbolic representation.

Using the Power Meter of the LVDAM-MW Software

The Power Meter of the LVDAM-MW Software is used to measure relative (dBm) and absolute (mW) power levels. It is intended to be used in conjunction with the Lab-Volt Thermistor Mount.

The Thermistor Mount is connected to the analog input of the Lab-Volt Data Acquisition Interface (DAI) that is dedicated to the Power Meter: MULTI-FUNCTION INPUT 4 (see Figure 1-8). The power factor (η) on the Thermistor Mount's waveguide is entered in LVDAM-MW, and Input 4 is assigned to the Power Meter.

The Data Acquisition Interface (DAI), which contains a Wheatstone bridge, provides the LVDAM-MW software with data used to measure and display the signal power in real time on the Power Meter. The measurement scale is changed by changing the gain on Input 4. The Power Meter MUST be zeroed each time the measurement scale is changed.

Figure 1-8 shows the DAI. This module stacks on top of the Gunn Oscillator Power Supply. A female, self-aligning, multi-pin connector at the top of the Gunn Oscillator

Power Supply fits into a male connector on the bottom of the DAI, supplying power to the DAI.

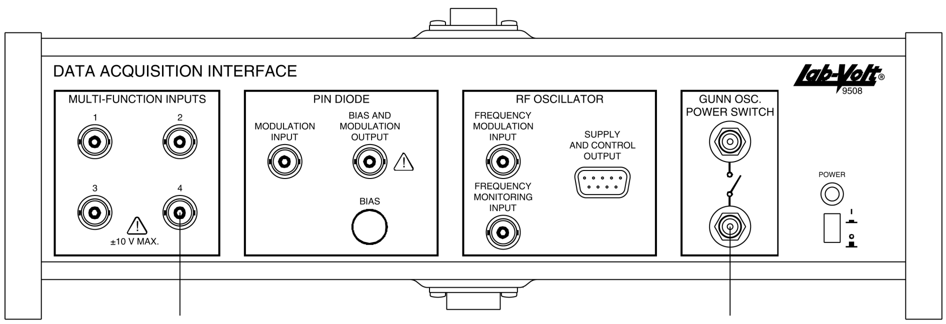


Figure 1-8. The Data Acquisition Interface (DAI).

Attenuation

Attenuation is the decrease in the power of a signal propagating between two points, a and b, point b being farther from the source than point a. In most cases, attenuation constitutes an undesirable phenomenon. In certain cases, however, attenuation is required by the system design.

Attenuation is usually expressed in decibels (dB).

At lower signal frequencies, where voltage or current measurements are easier to perform, attenuation is normally measured in terms of a voltage or current.

The formula for calculating the attenuation is:

$$A = 20 \log \frac{V_b}{V_a}$$

where A = Attenuation in signal power (dB);
log = Base-10 logarithm;
V_b = Signal voltage at point b (V);
V_a = Signal voltage at point a (V).

For example, if the ratio V_b/V_a is 0.75, the attenuation in signal power between points a and b will be 2.5 dB.

At high frequencies, attenuation is expressed in terms of the logarithm of a power ratio. The formula used is as follows:

$$A = 10 \log \frac{P_b}{P_a}$$

where A = Attenuation in signal power (dB);
log = Base-10 logarithm;
P_b = Signal power at point b (W);
P_a = Signal power at point a (W).

When the signal power at points a and b is measured in dBm, the attenuation, in dB, can be calculated by subtracting the power at point b, in dBm, from the power at point a, in dBm.

$$A = P_a - P_b$$

where A = Attenuation in signal power (dB);
P_a = Signal power at point a (dBm);
P_b = Signal power at point b (dBm).

Point b is farther from the source than point a.

Insertion Loss

Insertion loss, when talking about a component, is the attenuation caused by the insertion of the component into a circuit. Insertion loss is expressed in decibels (dB).

As Figure 4-1 shows, insertion loss is normally measured in terms of the logarithm of the ratio between the power supplied by the source, P_S, before the component insertion, to the power fed to the load, P_L, after the component insertion.

The insertion can be calculated by using the formula:

$$\text{Insertion Loss (dB)} = 10 \log \frac{P_L}{P_S}$$

where P_L = Power fed to the load after component insertion (W);
P_S = Power supplied by the source before component insertion (W).

> **Note:** *Sometimes, the term insertion loss is used by manufacturers to refer to the minimum attenuation of a signal through a component. In this case, the insertion loss of, for example, a variable attenuator, would be the residual attenuation produced by the attenuator when it is set to provide a minimum attenuation.*

As Figure 1-9 shows, a number of phenomena combine to limit the power fed to the load, P_L. Thus, some amount of power is dissipated as heat due to the warming up of the conductors when the current is flowing, and due to dielectric losses in the component. Also, a certain amount of the power that reaches the component is reflected back towards the source. The **reflected power** further reduces the power transferred to the load.

In general, the insertion loss of a component is a function of the source and load impedances. To measure the insertion loss and to characterize microwave components in a uniform way, the impedances of the source and the load must be matched to the waveguide.

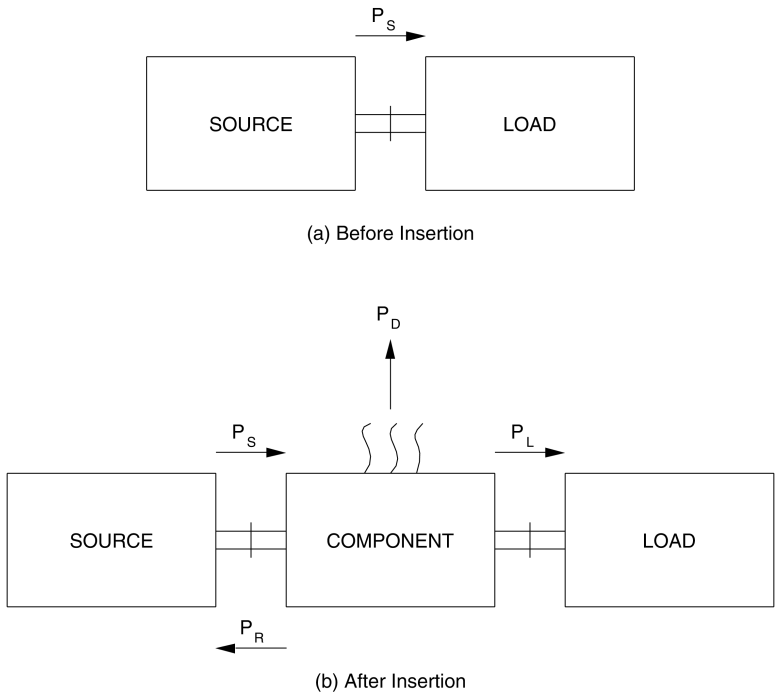


Figure 1-9. Insertion loss caused by a component.

Techniques Used to Measure Attenuation and Its Insertion Losses

There are many techniques used to measure attenuation and insertion losses. The best known methods are:

- the RF substitution method;
- the DC substitution method;
- the IF (intermediate frequency) substitution method;
- and the power ratio method.

In this exercise, you will use the power ratio method to measure the attenuation produced by a component. This method has the following advantages: it is simple, it provides relatively precise measurements, and it requires little equipment with no modulating signal:

- Firstly, the load is connected directly to the microwave source, and the power fed to the load is measured;

- Then the component is inserted between the source and the load, and the power fed to the load is measured again;

- The ratio of the two measured power values allows calculation of the attenuation and insertion loss produced by the component.

Calibration of the Variable Attenuator

It is important to note that the precision of the measurements made with the power ratio technique is highly dependent on the accuracy of the power meter. Thus, if the detector of the power meter is a thermistor, the power ratio method has a main disadvantage: the attenuation measurement range is limited to about 30 dB. Furthermore, this technique cannot be used to measure low power levels.

Procedure Summary

In this exercise, you will characterize the Lab-Volt Variable Attenuator.

You will first measure the maximum power fed to a known load, the Thermistor Mount, when the Variable Attenuator is not in the circuit. The measured power will be the maximum (reference) level.

You will then insert the Variable Attenuator into the circuit and measure the power fed to the Thermistor Mount for various positions of the Variable Attenuator's blade. Then you will plot the attenuation-versus-blade position curve of the Variable Attenuator.

IT IS IMPORTANT THAT YOU KEEP A COPY OF THE OBTAINED CURVE, AS IT WILL BE USED AS A REFERENCE IN THE NEXT EXERCISES.

EQUIPMENT REQUIRED

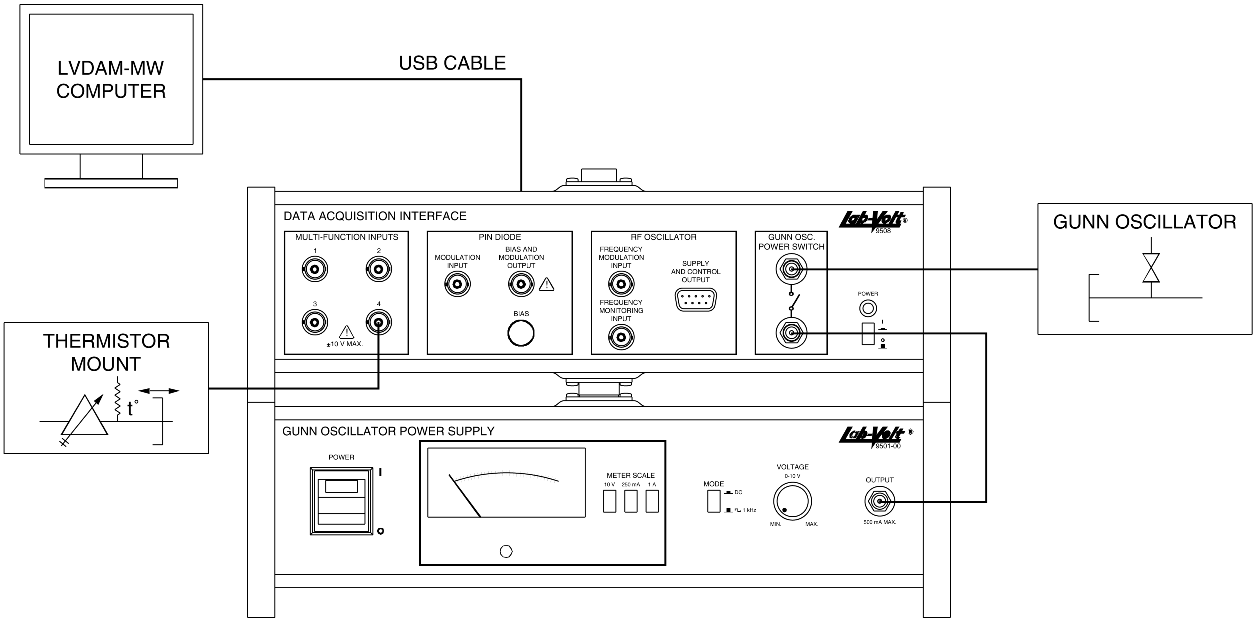
Refer to the Equipment Utilization Chart, in Appendix F of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

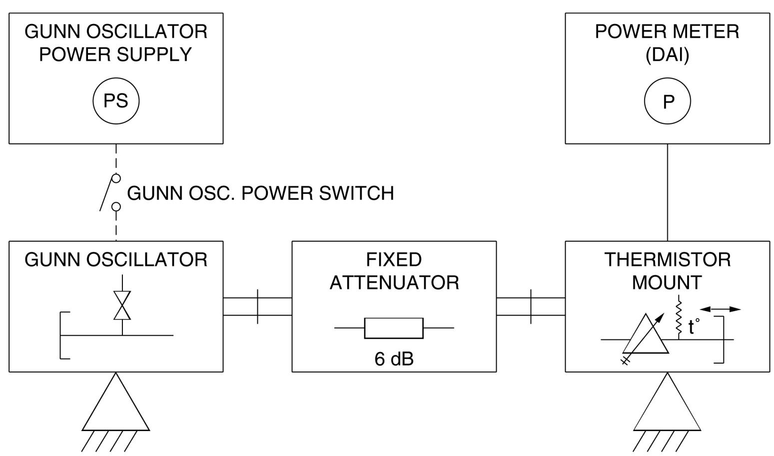
Measuring the Maximum Power Fed to the Load

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as shown in Figure 1-10.

> **Note:** *Before connecting the Thermistor Mount, unscrew the matching screws so that they do not penetrate into the waveguide; the screws do not need to be removed from the posts.*



(a)



(b)

Figure 1-10. Computer and module arrangement (showing electrical connections to microwave components), and microwave setup.

☐ 2. Make the following settings on the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . DC
METER SCALE . . . . 10 V

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Wait for about 5 minutes to allow the modules to warm up.

☐ 4. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 4 . . . . Power Meter
Gain Input 4 . . . . 0 dB

☐ 5. In LVDAM-MW, start the Power Meter and set it to display dBm readings. Enter the power factor (η) indicated on the Thermistor Mount's waveguide. Then, perform zeroing of the Power Meter.

☐ 6. Set the Gunn Oscillator supply voltage to 8.5 V.

On the Thermistor Mount, loosen the knurled lock-nut that holds the moveable short circuit into place. Adjust the short circuit to the position nearest the waveguide which gives a maximum reading on the Power Meter. Then, adjust each matching screw of the Thermistor Mount to maximize the power reading. Fine tune if necessary. Finally, lock the moveable short circuit into position.

☐ 7. Note and record the reading of the Power Meter. This corresponds to the maximum power, that is, in the context of this exercise, the power read when the Variable Attenuator is not in the circuit.

Maximum power = ______ dBm

Characterizing the Variable Attenuator by Plotting its Attenuation-Versus-Blade Position Curve

☐ 8. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF, so that there is no microwave signal injected into the waveguide.

Taking care not to modify the Thermistor Mount adjustments, modify your microwave circuit so as to insert the Variable Attenuator between the 6-dB Fixed Attenuator and the Thermistor Mount, as Figure 1-11 shows.

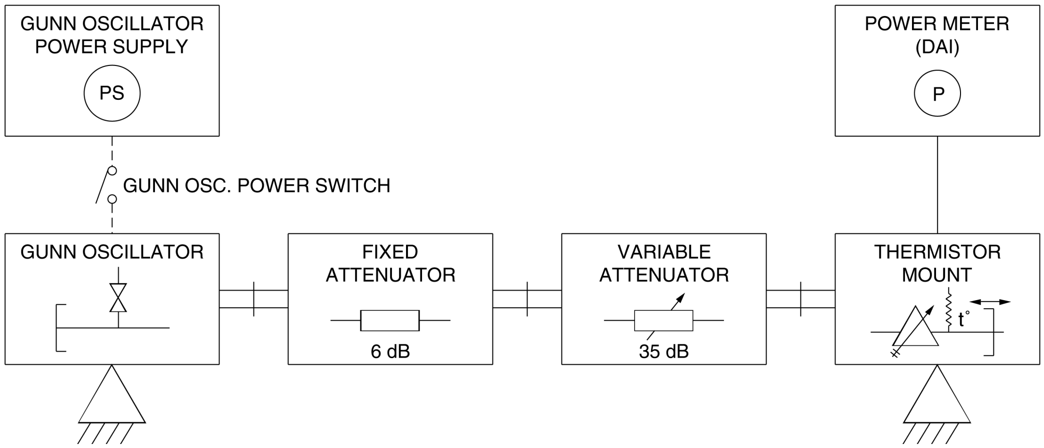


Figure 1-11. Microwave circuit used to measure the attenuation provided by the Variable Attenuator (for attenuations lower than 15 dB).

☐ 9. Set the blade position of the Variable Attenuator to 0.0 mm.

☐ 10. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to ON to inject the microwave signal into the waveguide.

Wait for about 5 minutes to allow the modules to warm up.

☐ 11. In LVDAM-MW, select the Data Table function, which will bring up the Data Table. In this Table, enter the column titles and figures already recorded in Table 1-1 below, and then save your Data Table.

Calibration of the Variable Attenuator

ATTENUATOR BLADE'S POSITION (mm)	POWER METER READING (dBm)	ATTENUATION (dB)
0		
0.5		
1		
1.5		
2		
2.5		
3		
3.5		
4		
4.5		
5		

Table 1-1. Characterizing the Variable Attenuator.

☐ 12. Fill in the first empty row of the Data Table just created by performing the steps below.

a. Note and record the reading of the Power Meter in the row "0.0 mm" under the column "POWER METER READING".

b. Subtract this power meter reading from the maximum power recorded in step 7, in order to obtain the attenuation produced by the Variable Attenuator, in dB. Record your result in the row "0.0 mm" under the column "ATTENUATION". Save your work.

Maximum Power (dBm) – Power Meter Reading (dBm) = Attenuation (dB)

☐ 13. Continue to fill the other rows of the Data Table. To do this, adjust the blade position of the Variable Attenuator to each of the other settings listed in the leftmost column of the Data Table. For each new setting, redo step 12 and record your results in the Data Table.

When the measured power gets **close to the lower end** of the measuring scale of the Power Meter (the indicator bar and the displayed value turn from green to blue), select the next lower scale by setting the Gain Input 4 to 20 dB (and then 40 dB). Each time you change the scale (that is, Gain Input 4) **do not forget to perform zeroing of the Power Meter**.

> **Note:** *You may not be able to fill in the last rows of the Data Table due to the very low power level measurements required to to so.*
>
> *When the Gain on Input 4 is set to 40 dB, it is recommended that you perform zero adjustment each time before taking a new reading on the Power Meter to maintain accuracy of measurement.*

☐ 14. In LVDAM-MW, select the Graph function of the Data Table and plot the attenuation-versus-blade position curve of the Variable Attenuator, using a linear scaling for both the X and Y axes.

The obtained curve should resemble that shown in Figure 1-12. Your curve can be slightly different than the one shown in Figure 4-4, as the attenuation characteristics differ from one variable attenuator to the other.

Print your graph and keep it in a safe place, as it will be required in several exercises of this manual. Also make sure you have properly saved the corresponding Data Table.

☐ 15. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 16. Close the LVDAM-MW software.

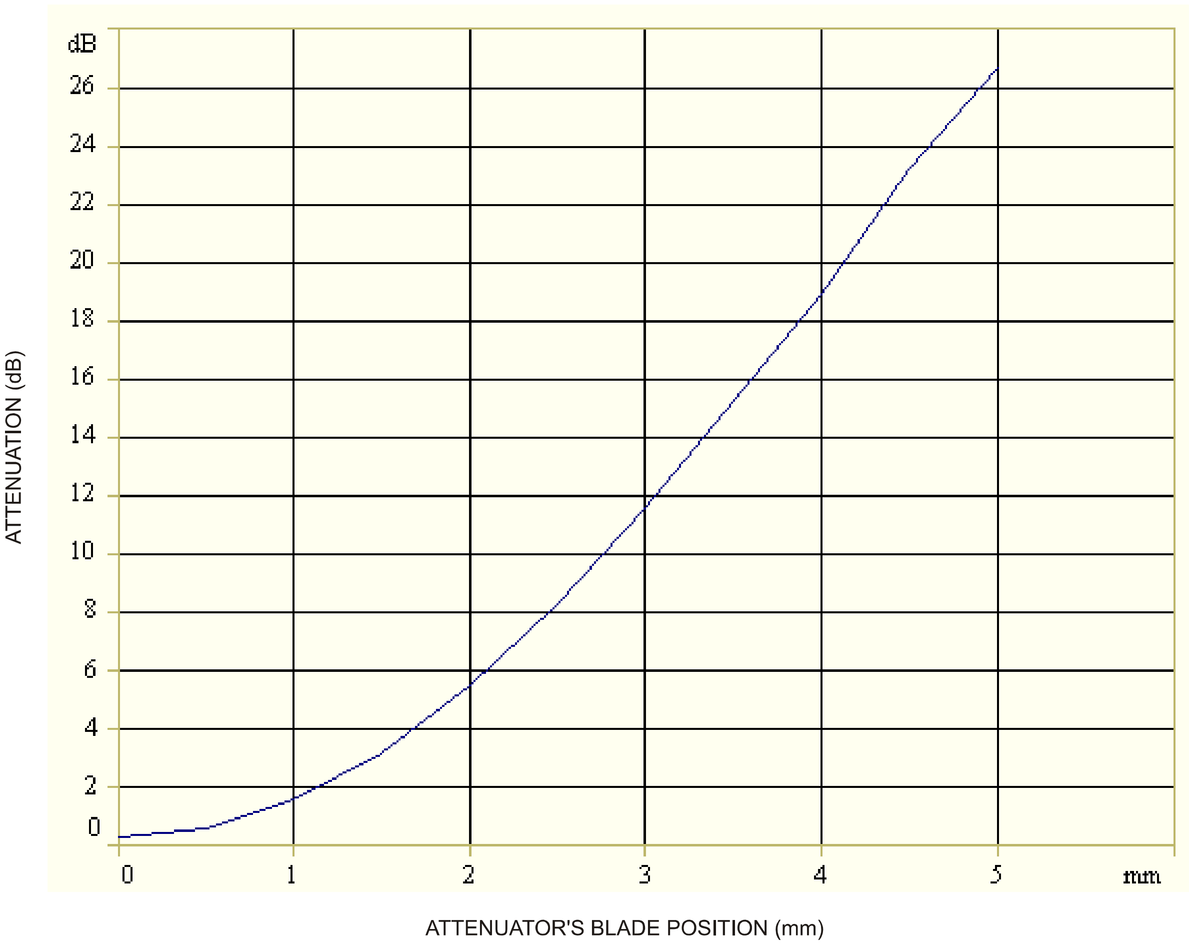


Figure 1-12. Calibration curve of the Variable Attenuator.

CONCLUSION

In this exercise, you became familiar with the concepts of insertion loss and attenuation.

You learned that, whenever a component is inserted into a circuit, an insertion loss is created. Insertion loss is expressed in terms of the logarithm of a ratio between the power supplied by the source before the component insertion, to the power fed to the load after the component insertion.

You learned that attenuation is the decrease in the power of a signal propagating between two points, a and b, point b being farther from the source than point a. You saw that attenuation is usually expressed in terms of the logarithm of a ratio between the power at point b to the power at point a. When these powers are expressed in dBm, the attenuation corresponds to the difference between them.

Finally, you learned how to plot the attenuation-versus-blade position curve of the 35-dB Variable Attenuator. This curve will be used as a reference in the next exercises.

REVIEW QUESTIONS

1. What types of signals are considered to be microwave signals?

____

____

2. What is a waveguide?

____

____

3. What causes the attenuation in the type of variable attenuator that you have used in this exercise?

____

____

4. What are the two main functions of a variable attenuator?

____

____

5. What is a thermistor?

____

____

6. Give a definition of attenuation.

____

____

7. Which phenomena contribute to the insertion loss of a component?

____

____

8. What is the main limitation of the power ratio method of measuring attenuation?

____

____

9. The power fed to a load after the insertion of a component, P_L, is 8 mW. The power supplied by the source before insertion of this component, P_S, is 0.20 mW. Calculate the insertion loss in dB of this component.

____

____

____

____

10. What does the calibration curve of a variable attenuator represent?

____

____

Exercise 2

The Gunn Oscillator

EXERCISE OBJECTIVES

When you have completed this exercise, you will be familiar with the basic operating principles of a Gunn oscillator. You will know how to characterize a Gunn oscillator by plotting the following curves: the current-versus-voltage curve, the delivered power-versus-voltage curve, and the efficiency-versus-voltage curve.

DISCUSSION

Introduction to Gunn Oscillators

A Gunn source consists of a **Gunn diode** placed inside a **resonant cavity**. Depending on the fabrication technique, Gunn diodes can supply from 1 mW to 5 W of microwave power.

The efficiency of these different sources can vary from 0.2% to 20%: most of the lost power is dissipated as heat. Therefore, Gunn diodes require heat sinks to efficiently dissipate the heat and prevent them from burning out. The generated microwave signal usually has a frequency in the range of 1 to 100 GHz, depending on the diode used and on the resonant cavity associated with it.

The term diode is really a misnomer because Gunn diodes are not actually diodes. The term diode is used because they are two-terminal semiconductor devices, and it allows the use of the term anode for the positive end of the device. The name Gunn comes from the Gunn effect, the principle behind the operation of the device.

The Gunn Effect

In the early 1960's, J.B. Gunn discovered that certain semiconductor materials could be used to produce microwave oscillations by way of the effect that now bears his name. The Gunn Effect is only possible in certain n-type semiconductor materials.

Gallium arsenide (GaAs) and indium phosphide (InP) are the most commonly used materials, although the effect has been demonstrated in cadmium telluride (CdTe) and indium arsenide (InAs).

These materials behave somewhat differently than normal semiconductor materials. Thus, when a relatively small DC voltage is applied across a thin slice of n-type GaAs, electrons flow as a current towards the positive end of the slice.

When the voltage is increased, the electrons move faster towards the positive end, which increases the current.

When the voltage is increased so that the potential gradient across the slice exceeds a threshold of about 3.3 kV/cm, the current starts to decrease and the slice exhibits negative resistance. Increasing the voltage eventually causes the current to increase again.

Current-Voltage Characteristic of a Gunn Diode

Figure 2-1 shows the current-versus-voltage characteristic curve of a Gunn diode.

In the first section of the curve, the current drawn by the diode increases as the supplied voltage is increased. Then the current decreases if the voltage is further increased: this causes the curve to have a negatively-sloping portion. This portion is called the *negative resistance* region.

This property of the Gunn diode that causes current to be a decreasing function of voltage over a certain voltage range is not possible in most semiconductor devices: usually, the further increase in voltage would result in a corresponding increase in the current, and this would continue until the electron collisions within the semiconductor crystal lattice generates enough heat to break down the crystal.

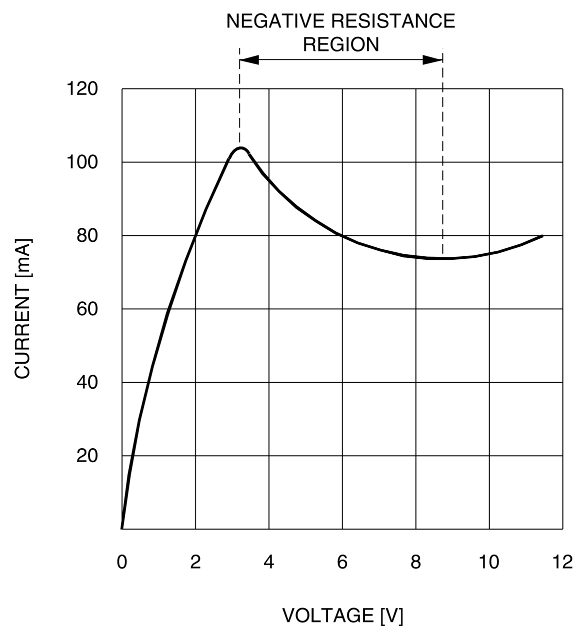


Figure 2-1. Current-versus-voltage characteristic curve of a Gunn diode.

Energy Levels of n-Type Semiconductor Materials

The negative resistance is a result of the bulk-properties of n-type semiconductor materials; that is, this property is due to the nature of the materials. Electrons in these n-type semiconductors have an empty, high-energy conduction band separated from the lower-energy filled (or partially filled) conduction band by a relatively narrow forbidden energy gap. This is illustrated in Figure 2-2.

Under normal conditions, the electrons contributing to the current are in the high-mobility partially-filled energy band. At a certain threshold voltage, the energy imparted to the electrons allows them to move into the lower-mobility high-energy band, causing the current to decrease. Then, as the voltage keeps increasing, electrons are removed from the low-mobility band and the current begins to increase again.

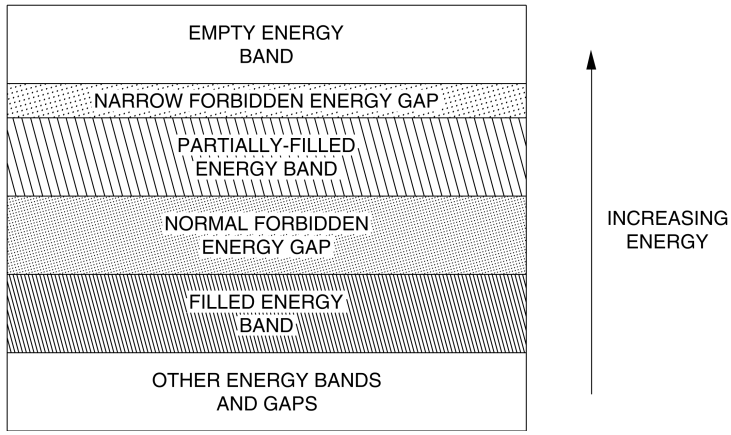


Figure 2-2. Relevant energy levels in gallium arsenide.

Creation of Microwave Oscillations

When the semiconducting material is not uniformly doped, there is a region in the crystal where the concentration of electrons is relatively low and the conductivity is lower than in the rest of the crystal.

Because of this, the electric field in this region is stronger than in the rest of the crystal, so that this region is the first area to transfer electrons into the higher-energy band when the voltage is increased. The electrons in this region are then slowed down as the voltage keeps increasing, so that the region becomes a negative-resistance domain.

Electrons in front of and behind this domain are traveling faster than the electrons within the domain. Electrons from behind the domain bunch up, decreasing the gradient at the back of the domain.

Electrons in front of the domain pull away from it, leaving an area with a low concentration of electrons. In this way, the domain moves towards the anode at a speed of approximately 10^7 cm/s, carrying along the bunch of electrons.

The arrival of a domain at the anode frees the electrons and a new domain forms at the cathode. This domain begins its own propagation towards the anode. This creation and propagation of domains gives rise to the microwave oscillations.

Natural Frequency of the Created Oscillation

The natural frequency of the created oscillation depends on the drift velocity of the domains and on the length of the slice. Taken as a circuit element, a typical Gunn diode may be approximated as a negative-resistance of about 100 Ω in parallel with a capacitance of 0.6 pF.

The Gunn Oscillator

Turning a Gunn Diode Into a Gunn Oscillator

All that is needed to turn a Gunn diode into a Gunn oscillator is an inductance to cancel its capacitance, and a resistance of approximately the same value as the negative resistance in parallel with the Gunn diode.

In general, cavity resonators are used to tune the circuit to the desired frequency of operation.

The arrival of domains at the anode is responsible for the oscillations. One domain is produced per cycle of oscillation. If a tuned LC circuit or cavity is periodically excited by an in-phase signal, oscillations will be sustained.

The band of operation of a Gunn diode is determined by the physical dimensions of the semiconductor crystal.

The exact frequency of oscillation depends on the tuned circuit.

The frequency of oscillation is also affected by the supply voltage. Therefore, it is possible to frequency modulate the signal provided by a Gunn oscillator by varying the supply voltage. However, too high a voltage can destroy the semiconductor crystal. So the Gunn diode must be protected against transient voltages and over-voltages.

Gunn oscillators are used as transmitting elements in police radars, continuous-wave (CW)-doppler radars, alarm systems, and as local oscillators in certain receivers.

Procedure Summary

In this exercise, you will characterize the Lab-Volt Gunn Oscillator. To do this, you will vary the voltage supplied to the oscillator by steps, over the 0-10 V variation range.

For each voltage setting, you will measure and record the current and microwave power supplied by the Gunn Oscillator Power Supply. This will allow you to plot the following characteristic curves:

- the current-versus-voltage curve of the Gunn Oscillator;
- the delivered power-versus-voltage curve of the Gunn Oscillator;
- the efficiency-versus-voltage curve of the Gunn Oscillator.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix F of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

Measuring the Current, Power, and Efficiency of the Gunn Oscillator Over the 0-10 V Supply Voltage Range

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as shown in Figure 2-3.

> **Note:** *Before connecting the Thermistor Mount, unscrew the matching screws so that they do not penetrate into the waveguide; the screws do not need to be removed from the posts.*

☐ 2. Make the following settings on the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . DC
METER SCALE . . . . 10 V

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Wait for about 5 minutes to allow the modules to warm up.

☐ 4. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 4 . . . . Power Meter
Gain Input 4 . . . . 0 dB

☐ 5. In LVDAM-MW, start the Power Meter and set it to display mW readings. Enter the power factor (η) indicated on the Thermistor Mount's waveguide. Then, perform zeroing of the Power Meter.

☐ 6. Set the Gunn Oscillator supply voltage to 8.5 V.

On the Thermistor Mount, loosen the knurled lock-nut that holds the moveable short circuit into place. Adjust the short circuit to the position nearest the waveguide which gives a maximum reading on the Power Meter. Then, adjust each matching screw of the Thermistor Mount to maximize the power reading. Lock the moveable short circuit into position.

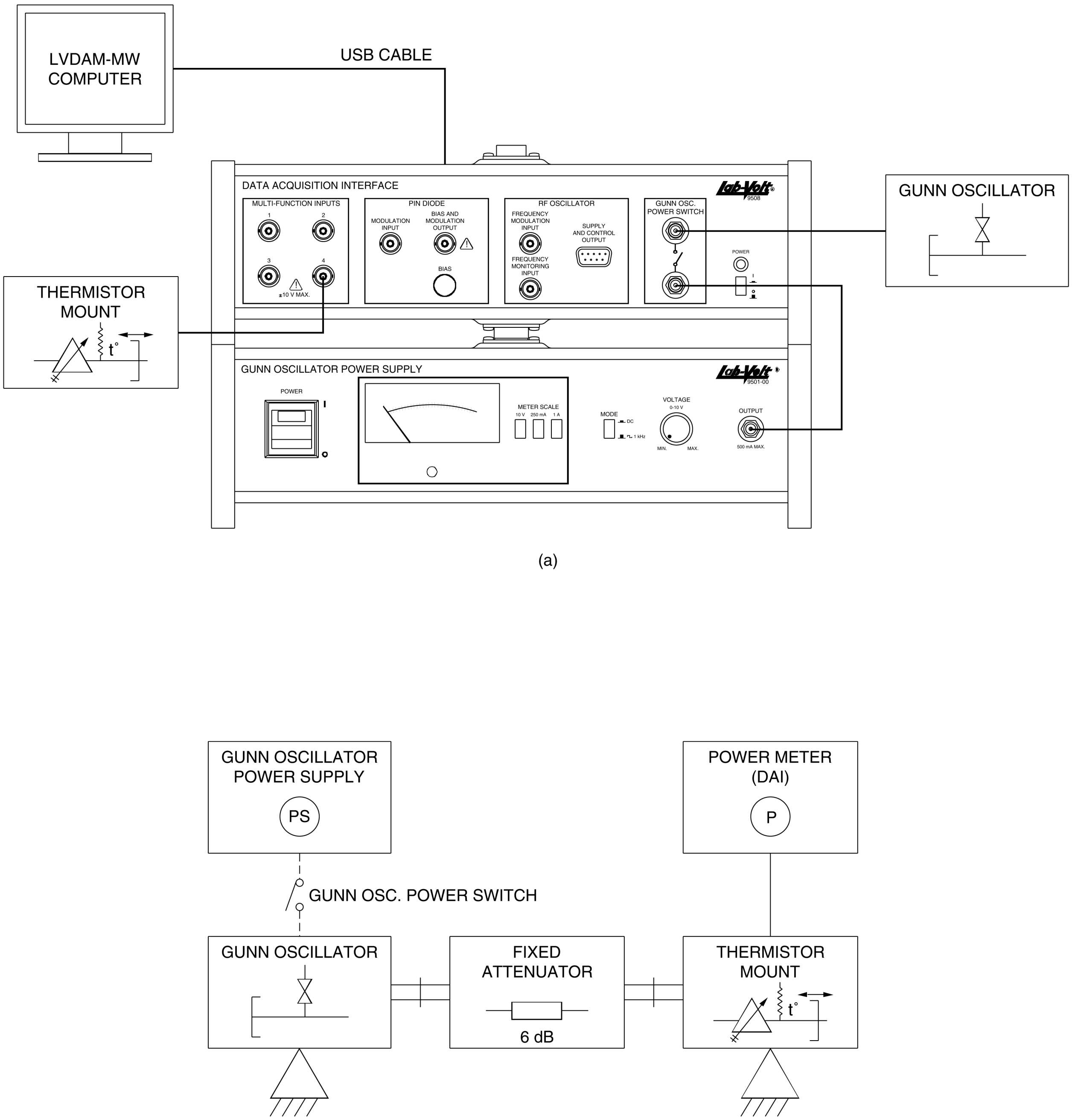


Figure 2-3. Computer and module arrangement (showing electrical connections to microwave components), and microwave setup.

☐ 7. In LVDAM-MW, select the Data Table function, which will bring up the Data Table. In this Table, manually enter the column titles and figures already recorded in Table 2-1 below. Use the Properties command of the DataTable's Edit Menu to enter the columns header, enter the figures in the proper cells, and then save your Data Table.

Note: *To fill the Data Table, the students will have to enter the parameter values manually, since these parameters (Supplied Voltage, Supplied Current, Delivered Power, and Efficiency) must be adjusted or calculated, and since these parameter values are not acquired by the Data Acquisition Interface. (Only the Power Meter reading can be recorded automatically, if the students want to use automatic recording, since this parameter value is acquired by the interface. This parameter values can also be recorded manually, as for the other parameters of the Data Table). For detailed information on manual and automatic recording of parameters in the Data Table, please refer to Section 4 of the Lab-Volt User Guide "Microwave Data Acquisition and Management", part number 85756-E.*

SUPPLIED VOLTAGE (V)	SUPPLIED CURRENT (mA)	POWER METER READING (mW)	DELIVERED POWER (mW)	EFFICIENCY (%)
0	0	0	0	0
0.5				
1				
1.5				
2				
2.5				
3				
3.5				
4				
4.5				
5				
5.5				
6				
6.5				
7				
7.5				
8				
8.5				
9				
9.5				
10				

Table 2-1. Determining the characteristics of the Gunn Oscillator.

☐ 8. Fill in the first empty row of the Data Table just created by performing the steps below.

a. On the Gunn Oscillator Power Supply, make sure the 10-V METER SCALE is selected. Adjust the VOLTAGE knob of the Gunn Oscillator Power Supply until the supplied voltage, as indicated by the meter, is 0.5 V.

b. Select the 250-mA METER SCALE on the Gunn Oscillator Power Supply. Note and record the current supplied by the Gunn Oscillator, as indicated by the meter, in the row "0.5 V" under the column "SUPPLIED CURRENT".

c. Note and record the reading of the Power Meter in the row "0.5 V" under the column "POWER METER READING".

d. Multiply the Power Meter reading by 4 to obtain the power delivered by the Gunn Oscillator (this is necessary to account for the power lost in the 6-dB Fixed Attenuator.) Record your result in the row "0.5 V" under the column "DELIVERED POWER".

e. Using the equation below, calculate the efficiency of the Gunn Oscillator. Record your result in the row "0.5 V" of the table, under the column "EFFICIENCY".

$$\text{Efficiency (\%)} = \frac{\text{Delivered Power (mW)}}{\text{Supplied Voltage (V)} \times \text{Supplied Current (mA)}} \times 100\%$$

☐ 9. Fill in the remainder of the Data Table. To do this, adjust the voltage supplied by the Gunn Oscillator to each of the settings listed in the leftmost column of the Data Table. Redo step 8 for each new voltage setting and record your results in the Data Table. Save your work.

Note: *To maintain accuracy of measurement, it is recommended that you frequently perform zeroing of the Power Meter.*

Plotting the Current-Versus-Voltage Curve of the Gunn Oscillator

☐ 10. In LVDAM-MW, select the Graph function of the Data Table. In the Axis section of the Graph, select the proper variables for the X and 1-Y Axes in order to plot the current-versus-voltage curve of the Gunn Oscillator, using a linear scaling for both the X and Y axes (lin-lin).

The obtained curve should resemble that shown in Figure 2-4. The region of negative resistance corresponds to the negatively sloping portion of the curve.

Note: *For detailed information on how to use the Graph function of the Data Table, please refer to Section 4 of the Lab-Volt User Guide "Microwave Data Acquisition and Management", part number 85756-E.*

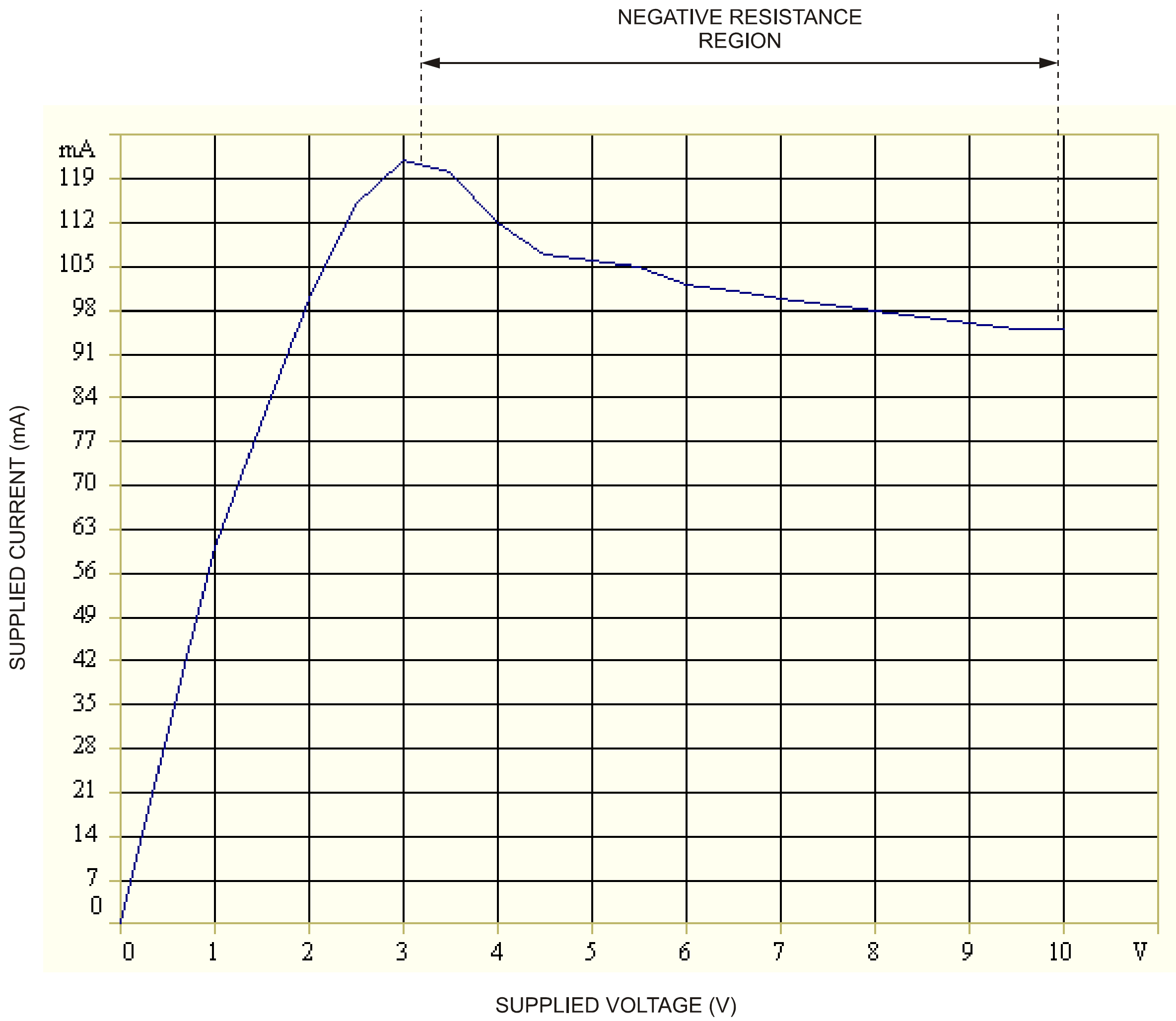


Figure 2-4. Current-versus-voltage curve of the Gunn Oscillator.

Plotting the Power-Versus-Voltage Curve and the Efficiency-Versus-Voltage Curve of the Gunn Oscillator

☐ 11. In the Graph, select the proper variables for the X, 1-Y, and 2-Y Axes in order to plot the delivered power-versus-voltage curve and the efficiency-versus-voltage curve of the Gunn Oscillator on a same graph, using a linear scale for the X and Y axes.

The obtained curves should resemble those shown in Figure 2-5.

The Gunn Oscillator

Examine the delivered power-versus-voltage curve and note the voltage at which the Gunn Oscillator starts to oscillate (turn-on voltage). Referring to the current-versus-voltage curve previously obtained, is this voltage within the region of negative resistance? Explain.

____

____

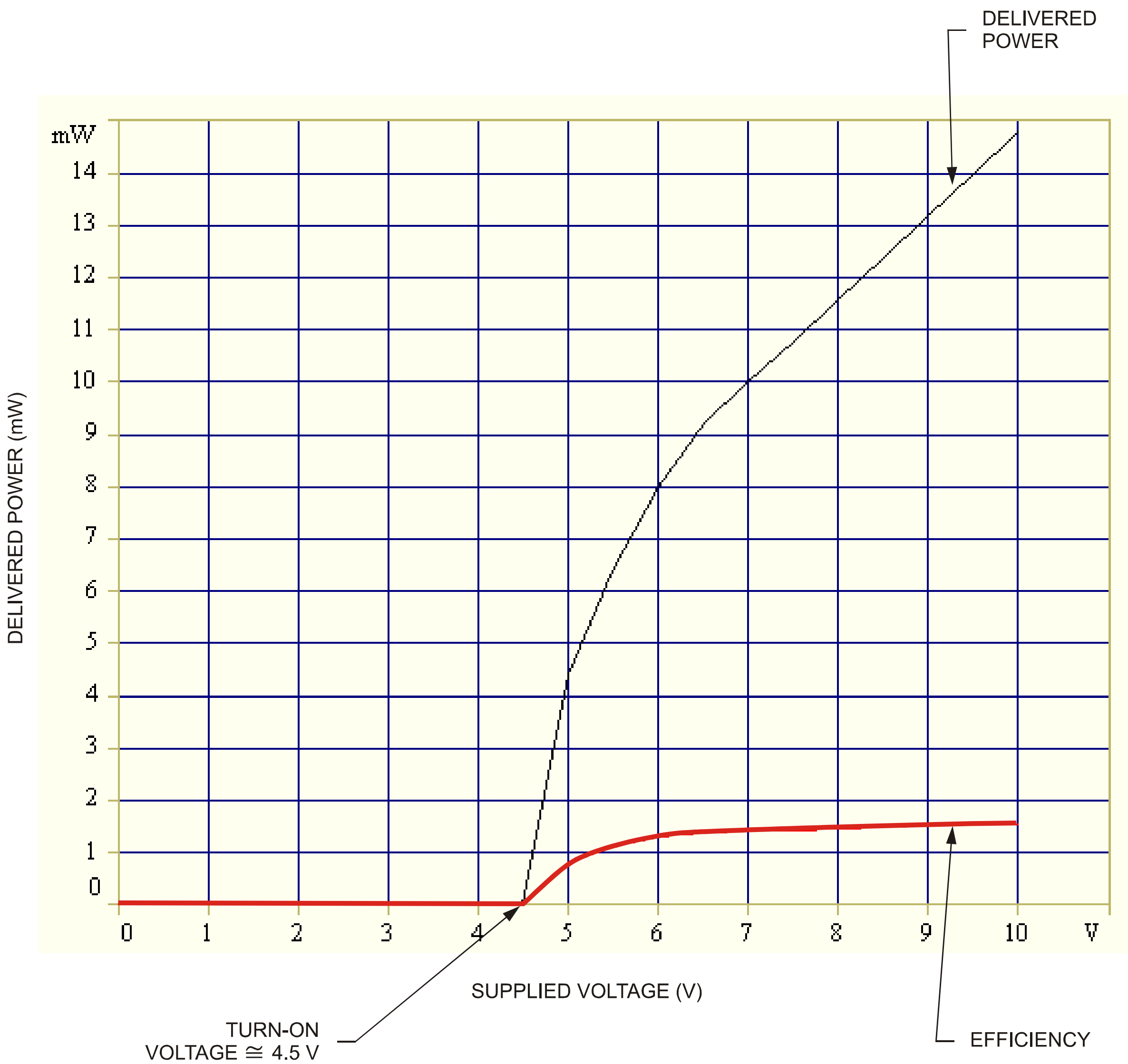


Figure 2-5. Delivered power-versus-voltage curve and efficiency-versus-voltage curve of the Gunn Oscillator.

☐ 12. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 13. Close the LVDAM-MW software.

CONCLUSION

In this exercise, you became familiar with the operating principles of a Gunn diode oscillator. You plotted the current-versus-voltage curve of a Gunn diode, and you saw that the curve had a region of negative resistance (negatively sloping portion). You also plotted the delivered power-versus-voltage curve and the efficiency-versus-voltage curve of the Gunn Oscillator on a same graph. You saw that the voltage at which the Gunn Oscillator starts to oscillate is within the region of negative resistance.

REVIEW QUESTIONS

1. What are the main components of a Gunn oscillator?

____

____

2. In what materials is the Gunn Effect possible?

____

____

3. Describe the phenomenon that gives rise to a negative dynamic resistance in a semiconducting crystal.

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____

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4. What determines the exact frequency of oscillation of a Gunn oscillator?

____

____

5. A Gunn oscillator generates a continuous-wave (CW) microwave signal having a power, P_O, of 100 mW with an efficiency, η, of 2%. How much DC power (P_{DC}) must the heat sink be able to dissipate to adequately protect the oscillator?

____

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 3 Dipole Radiation Pattern

Radiation Pattern of a λ/2, λ ,3 λ /2 Dipole at 1 GHz

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the radiation pattern of a half-wavelength (λ/2) dipole antenna in the E and H-planes, and you will be familiar with the characteristics of λ/2, λ, and 3λ/2 dipole antennas.

DISCUSSION

An antenna is a device for radiating or receiving radio waves. Antennas are the transition devices between waveguides or transmission lines and free space.

In general, a given antenna can be used to transmit or receive a signal. The orientation of the antenna is important. When receiving, the strength of the received signal will be stronger in some directions than in others. If the same antenna is used to transmit a signal, the radiated power will be greater in some directions than in others. It turns out that, for the same antenna, the direction of maximum power transmission coincides with the direction of maximum power reception.

An **isotropic source** is a hypothetical antenna which is nondirectional, that is, which has equal radiation intensity in all directions. Although a perfectly isotropic antenna does not exist in practice, the concept is very useful in the study of antennas. This concept gives a convenient reference for discussing the directional properties of antennas.

The dipole antenna and the ideal dipole

The **dipole antenna** is a simple type of antenna consisting of two rods or wires aligned as shown in Figure 1-1. The length of this antenna is L. The dipole is connected at the centre to the transmitter through a transmission line.

The transmitter supplies an alternating current signal to the antenna. At a given instant, the current I flows into one terminal of the dipole and out of the other, as shown in the figure. The direction of current is then reversed.

The **current distribution**, that is, the magnitude of the alternating current along the length of the dipole antenna, is not uniform. Instead, it is zero at the ends, and may be highest at the centre or at other points, depending on the length of the dipole and the frequency of the signal from the transmitter.

Radiation Pattern of a λ/2 Dipole at 1 GHz

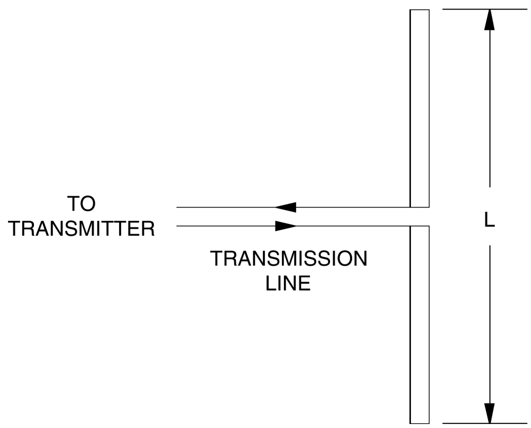


Figure 1-1. Dipole antenna

An **ideal dipole** is another hypothetical antenna which is useful in the study of antennas. It can be considered to be a dipole of infinitesimal length with a uniform current distribution. The theoretical characteristics of an ideal dipole approximate those of electrically small dipole antennas.

Radiation patterns

A **radiation pattern** is a three-dimensional, graphical representation of the **far-field** radiation properties of an antenna as a function of space coordinates. The far-field region is a region far enough for the radiation pattern to be independent of the distance from the antenna. The radiation pattern of a particular antenna can be measured by experiment or can be calculated, if the current distribution is known.

A radiation pattern represents the energy distribution as a function of direction of the signal transmitted by the antenna. It indicates the relative level of transmitted power as a function of direction. Although the term "radiation" pattern is used, it applies just as well to receiving antennas. The reception pattern of an antenna is identical to its radiation pattern. This is a general rule, known as the **reciprocity theorem**.

Although the complete radiation pattern is a three-dimensional function, two two-dimensional patterns are usually sufficient to characterize the directional properties of an antenna. In most cases, the two radiation patterns are measured in planes which are perpendicular to each other. A plane parallel to the electric field is chosen as one plane and the plane parallel to the magnetic field as the other. The two planes are called the **E-plane** and the **H-plane**, respectively (see Figure 1-2).

The radiation pattern in one plane can be measured by rotating the antenna in that plane while measuring the level of received power as a function of the antenna orientation. To obtain a valid pattern, the surrounding environment should be free from objects which could reflect the transmitted signal towards the antenna being tested and cause errors in the results.
E-plane

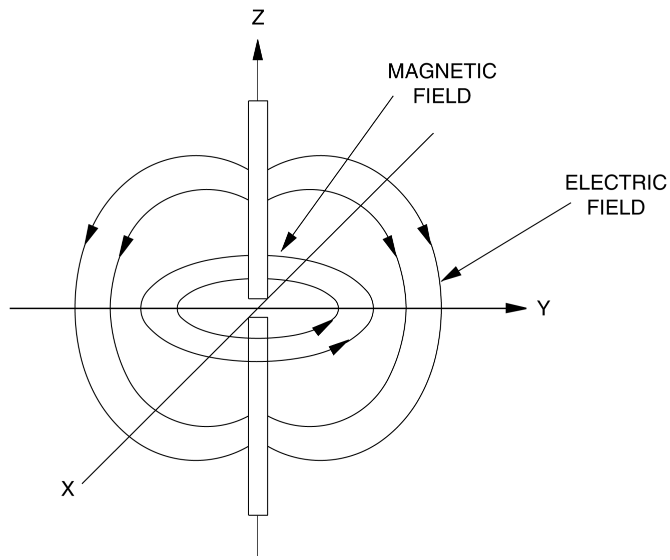


Figure 1-2. E-plane (y-z) and H-plane (x-y) of a dipole

Figure 1-3 shows the E-plane radiation pattern of an ideal dipole. This pattern shows that the ideal dipole is omni directional because the radiation is stronger in some directions than in others. The H-plane pattern is shown in Figure 1-4. In this plane, the radiation is uniform.

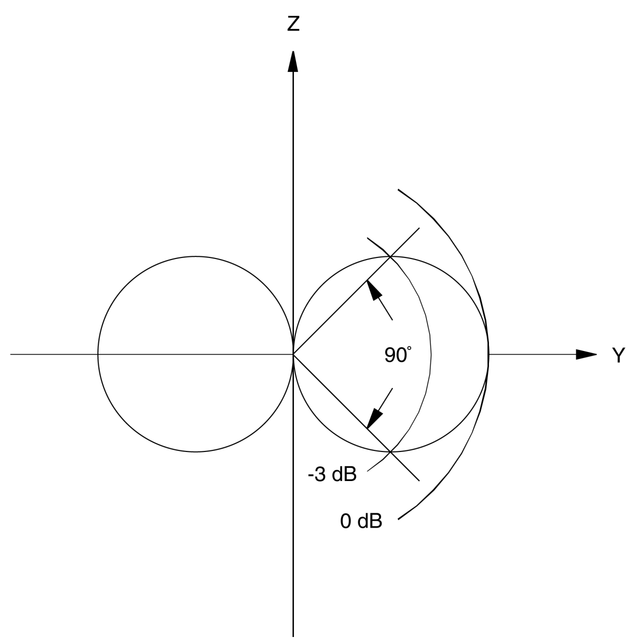


Figure 1-3. Theoretical E-plane radiation pattern of an ideal dipole

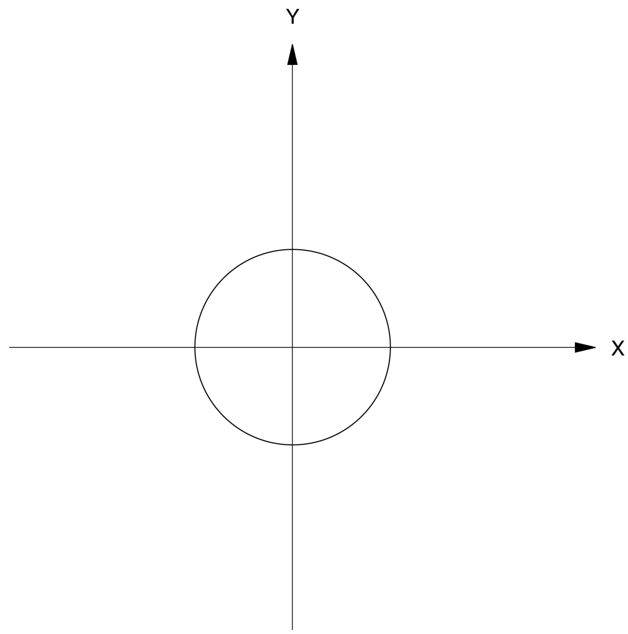


Figure 1-4. Theoretical H-plane radiation pattern of an ideal dipole

The **half-power beamwidth (HPBW)** of an antenna is the angular separation of the points in the main beam where the power equals one-half (-3 dB) the power radiated in the direction of maximum power.

$$HPBW = |\theta_{HPBW\ left} - \theta_{HPBW\ right}| \tag{1}$$

The HPBW of an ideal dipole in the E-plane is 90°, as indicated in Figure 1-3.

A practical dipole antenna has a finite length L. Common lengths are λ/2, λ, and 3λ/2, where λ is the wavelength of the signal. The current distribution in a λ/2 dipole has a half-sinusoidal shape, as shown in Figure 1-5. The current is highest at the centre, tapering off to zero at the ends.

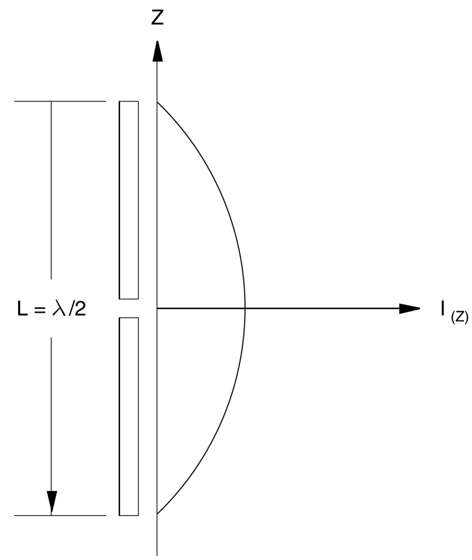


Figure 1-5. Current distribution in a λ/2 dipole

Figure 1-6 shows the E-plane radiation pattern for both a λ/2 dipole and an ideal dipole. The λ/2 dipole has a HPBW of 78° in the E-plane and is therefore slightly more directional than the ideal dipole. The H-plane radiation for a λ/2 dipole antenna is circular, as in Figure 1-4.

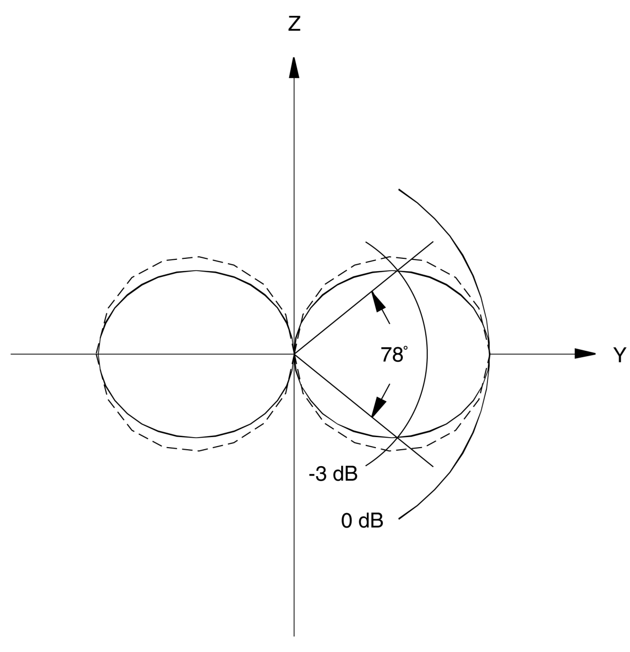


Figure 1-6. E-plane radiation pattern for a λ/2 dipole (solid line) and an ideal dipole (dotted line)

Antenna polarization

The polarization of an antenna describes the direction in space of the electric field of the electromagnetic wave transmitted by the antenna, in the far field. More exactly, it describes the direction where the field intensity is maximum.

Many antennas are **linearly polarized**, that is, during one cycle, the displacement of the electric field vector describes a straight line in space. Such antennas are referred to as being **horizontally** or **vertically polarized**. There are also polarizations called circular or elliptical. These will be seen in a later exercise.

It is often possible to deduce the polarization of an antenna from its geometry. In the case of wire antennas composed of one or several elements aligned parallel to each other (dipoles and Yagi antennas, for example), one can assume that the electric field is linearly polarized and is parallel to the elements. Other types of antennas are also linearly polarized although this is not obvious from their geometry. This is the case for horns, loops, and slits.

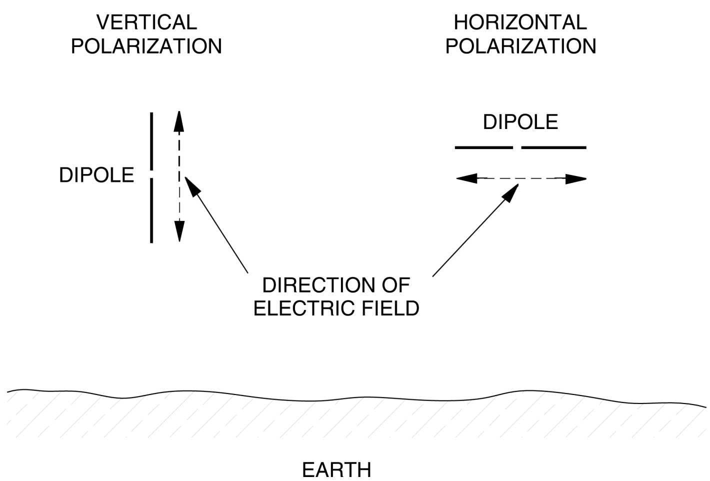


Figure 1-7. Polarization of a dipole antenna

In order to obtain a received signal of the highest quality possible, it is important that the reception antenna have the same polarization as the incoming signal. When a signal loss occurs because of poor alignment of the polarizations (for example, a vertically polarized signal received by a horizontally polarized antenna), we speak of **cross-polarization isolation**.

Resonance in dipoles

As stated previously, the current distribution of the dipole antenna is not uniform. Instead, it is zero at the ends of the antenna wires, and may be highest at the centre or at other points, depending on the length of the dipole and the frequency of the signal from the transmitter. Figure 1-8 shows the current distribution in centre-fed dipoles of lengths λ/2, λ, and 3λ/2. In this figure, the arrows represent the current directions at a particular instant. The magnitude and polarity of the current at different points along the dipole is shown by the sinusoidal line.

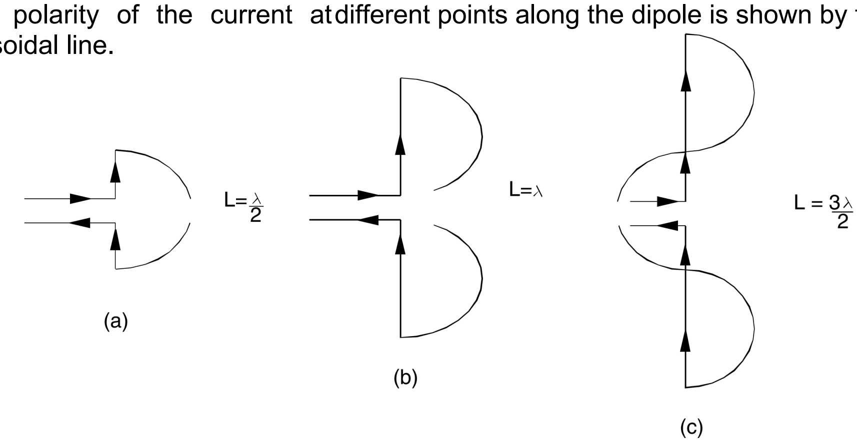


Figure 1-8. Current distributions in centre-fed dipoles

Input impedance

A dipole of length λ/2, λ, or 3λ/2 acts as an efficient radiator. This means that the antenna appears to be a resistive element—the current and the voltage are in phase, and therefore the reactance of the antenna is small. Note however, that a dipole of length λ is very difficult to tune.

If one measures the input impedance of a λ/2 or 3λ/2 dipole antenna, one will find that the reactance is close to zero. The resistance is theoretically 73 Ω.

$$Z_{in} = R_{in} + jX_{in} = 73 + j0 \quad \Omega \tag{2}$$

At other antenna lengths (greater than λ/2 but not equal to λ or 3λ/2), the input resistance is greater than 73 Ω and the reactance is not zero. Since the resistance is greater, the current is smaller; and because of the non-zero reactance, the voltage and current are out of phase. In this case, the antenna is not an efficient power radiator.

Experiments with λ/2, λ, and 3λ/2 Dipoles

Table 1-1 gives formulas for calculating the approximate resistance of dipoles.

Length L	Input Resistance Rin (Ω)
$0 < L < \frac{\lambda}{4}$	$20\pi\left(\frac{L}{\lambda}\right)^{2}$
$\frac{\lambda}{4} < L < \frac{\lambda}{2}$	$24.7\left(\pi\frac{L}{\lambda}\right)^{2.4}$
$\frac{\lambda}{2} < L < 0.637\lambda$	$11.14\left(\pi\frac{L}{\lambda}\right)^{4.17}$

Table 1-1. Formulas for calculating input resistance of dipole antennas

Figure 1-9 shows the input resistance R_{in} and reactance X_{in} as functions of antenna length. This graph shows that when the length is approximately λ/2 or 3λ/2, the reactance is zero and the input resistance is close to 73 Ω. The figure applies to very thin-wire antennas.

This figure shows that when the antenna length is approximately equal to λ, the resistance is very high and the reactance is capacitive. The reactive part of the input impedance can be reduced to zero by reducing the antenna length to approximately 0.9 λ, but at this length, the resistance is at its maximum. It is for this reason that the λ dipole antenna is very difficult to tune.

> **Note:** *The high impedance of the λ dipole can be seen from Figure 1-8. This figure shows that the current is null at the centre of the antenna, where the transmission line is connected. The resistance is therefore infinite, in theory, at this point.*

Radiation patterns

In the H-plane, the radiation pattern of the dipole antenna is approximately circular. In the E-plane, it is described by Equation (3).

$$E_\theta = E_o \frac{\cos[(\beta L/2)\cos\theta] - \cos(\beta L/2)}{\sin\theta} \qquad (3)$$

where E is the maximum value of E_θ
β = 2π/λ

For L = λ/2, the equation becomes:

$$E_\theta = E_o \frac{\cos[(\pi/2)\cos\theta]}{\sin\theta} \qquad (4)$$

This has the shape shown in Figure 1-10. The maximum value E_o is at θ = 90°.

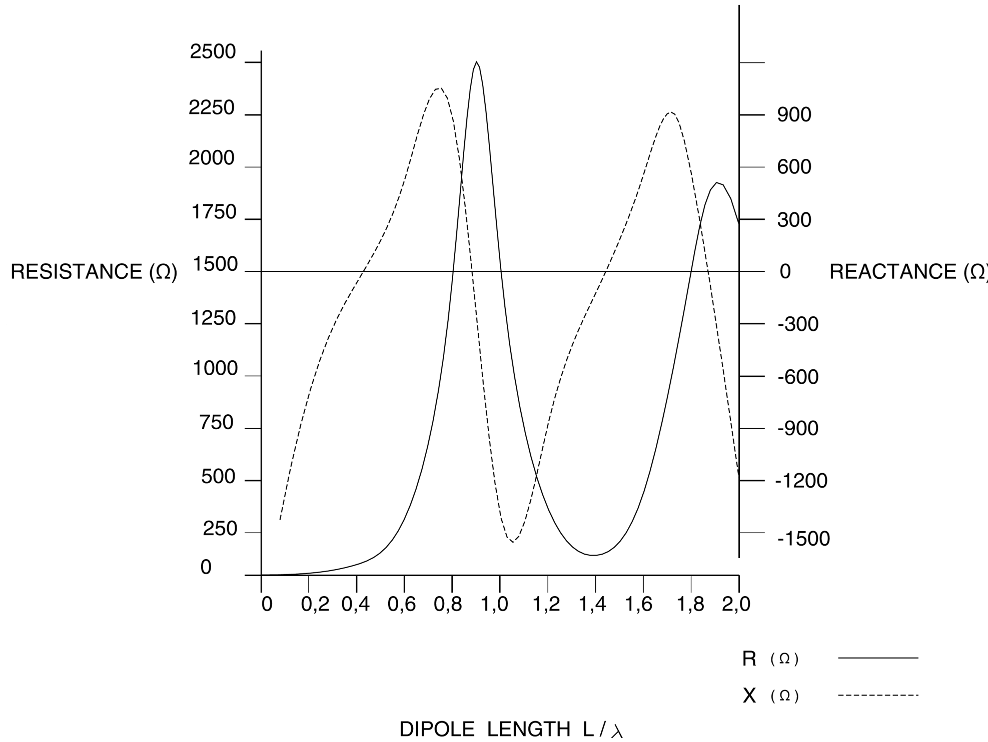


Figure 1-9. Input resistance (solid line) and reactance (dotted line) of a dipole antenna as a function of antenna length.

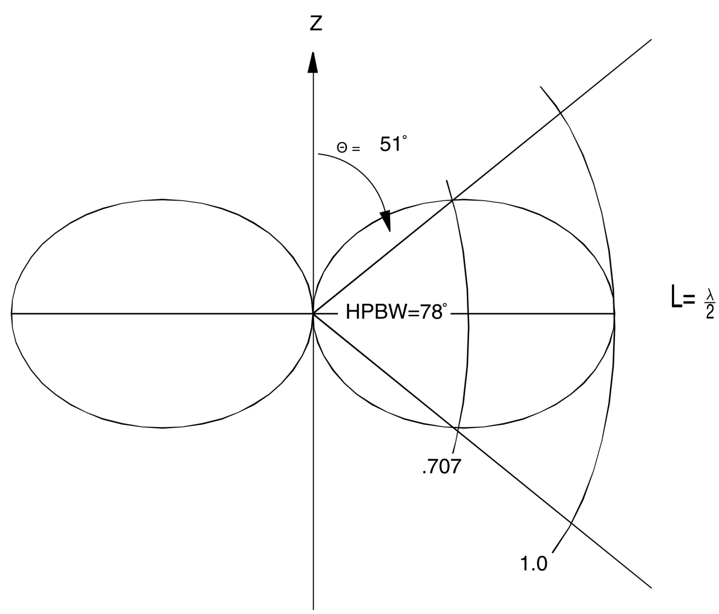


Figure 1-10. Radiation pattern of the λ/2

At $\theta = 51°$, $E_\theta = 0.707\ E_o$. This is the half power point. The half-power beamwidth is given by

$$HPBW = 2(90 - 51) = 78° \quad (5)$$

The directivity of the antenna is D = 1.64 = 2.15 dB.

The radiation pattern of the λ dipole and the 3λ/2 dipole are plotted in Figure 1-11. The directivity of dipoles longer than 1.25λ drops as the length is increased. This is because the currents in different parts of the dipole are such that the fields cancel each other. The resulting radiation pattern has many lobes.

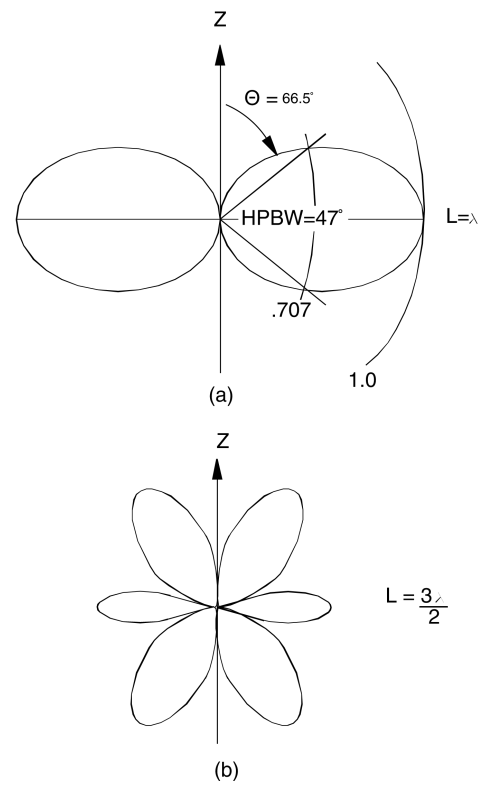


Figure 1-11. Radiation patterns of the λ dipole (a) and the 3λ/2 dipole (b)

Antenna fields

The concept of fields is important in the study of antennas. One distinguishes three different regions for antenna fields: the **Rayleigh (near) field**, the **Fresnel field**, and the **Fraunhofer (far) field**, as illustrated in Figure 1-12.

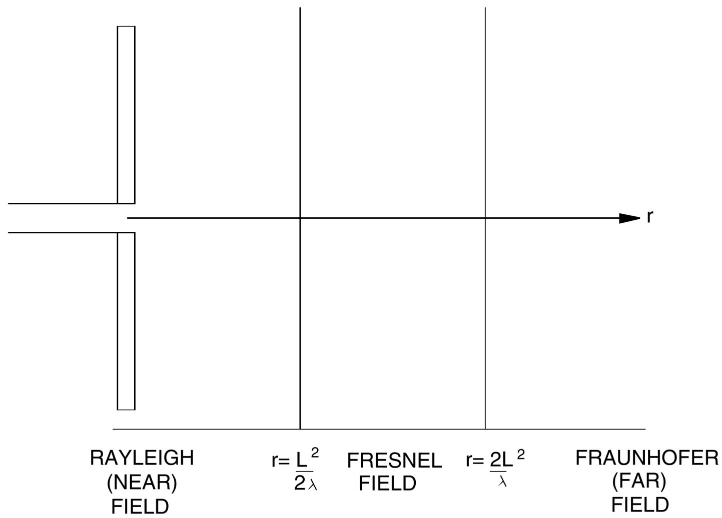


Figure 1-12. Antenna field regions

The far field is the region where

$$r > \frac{2L^2}{\lambda} \tag{6}$$

where r is the distance from the antenna
L is the length of the antenna (or the largest dimension of the aperture).

This is the region of interest when studying antennas and it is the region where the antennas must be placed when plotting the radiation pattern or making other measurements.

If the transmit and receive antennas are of different lengths, the length of the longest antenna should be used as L in Equation (6). This will ensure that the correct region is being used.

> **Note:** *The antennas should never be placed in the Rayleigh (near) field for measurement. In some cases it may be acceptable to place them in the Fresnel field.*

PART ONE:

Procedure Summary

In this exercise you will set up a 1 GHz λ/2 dipole and measure its radiation pattern in the E and H-planes. You will become familiar with the concept of polarization for the Yagi and the dipole antennas. Using the cursors option of the LVDAM-ANT program, you will calculate the half-power beamwidth of the λ/2 dipole antenna.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/ Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 in the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place the antenna mast with horizontal clips on the transmission support and clip the Yagi antenna onto it. Orient the elements so they are horizontal; the transmission antenna is **horizontally polarized**, as shown in Figure 1-13.

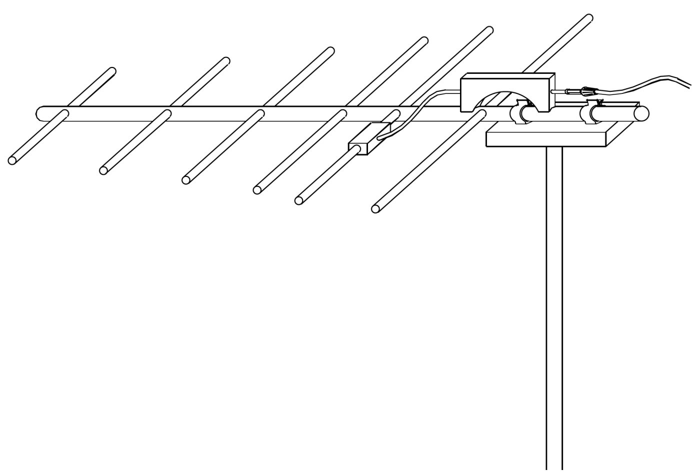


Figure 1-13. Set-up of the Yagi antenna horizontally polarized

Install the long SMA cable on the 1 GHz OSCILLATOR output of the RF Generator, then connect the Yagi antenna.

☐ 3. Using the following equation, calculate the length of a λ/2 dipole at 1 GHz. Note that the exact transmission frequency of the RF Generator is 915 MHZ.

$$\lambda = \frac{c}{f}$$

where c is the velocity of light
f is the transmission frequency

λ = ______ m

then

λ/2 = ______ m

To correctly evaluate the antenna length, the ratio of the length of the conductor to its diameter, the *end effect* (a loading effect at the end of the wires), and the impedance mismatch resulting from the presence of the balun should be considered. To respect these considerations, the antenna length must be shortened. In the present case, a length of 0.45 λ, rather then 0.50 λ, is a good approximation.

Then

0.45 λ = ______ m

☐ 4. Using the answer of your calculation as a reference, choose the appro-priate pair of wires to set up the λ/2 dipole. Adjust the dipole length in accordance with your last result, as shown in Figure 1-14.

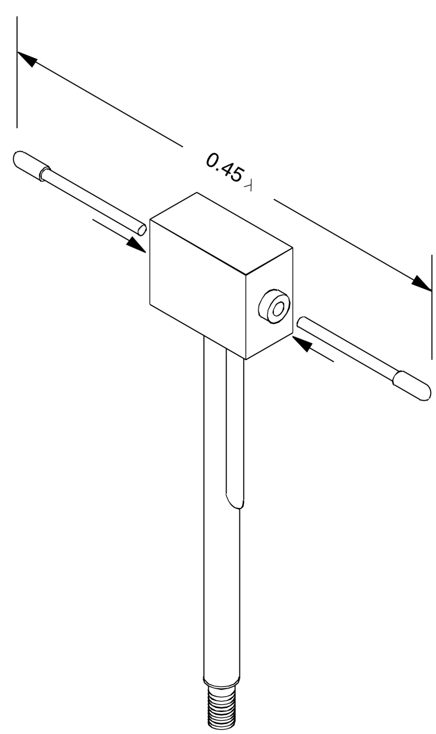


Figure 1-14. λ/2 dipole assembly

☐ 5. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner, then clip on the λ/2 dipole; the antenna is horizontally polarized. Using the sliding support, ensure that the antenna is in line with the rotation centre of the Antenna Positioner. Refer to Figure 1-15 to check your set-up.

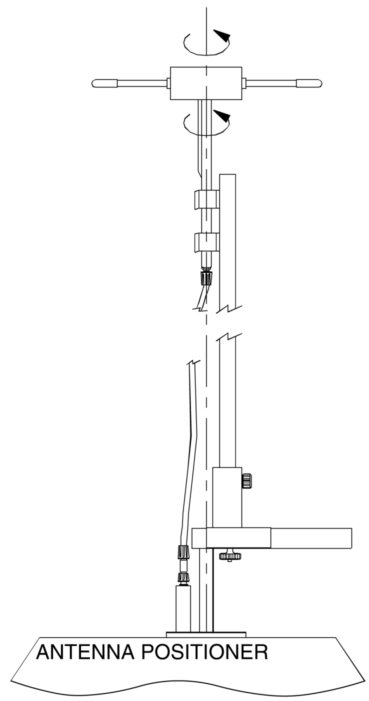


Figure 1-15. Set-up of the receiving antenna horizontally polarized.

Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

☐ 6. Referring to Figure 1-16, position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

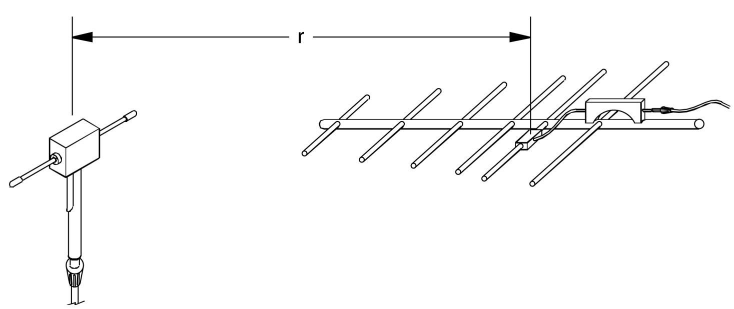


Figure 1-16. Distance r between the antennas.

☐ 7. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern acquisition and polarization

☐ 8. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

Use the Attenuation control to optimize the acquisition of your radiation pattern (refer to Section 4 in the User's Manual).

☐ 9. Start the first acquisition.

When the acquisition is completed, turn OFF the RF POWER on the RF Generator.

Store the radiation pattern as the E-plane of a new document (Document1). Use the Information box to clearly identify the pattern.

Orient the pattern so that the MSP (maximum signal position) is at 0°.

☐ 10. Rotate the transmission antenna so it is perpendicular with respect to its initial position, as shown in Figure 1-17. Do not modify the orientation of the receiving antenna.

Note: *Remember to loosen the connectors before you rotate an antenna; when it is correctly positioned, screw the connectors tightly together to avoid power loss.*

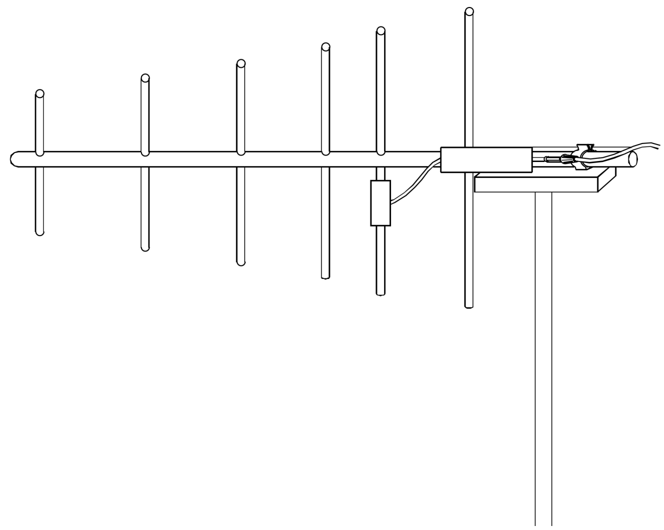


Figure 1-17. Rotation of the transmission antenna

Keep the same attenuation level. Start a new acquisition and store this pattern as the E-plane of a new document (Document2).

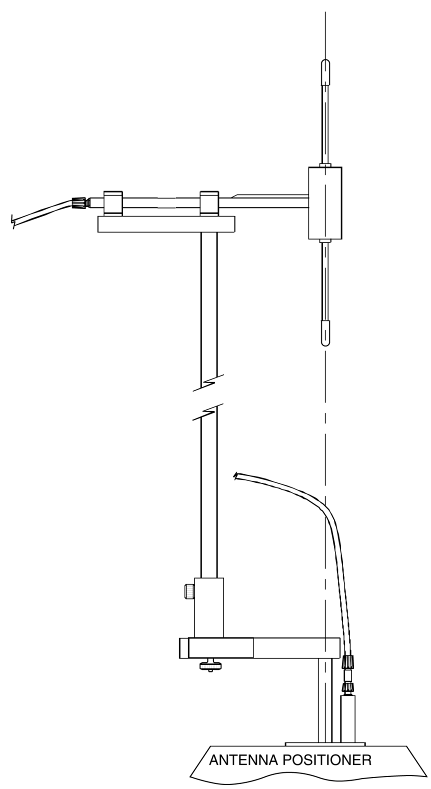


Figure 1-18. Set-up of the dipole

☐ 11. Remove the dipole antenna, and change the receiving mast for the one with horizontal clips. Install the $\lambda/2$ dipole on the mast, as shown in Figure 1-18.

Using the intermediate SMA cable, connect the antenna to the attenuator on top of the Antenna Positioner.

> **Note:** *Depending on its position in space, the receiving cable may collect part of the transmitted signal. To avoid distortion during the plotting of the radiation patterns, you will sometimes have to alternate between the short length and the intermediate length cables to connect the receiving antenna. Try to maintain the shortest section of cable possible between the antenna and the detector. Also, to ensure good symmetry, try to install the cable so that it lies close to the mast. Figure 1-19 shows the correct way of installing the cable. This will allow more reliable plotting of the radiation patterns.*

☐ 12. Using the same attenuation level, perform another acquisition and store the pattern as the H-plane of Document1.

Orient the pattern so that the MSP is at 0°.

☐ 13. Observe your three radiation patterns. Did you expect the result of the second acquisition? Explain.

____

____

____

☐ 14. Referring to steps 2 and 5, redo the set-up using the transmission and the receiving antennas with horizontal polarization. Position the antennas a distance of r = 1.25 m apart, directly facing each other.

DO NOT change the attenuation level, and make sure that the environment (including your position) around the antennas is the same as for the first acquisition. Acquire the radiation pattern of the dipole E-plane and store it in a new document (Document3).

According to theory, except for its size which is affected by the power loss, this diagram should have the same shape as the first one. If this is not the case, try to find where reflections could have occurred and, if possible, prevent them. Then, do another acquisition and replace the old pattern in the antenna3 data box.

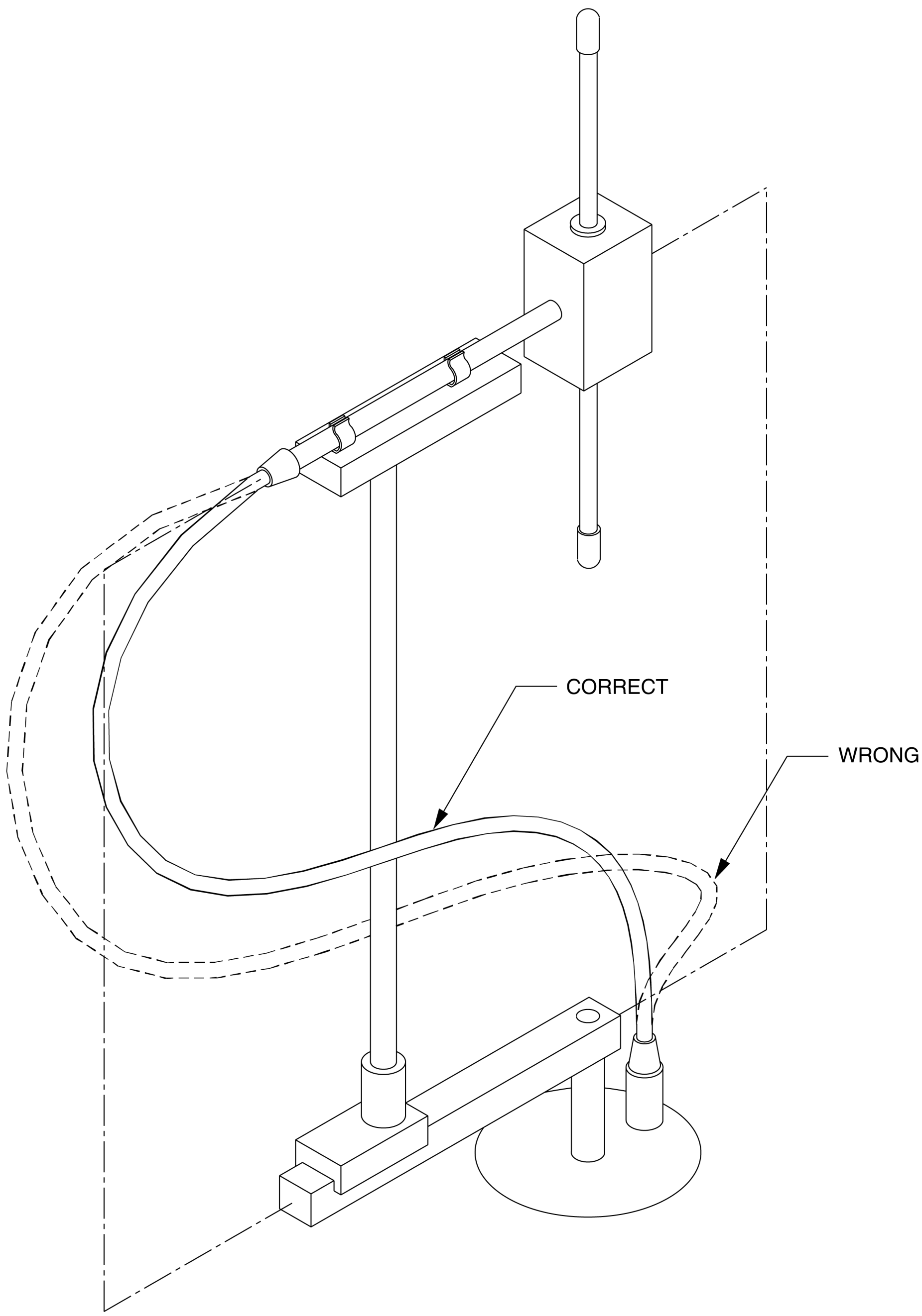


Figure 1-19. Appropriate cable installation

Half-power beamwidth

☐ 15. Click the Cursors button on the tool bar. Two cursors appear, one on each side of the 0° angle. The values displayed in the File Manager will also change. These now include two power levels (in dB), the maximum value of the main beam (in dB) and, at the top right of the 2D view, the positions of the cursors and the difference between these positions (in degrees).

Select and drag the cursor 2. When you move this cursor around the window, the Curs2 value changes. This is the difference (in dB) between the maximum of a pattern and the position where the cursor crosses the pattern. You can do the same with the other cursor.

☐ 16. Using these two cursors, find the angles where the power level of the main beam drops to one half on the E-plane pattern of the Document1.

> **Note:** *Remember that a power decrease of one half is equivalent to an attenuation of 3 dB: 10 log 0.5 = -3 dB*

Using the following equation, calculate the E-plane half-power beamwidth (HPBW) of the λ/2 dipole antenna.

> **Note:** *If the left and right HPBW points are positioned on each side of the 0° angle, you should add 360° to the* $\theta_{HPBW\ right}$ *in the following equation.*

$$HPBW_E = \left| \theta_{HPBW\ left} - \theta_{HPBW\ right} \right|$$

$HPBW_E$ = ______°

☐ 17. Repeat Step 16 with the radiation pattern of the third data box.

$HPBW_E$ = ______°

☐ 18. Close the cursor option (the window returns to the initial display). Compare your answers with the values given by LVDAM-ANT (you will find the HPBW value of each antenna in the third column of the antenna data box). If your results do not agree with those values (i.e. the difference exceeds 7°), redo the procedure steps and your calculations.

> **Note:** *The half-power position estimated by LVDAM-ANT may sometimes differ slightly from the exact -3 dB point. To observe the cursor positions selected by the software, open the cursors option, then select the pattern you wish to evaluate. Click the Options, Set Cursors at -3 dB command; the cursors will be positioned automatically. In the next exercises, you can use this command for a rapid approximation of the half-power beamwidth. This can then be adjusted with more accuracy if necessary.*

☐ 19. Save the Document1 and Document3 data, then print your results. Your printout should show the radiation patterns of these two data boxes with the main display.

PART TWO:

Procedure Summary

In this exercise you will plot the radiation pattern of λ/2, λ and 3λ/2 dipole antennas. You will observe how the impedance of the λ dipole affects the efficiency of this antenna. You will determine the far-field region of an antenna. You will evaluate the half-power beamwidth of the λ/2 and λ dipoles and, finally, the directivity of the λ/2 dipole antenna.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission support. Clip the Yagi antenna on the mast, oriented for an acquisition in the E-plane, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator, using the long SMA cable.

☐ 3. Choose the appropriate pair of wires and set up a λ dipole by simply inserting the wires into the bottom of the dipole connector, as you did in part one.

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

☐ 4. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner. Install the λ dipole on the mast.

Using the sliding support, ensure that your antenna is in line with the rotation centre of the Antenna Positioner. The dipole is oriented to rotate in the E-plane.

Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

☐ 5. Position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF generator to the ON position. Use the Attenuation control to optimize reception of the signal.

Start your acquisition. Store the radiation pattern in a new document (Document4), making sure you select the correct plane.

☐ 8. Remove the antenna mast with vertical clips from the sliding support and replace it with the second antenna mast that has horizontal clips. Disconnect the short SMA cable, and replace it with the intermediate one. Install your dipole on the new mast making sure that it rotates in the H-plane.

Rotate the Yagi antenna so that it is vertically polarized.

Perform a new acquisition and store it as the H-plane of Document1.

Orient the patterns so that their MSP is at 0°.

> **Note:** *Due to the reflections of the signal from the table, the modules, or any other object, it is possible that the maximum amplitudes of the E and H-planes may differ slightly. To minimize this problem, short distances have been privileged between the transmitting and receiving antennas. However, since reflections are not easy to predict, we consider a difference of 1 or 2 dB as acceptable in your various acquisitions.*

☐ 9. Compare the patterns of the λ and the λ/2 dipoles. Do they have the same gain (MSL) (Do not forget to take into account the difference in attenuation levels.)? Which antenna has the better gain? Give the difference between their MSLs.

____

____

☐ 10. We observed in Step 9 that, due to the high value of its resistance, the λ dipole is not an efficient power radiator. Evaluate the impedance of the λ dipole.

Record the length of the antenna.

Length of the λ dipole L_λ = ______ cm = ______ λ

Referring to Figure 1-9, give the approximate input impedance of this antenna.

Z_{in} = ______ Ω

☐ 11. Remove the dipole antenna from the mast and remove the wires from the connector; replace them with the appropriate wires to make a 3λ/2 dipole. Clip this new antenna on the mast.

☐ 12. Using Equation (6), calculate the distance required in order to be in the far-field region with this set-up. The 3λ/2 dipole is longer than the Yagi antenna so

$$L = \frac{3\lambda}{2} = \_\_\_\_\_\_\_\_ \text{ m}$$

Then

$$r > \frac{2L^2}{\lambda} > \_\_\_\_\_\_\_\_ \text{ m}$$

Position your antennas at a distance [r + 10 cm] apart.

☐ 13. Optimize the reception of the signal and perform an acquisition of the E-plane.

Make the appropriate modifications, then perform an acquisition of the H-plane radiation pattern. Store the E- and H-plane patterns of the 3λ/2 dipole in a new document (Document5).

Note: *Carefully examine the plots of the E- and H-plane radiation patterns in order to understand the relation between these patterns. Observe that the signal level of the H-plane should equal the maximum signal level of the two small lobes of the E-plane. However, the 3λ/2 dipole is particularly sensitive to reflections from the mast or other objects. Because of this, the H-plane pattern may be distorted and the signal level of the two patterns can diverge significantly.*

☐ 14. Make the appropriate modifications in order to perform an E-plane acquisition. Remove the wires from each socket of the connector.

The short sections of wire on both sides (inside the plastic block of the connector) act as a short dipole having a total length of approximately 4 cm or 0.125λ.

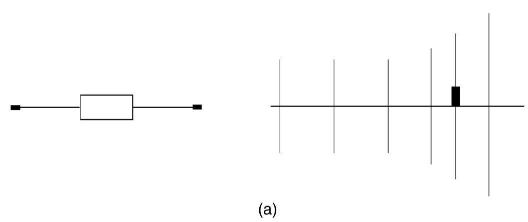
Position the antennas a distance of r = 1 m apart. Set the attenuation level to 0 dB, then perform an acquisition of the E-plane. Do not store the pattern.

Compare this radiation pattern with the E-plane pattern of the λ/2. Taking into account the difference in attenuation levels, give the difference between the maximum signal level obtained using this short dipole and that obtained from the λ/2 dipole. Referring to Figure 1-9, explain this result.

____

____

____



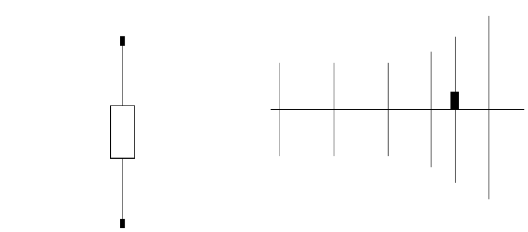


Figure 1-20. Alignment of a dipole with the transmission antenna producing a null (a) and a maximum (b) in the radiation pattern

☐ 15. You now have the radiation patterns of your three antennas. Make sure that their MSPs are oriented to 0°, then observe the spatial representation of the patterns with the E-H and 3-D tabs.

> To properly understand the 3-D representations of the different radiation patterns of 1 GHz antennas, it is important to carefully examine the plot of the E-plane. For example, notice that the nulls of a dipole are formed when the receiving antenna is perpendicular to the transmission antenna, and that its maximums appear when the antennas are parallel.
>
> To obtain a representative 3-D image of an antenna pattern, you have to position the nulls of the E-plane on the 90°- 270° axis, as shown in Figure 1-21.
>
> This positioning is normally done automatically, when you orient the MSP of the dipole antennas to 0° or 180°. However, you will have to do this adjustment by yourself when the radiation patterns are not symmetrical, or for certain types of 1 GHz antenna such as, for example, the monopole.

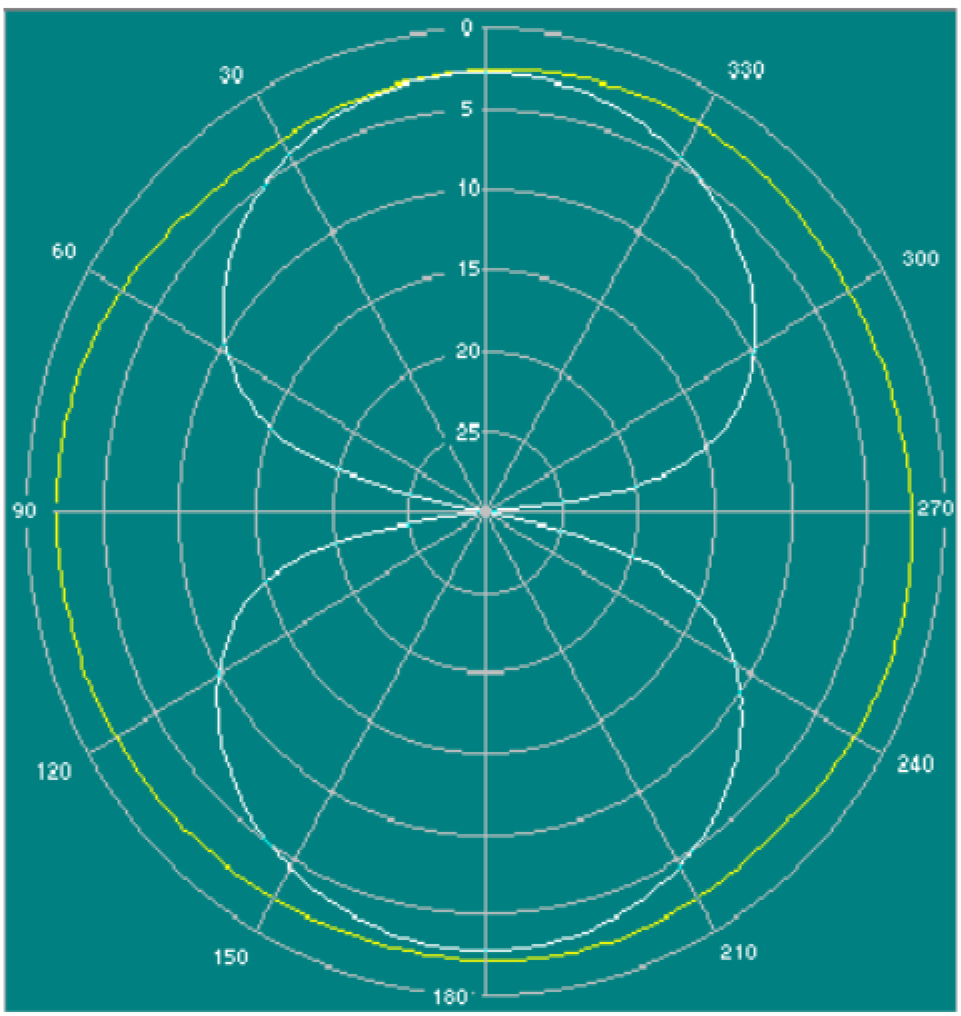


Figure 1-21. Position of the E-plane producing a correct 3-D representation

After having saved the patterns of Document1, Document4, and Document5, print the radiation patterns (in the 2-D configuration) together, for each antenna. Also print the 3-D representation of the λ/2 dipole and keep it as reference for Exercise 1-5.

Half-power beamwidth and directivity

☐ 16. Evaluate the half-power beamwidth of the λ/2 and λ dipole's E-plane patterns.

$HPBW_{E\text{-}\lambda/2}$ = ______ °

$HPBW_{E\text{-}\lambda}$ = ______ °

Compare your evaluations of the HPBW of the E-planes with the theoretical value.

☐ 17. From the formula

$$D \simeq \frac{101}{\text{HPBW (degrees)} - 0.0027\ [\text{HPBW (degrees)}]^2}$$

estimate the directivity of the λ/2 dipole.

Note: *Since the radiation pattern in the H-plane is circular, let $HPBW_H = 180°$.*

D = ______

Remember that the formula used to evaluate the directivity is not very accurate in the case of an antenna having a large radiation beam; the calculation is used only to give an approximation of the gain.

In this exercise you plotted the measured radiation patterns of the λ/2, λ and 3λ/2 dipoles and visualized their representations in space. You observed that, due to its impedance, the λ dipole antenna is not an efficient power radiator. You compared the theoretical half-power beamwidths of the E-plane of the λ/2 and λ dipoles with the ones calculated from their measured radiation patterns. Finally, using the HPBW value, you gave an approximate evaluation of the directivity of the λ/2 dipole.

CONCLUSION

In this experiment, you learned to calculate the length of a dipole antenna by using the frequency of the transmission signal. You learned to recognize the horizontal and vertical polarizations of the Yagi and the dipole antennas. You plotted the radiation patterns of the E and the H-planes of a λ/2 dipole and observed that the shape of an antenna pattern is not affected by the strength of the signal. Finally, you learned to use the power pattern of an antenna to evaluate its half-power beamwidth (HPBW).

Also , you plotted the measured radiation patterns of the λ/2, λ and 3λ/2 dipoles and visualized their representations in space. You observed that, due to its impedance, the λ dipole antenna is not an efficient power radiator. You compared the theoretical half-power beamwidths of the E-plane of the λ/2 and λ dipoles with the ones calculated from their measured radiation patterns. Finally, using the HPBW value, you gave an approximate evaluation of the directivity of the λ/2 dipole.

REVIEW QUESTIONS

1. What is the purpose of an antenna?

 ____

 ____

 ____

2. What is an isotropic source and why it is so useful?

 ____

 ____

 ____

3. What is a radiation pattern? Give the difference between the receiving and the transmission radiation patterns of an antenna.

 ____

 ____

 ____

4. Describe the dipole antenna.

 ____

 ____

 ____

 ____

5. What is meant by antenna polarization? How is the dipole antenna polarized?

 ____

 ____

 ____

6. Among the three dipoles you have studied, which one, as far as signal trans-mission is concerned, offers the best performance, and why is this so?

____

____

____

7. If the directivity of the λ dipole is better than that of the λ/2 dipole, why wasn't this antenna chosen as the answer to Question 6?

____

____

____

8. Briefly explain the relation between the current, the impedance and the length of a dipole.

____

____

____

9. Does the distance of 1 m satisfy the condition for far-field measurements with the λ/2 and λ dipoles operating at 915 MHz? Give the minimum separating distances required by these antennas.

____

____

____

10. Demonstrate that the half-power beamwidth of a λ/2 dipole is 78°.

____

____

____

____

EXP. 4 Frequency Response and Standing Waves in Transmission Lines

Part 1
Matching and Frequency Response

Objectives of this Part

Having completed this part you will be able to:

- Identify the relationship between velocity, frequency and wavelength of a wave.
- Explain that a mismatched transmission line has an impedance which varies with frequency.
- Plot the frequency response of a mismatched simulated 50 ohm line.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.
- Function Generator.

1.1 Reflections with a Sinewave Input

Until now we have only considered reflections in pulse waveforms.

If a sinewave is propagated down a matched transmission line then, at the termination, all the power is absorbed by the load and no reflection will take place.

However, if a sinewave is propagated down a mismatched transmission line then, at the termination, a reflection will take place.

That is:

If the line is open circuit the sinewave is reflected non-inverted.

If the line is short circuit the sinewave is reflected inverted.

Although this is similar to the condition with the pulse input, this reflected sinewave has an interesting effect, which will be explored in the next section.

1.2 Wavelengths

A reflected wave will travel back down the line and will be phasor added with the transmitted wave. If, at the input, the result of the mismatch and the delay is such that the reflected sinewave is 180° out of phase, then this is the same as a subtraction, and the resultant wave will be smaller than the sinewave initially transmitted.

Assuming the delay of the transmission line and the termination conditions remain constant then the resultant wave at the input will depend on the phase of the reflected wave. As the time delay is the same, the phase will only be dependent on the frequency of the sinewave.

When considering this effect it is useful to measure the length of a transmission line in **wavelengths**. A wavelength is the distance traveled by a wave in the time taken for one cycle of oscillation.

In mathematical terms a wavelength is:

$$\lambda = \frac{v}{f}$$

where v is the velocity in m/s, f is the frequency in Hertz and gives λ in meters.

You will recall from Assignment 1 part 3 that transmission velocity depends on the physical properties of the line. For a given transmission line, this velocity will be constant for any input signal.

If, at a particular frequency, a transmission line is one wavelength long then the sinewave at the output will lag the input by 360°. In other words, the two waves will be in phase. If the line has an open circuit termination this will result in a reflected wave in phase at the output. This reflected wave will travel down the transmission line and arrive another 360° out of phase. In other words, the transmitted and reflected pulse will arrive at the input in phase. This means these two waves will add and give a maximum amplitude.

At another frequency the phase difference will be different and so the amplitude at the input will be different too.

In other words, the frequency response will depend upon the line termination.

1.2a A wavelength is defined as:

- a the time taken for one oscillation
- b the distance a wave travels in one oscillation.
- c a radio signal.
- d the time taken for a wave to travel down a transmission line.

1.2b A wave has a velocity of 3 x 10^8 m/s and a frequency of 200kHz, calculate and enter the wavelength (in meters).

1.3 Input Impedance

If, as a result of a mismatch, the input amplitude is reduced compared to the matched state then the input impedance input is said to have been reduced. Conversely, if the input amplitude is increased compared to the matched state then the input impedance of the line is said to have increased.

So with a mismatched line, the input impedance of the line also varies with frequency.

1.4 Practical Exercise

In this practical exercise we shall measure the frequency response of the simulated 50 ohm line with different terminations.

- Connect the power supply to the Transmission Line Trainer.
- Ensure all switched faults are off.
- Switch the Pulse Generator off.
- Connect the function generator output to the 50 ohm BNC to 4mm adapter on the Transmission Line Trainer and then use a 4mm lead to connect the BNC to 4mm adapter to the input of the Summing Amplifier.
- Connect the output of the Summing Amplifier to the input of the simulated 50 ohm line.

- Set the Summing Amplifier output coupling switch to DC.
- Set the Summing Amplifier FIXED/VAR switch to FIXED.
- Set Summing Amplifier gain to minimum (fully counter-clockwise).
- Set the Noise Generator AMPLITUDE control to minimum (fully counter-clockwise).
- Use a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit. Set the resistor to its mid point.
- Switch on the power supply.
- Connect channel 1 of the oscilloscope to examine the input of the simulated 50 ohm line at test point **A1**.
- Connect channel 2 of the oscilloscope to examine the output of the simulated 50 ohm line at test point **A25**.
- Set the function generator to give a 2 volt peak-to-peak sinewave at the input to the simulated 50 ohm line, A1.
- For each of the following conditions, adjust the frequency control of your Function Generator to the values shown in Table 1, and measure the voltage of the sinewave at the input with:

  i) a matched termination

  ii) a short circuit termination

  iii) an open circuit termination.

Record your results in Table 1 in your workbook:

Frequency (kHz)	Match Termination (Vp-p)	Short Circuit Termination (Vp-p)	Open Circuit Termination (Vp-p)
1			
2			
5			
10			
20			
30			
40			
50			
60			
70			
80			
90			
100			
150			
200			
250			
300			
350			
400			
450			
500			

Table 1

- Switch off the power supply.
- Use the log/lin graphs in your student workbook to plot each of the frequency response curves. Each of these graphs has the form shown in Figure 1. The X axis represents frequency on a logarithmic scale and the Y axis represents voltage on a linear scale.

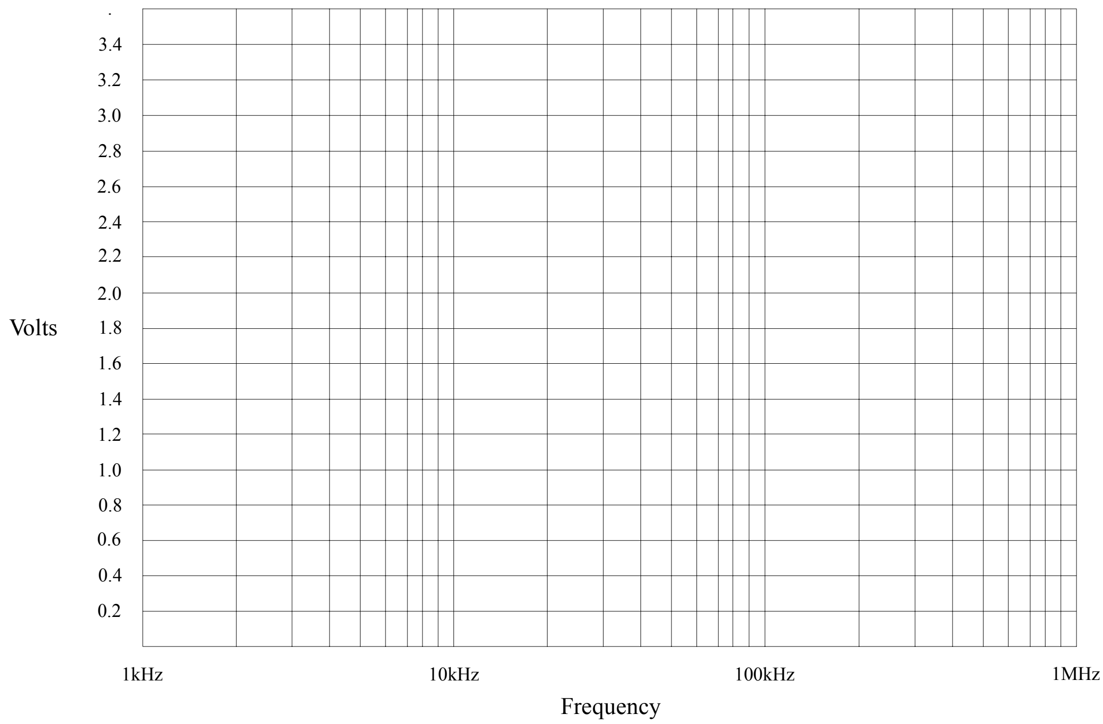


Figure 1

1.4a Enter the frequency at which the first minimum (dip) in the plot occurred for a short circuit termination on the simulated 50 ohm line.

1.4b Enter the frequency at which the first minimum (dip) in the plot occurred for an open circuit termination on the simulated 50 ohm line.

1.5 Summary of Practical Exercise

Practical Exercise 1.4 has shown the effect that the termination resistance has on the frequency response.

i) Matching the line gives the best (straightest) frequency response.

ii) Mismatching the line gives a response that after a certain frequency starts to rise and fall with increasing frequency.

This exercise shows the importance of matching for a good frequency response.

You may have noticed that the first part of the response looks a little like the response of a tuned circuit. Could this be put to some use? In theory it could, but in practice this effect is not often used, as the mismatched line is ‘resonant’ at more than one frequency.

The next chapter investigates standing waves.

Student Assessment 1

1. **A sinewave propagated down a matched transmission line will produce:**
   - a an inverted reflected wave.
   - b a non-inverted reflected wave.
   - c no reflections.
   - d no output.

2. **A wave with a velocity of 2×10^8 m/s and a frequency of 20MHz has a wavelength of:**
   - a 1m
   - b 10m
   - c 100m
   - d 1km

3. **A transmission line with a sinewave input such that the line is half a wavelength long, has a phase relationship between input and output of:**
   - a 90°
   - b 180°
   - c 270°
   - d 360°

4. **If the phase relationship between transmitted wave and reflected wave at the input of the transmission line is 360°, the two waves will:**
   - a add.
   - b subtract.
   - c multiply.
   - d divide.

Student Assessment 1 Continued...

5. For a mismatched transmission line, which of the following does <u>not</u> depend on the input signal frequency?

- [a] Wavelength.
- [b] Input impedance.
- [c] Phase shift between transmitted and reflected waves at the input to the line.
- [d] Velocity.

6. The plot of the frequency response (as measured from the input) of an open circuit line is best described as:

- [a] a straight line.
- [b] a level which falls off after a certain frequency.
- [c] a level which first dips then rises with increasing frequency.
- [d] a level which first rises then dips with increasing frequency.

Notes:

Part 2
Standing Waves

Objectives of this Part

Having completed this part you will be able to:

- Explain the principles of standing waves on a transmission line.
- Predict the Voltage Standing Wave Ratio (VSWR) of a transmission line.
- Observe standing waves using the Standing Wave Display circuit.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.
- Function Generator.

2.1 Standing Waves

In the last chapter we considered the effect of frequency response on a transmission line with matched, open circuit and short circuit terminations.

We saw that the sinewave was reflected back down the line and that the resultant wave at the input was the phasor addition of the transmitted wave and the reflected wave.

This effect not only happens at the input to the transmission line, but occurs all the way along the line. So at a particular frequency the amplitude at the input may be a minimum, but in other places along the length of the line the amplitude may be a maximum. If the amplitude was measured at regular intervals along the line and a graph were plotted of amplitude against distance, the result would be a series of minima and maxima, giving the appearance of a 'wave'. This plotted 'wave' is called a **standing wave** because for a given frequency the amplitude at a particular point along the line does not change - in other words, the wave is stationary or 'standing'.

We can measure the length of the line in wavelengths of the standing wave. A wavelength is twice the distance between adjacent minima or adjacent maxima, as shown in Figure 2 below:

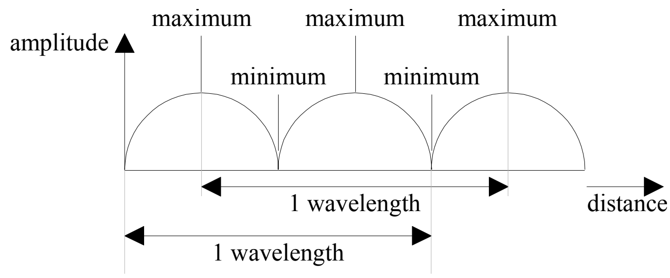


Figure 2

The wavelength of the standing wave is equal to the wavelength of the input signal, so it depends on the velocity and frequency of the input signal. If a line is 2 wavelengths long at one input frequency then it will always be 2 wavelengths long at that frequency regardless of termination impedance. However, what will vary with the termination impedance are the precise points along the line at which the minima and maxima occur.

For example, if a line has a short circuit termination, its voltage will be a **minimum** at the short circuited end. On the other hand if the line has an open circuit termination its voltage will be a **maximum** at the open circuited end.

Figure 3 shows three different examples of standing wave patterns along a transmission line, for a given input frequency.

Pattern A) shows a line of length 1.5 wavelengths with a short circuit termination.

Pattern B) shows a line of length 1.5 wavelengths with an open circuit termination.

Pattern C) shows a line length of 1.5 wavelengths with a slightly mismatched termination.

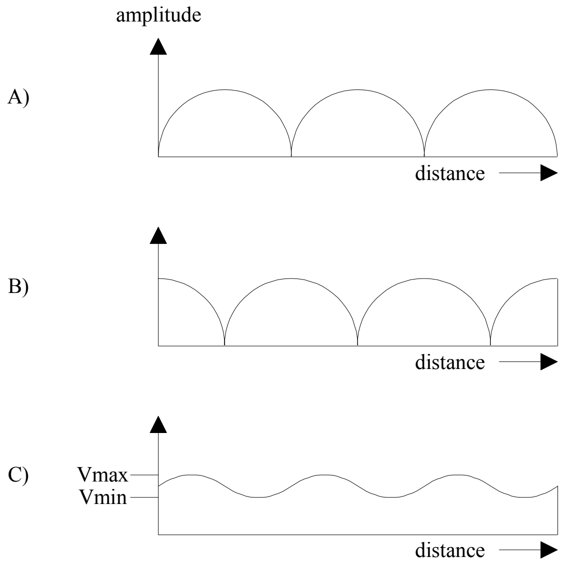


Figure 3

If we take readings at regular intervals along the line and record the maximum and minimum amplitudes, we can calculate the **Voltage Standing Wave Ratio** or **VSWR**. This is calculated using the formula:

$$VSWR = \frac{V\max}{V\min}$$

Note that Vmin = 0 with an open circuit or short circuit line termination, so VSWR = ∞ under either of these conditions.

You may recall from Exp.1 that we used the voltage reflection coefficient (Γ), which was calculated using the following formula:

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

You should note that the VSWR can also be calculated using the formula:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

Note that $|\Gamma|$ is always a positive quantity, where $|\Gamma|$ is the **magnitude** of Γ even when Γ is negative.

You will recall from Exp. 1 that with an open circuit line termination Γ = 1 and with a short circuit line termination Γ = -1. In either case |Γ| = 1, giving VSWR = ∞ under wither of these conditions.

2.1a Where does a line, which is one half-wavelength long, and terminated in a short circuit have minimum voltage points?

- a Nowhere.
- b At the end only.
- c At the middle and the end.
- d At the beginning and the end.

2.1b A signal is applied to the input of a transmission line, the amplitude of the signal is measured at intervals along the line and the values are recorded. The maximum value is 8 volts and the minimum value is 2 volts. Calculate and enter the VSWR.

2.2 Practical Exercise

Although we could examine standing waves by plotting on graph paper the signal amplitude against distance along the line, the Transmission Line Trainer provides us with an easier way.

It does this by displaying, on an oscilloscope, the peak-to-peak amplitude of the signal at different points along the transmission line. In this way the oscilloscope display shows the actual standing wave. However, since this standing wave display shows the **peak-to-peak** (rather than the peak) amplitude along the line, the traces displayed will appear to be slightly different from those shown earlier in Figure 3. For example, pattern A (for a line with 1.5 wavelengths and a short circuit termination) would be displayed by the standing wave display circuit of the Transmission Line Trainer as shown in Figure 4 below:

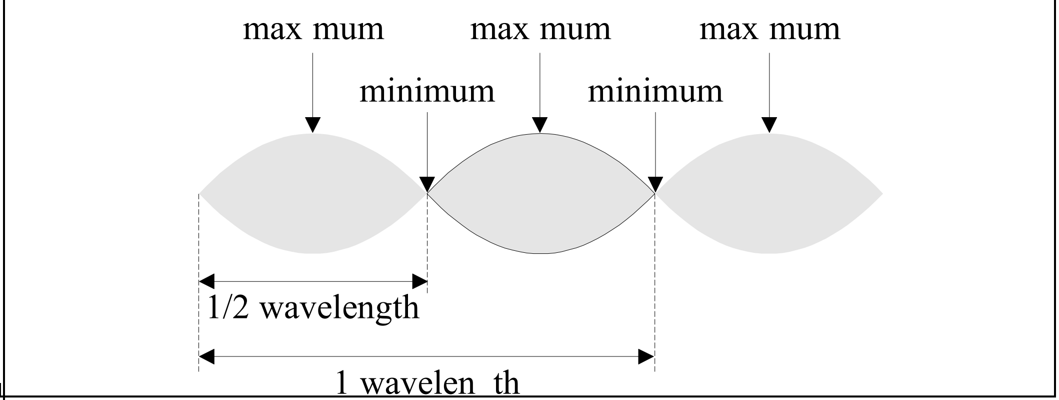


Figure 4

In this practical exercise we will display standing waves on the oscilloscope.

- Connect the power supply to the Transmission Line Trainer.
- Ensure all switched faults are off.
- Switch the Pulse Generator off.
- Connect the Function Generator to the input of the simulated 50 ohm line via the Summing Amplifier, using settings as described in Practical Exercise 1.4.
- Switch on the power supply.
- Using channel 2 of the oscilloscope, set the function generator to give a 4 volt peak-to-peak sinewave, frequency 100kHz at the input of the 50 ohm simulated transmission line, test point **A1**.
- Connect channel 1 of the oscilloscope to test point **TPA** in the Standing Wave Display circuit. The oscilloscope should display a square wave. Trigger the oscilloscope with the negative edge of this signal.
- Set the timebase so that the negative going edge of this square wave is on the left most graticule and the next positive going edge is on the right most graticule. In other words, half a cycle of square wave should be displayed on the oscilloscope display.
- As the square wave is only used for setting up the oscilloscope it can be moved out of view.
- Use a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit. Set the resistor to its mid way position.
- Connect channel 2 of the oscilloscope to examine the output of the Standing Wave Display at **TPB**.

■ Use a 4mm lead to connect the input of the simulated 70 ohm line to 0V (as shown in Figure 5 below).

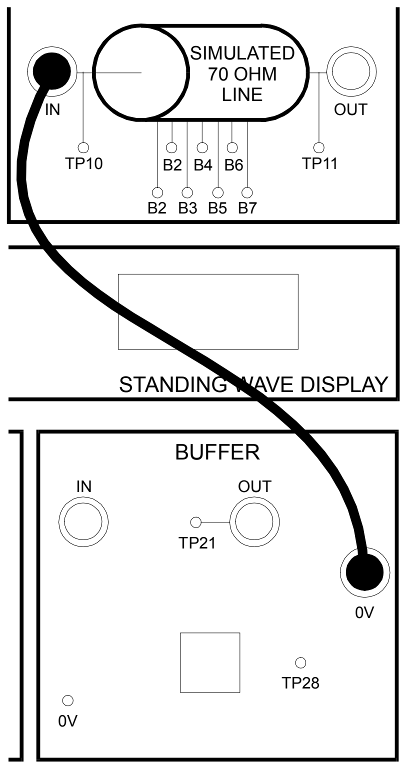


Figure 5

Normally an oscilloscope displays a plot of voltage against time, but the standing wave display circuit turns this into a plot of voltage against distance along the line. The left hand side of the trace displays the input of the simulated 50 ohm line. What then follows is the next 24 sections of this line. After that follows the 8 sections of the simulated 70 ohm line. As the simulated 70 ohm line is not used for this exercise this last part of the oscilloscope display can be ignored.

In Figure 6 below is a diagram of the kind of display that you can obtain on the oscilloscope. This display shows the transmission line with a short circuit termination and a half wave standing wave. Each 'step' represents one section.

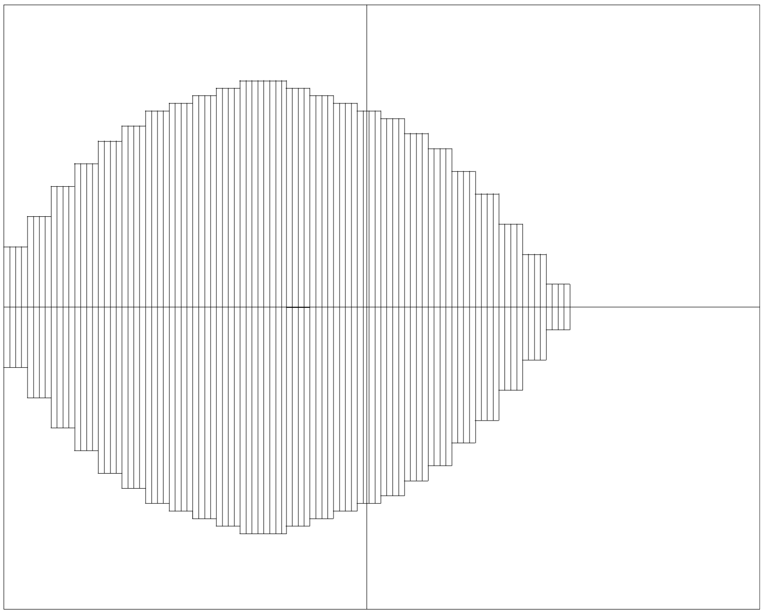


Figure 6

- With the simulated 50 ohm line matched, you should find that the amplitude along the line remains fairly constant between frequencies of 100kHz & 1MHz. Note that at higher frequencies (500kHz and above) there may be small amplitude standing waves due to the imperfections of the line.

- Short circuit the 50 ohm line termination. Obtain displays for a:

  i) quarter wave standing wave.

  ii) half wave standing wave.

  iii) full wave standing wave.

  by varying the input sinewave frequency.

- Sketch waveforms i) & ii) in your workbook and note the frequency at which these displays occur.

- Open circuit the 50 ohm line termination. Obtain displays for a:

  iv) quarter wave standing wave.

  v) half wave standing wave.

  vi) full wave standing wave.

  by varying the input sinewave frequency.

- Sketch waveforms v) & vi) in your workbook and note the frequency at which these displays occur.

- Switch off the power supply.

2.2a Enter the frequency (in kHz) at which the simulated 50 ohm line displayed a quarter wave standing wave with a short circuit termination.

2.2b Calculate and enter the VSWR when the simulated 50 ohm line displayed a half wave standing wave and the line had an open circuit termination.

2.3 Summary of Practical Exercise

Practical Exercise 2.2 has explored standing waves.

i) Matching the line gives the smallest standing waves and the smallest VSWR.

ii) Mismatching the line gives a larger VSWR, depending on the amount of mismatching.

For transmission of signals down a line it is normal to minimize the VSWR.

However, the antenna of a transmitter could be considered as a transmission line with a high VSWR. A quarter wavelength line with an open circuit end would have a voltage maximum at the output and a voltage minimum at the input. Indeed a wire of length $\lambda/4$ would make an antenna (although a very inefficient one by today's standards).

Student Assessment 2

1. A standing wave is so called because:

- a it is upright.
- b it does not move.
- c it is measured in wavelengths.
- d it is caused by reflections.

2. Altering the termination impedance changes the:

- a voltage amplitude along the line.
- b characteristic impedance.
- c transmission velocity.
- d wavelength.

3. **The Standing Wave Display circuit on the Transmission Line Trainer uses the oscilloscope to display:**

   a voltage against time.

   b voltage against distance along the line.

   c voltage against frequency.

   d square waves.

4. **A line has a maximum voltage of 20 volts and a minimum voltage of 4 volts along its length. The VSWR is:**

   a 0.2

   b 5

   c 10

   d 20

5. **If the Standing Wave Display shows a full wave standing wave and there is a short circuit termination on the line, the voltage minima (dips) are at:**

   a the end.

   b the beginning.

   c the beginning and the end.

   d the beginning, the middle and the end.

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 5 Standing Waves in Waveguids and Directional Coupler

Exercise 1

Standing Waves

EXERCISE OBJECTIVES

When you have completed this exercise, you will know how standing waves are created in waveguides. You will be able to perform microwave frequency measurements and standing wave measurements with the Slotted Line and the SWR Meter of LVDAM-MW.

DISCUSSION

Creation of Standing Waves

When a sinusoidal microwave source is connected to a waveguide, sinusoidal waves of voltage and current propagate along it.

> **Note:** *In fact, we could also say that both an electric field wave and a magnetic field wave propagate inside the waveguide. Considering voltages and currents instead of electric and magnetic fields is simply a different way of viewing things. The voltage is present between the top and the bottom of the waveguide, whereas the current flows in the side walls. Throughout this exercise, we will deal with voltages and currents to facilitate the understanding.*

The amplitude of the voltage and the current depend on the characteristic impedance of the waveguide and on the impedance of the terminating load.

When the impedance of the load is equal to the characteristic impedance of the waveguide, the load continually absorbs all the received energy. No energy is reflected back toward the source. The waves travel only from the source to the load.

Conversely, when the impedance of the load is not equal to the characteristic impedance of the waveguide, not all the received energy is absorbed by the load. Instead, part of it is reflected back toward the source.

Figure 1, for example, shows the waves traveling along a waveguide when the impedance of the load is not equal to the characteristic impedance of the waveguide.
In this example, the load is in the **short-circuit** condition:

- the incident wave is completely reflected at the load end.
- the reflected and incident waves travel through each other, but in opposite directions, thereby combining vectorially.

This results in the creation of a standing wave along the waveguide. The standing wave is the sum of the instantaneous values of the incident and reflected waves at each point all along the line. This wave does not move or travel along the line, hence the term "standing".

Standing Waves

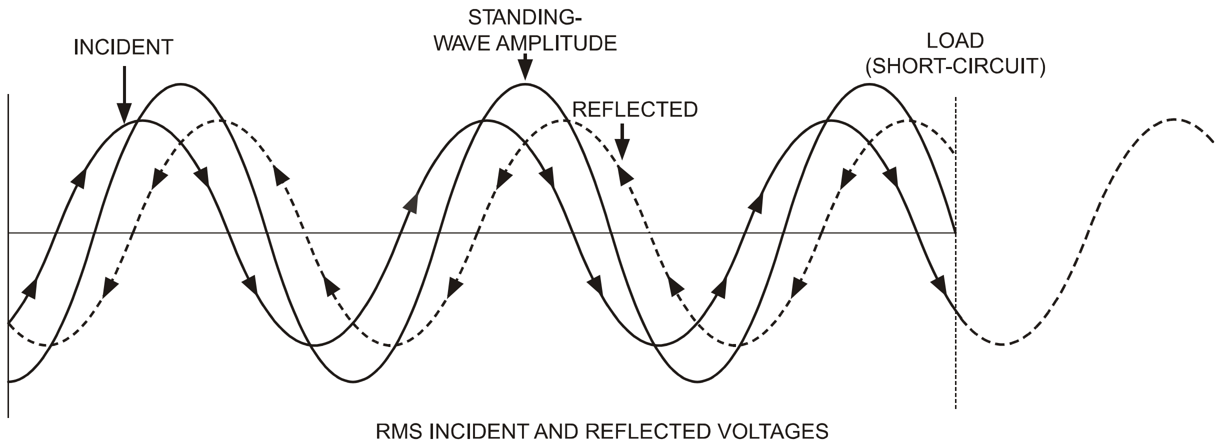


Figure 1. Creation of a standing wave along a short-circuited waveguide.

Conventional Representation of Standing Waves

Even if the voltage or current of standing waves continually changes polarity with time, the conventional way of representing these waves is with their negative and positive half-cycles pointing upward.

Figure 2 shows the conventional representation of a standing wave of voltage along a short-circuited waveguide.

- The points where the voltage is minimum are called minima, or nodes.
- The points where the voltage is maximum are called maxima, or loops.

The amplitude of the minima and maxima is determined by the amplitude of the reflected wave. The amplitude of the reflected wave is determined by the nature of the load.

When the load is a short circuit or an open circuit, the amplitude of the reflected wave is maximum. In fact, the amplitude of the maxima is theoretically equal to twice the amplitude of the incident wave, while the amplitude of the minima is null (or practically zero).

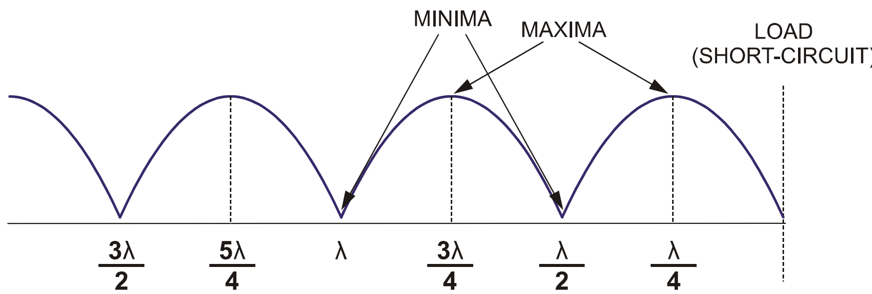


Figure 2. Conventional representation of a standing wave of voltage along a short-circuited waveguide.

Frequency Measurement

When examining Figure 2, the statements below can be inferred.

- At the load end of the waveguide, a minimum invariably occurs.
- Minima also occur at every even multiple of $\lambda_g/4$ from the load end (where λ_g is the wavelength of the propagating wave in the waveguide.)
- Maxima occur at every odd multiple of $\lambda_g/4$ from the load end.

Figure 2 allows you to determine the frequency of a microwave signal propagating in a short-circuited waveguide:

1. Measure the distance d between two successive minima.

   (Since minima are usually more sharply defined than maxima, measuring the distance between minima provides more accurate results. The presence of large reflections is also advantageous. Terminating the waveguide by a short-circuited load provides large reflection. A matched load could not be used as there would be no standing wave in this case.)

2. Multiply the measured distance by 2 to obtain the wavelength of the guided signal, λ_g.

3. Calculate the frequency of the guided signal, f, using the following equation:

$$f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$$

where
- c = velocity of propagation of the signal in **free space** ($3.0 \cdot 10^8$ m/s);
- λ_g = wavelength of the guided signal (m);
- a = width of the waveguide (m);
- f = frequency of the guided signal (Hz).

The Lab-Volt Slotted Line

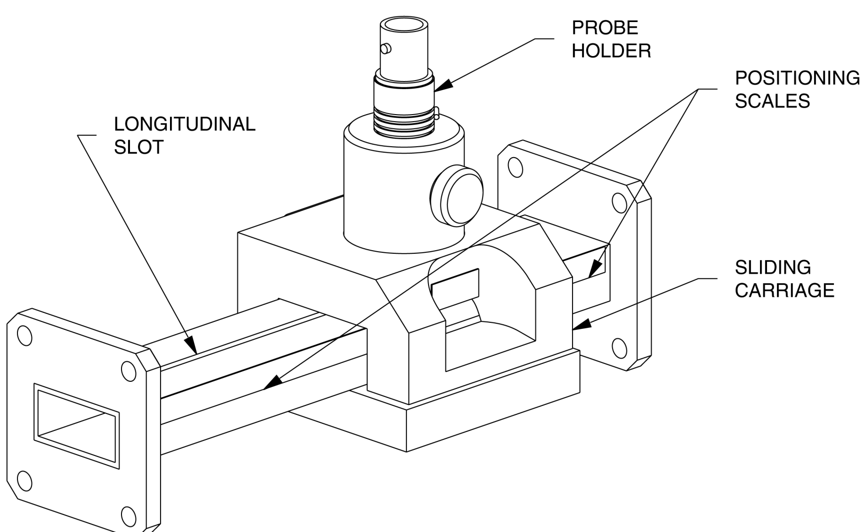
Figures 3 and 4 show the Lab-Volt Slotted Line, Model 9520. This device can be used to measure the distance between the minima and the maxima of a standing wave.

The Slotted Line consists of a low-loss waveguide section with a narrow, longitudinal slot in the top wall, as Figure 3 shows. A sliding carriage, containing a probe connected to a crystal detector, can be moved along the waveguide.

The probe is inserted into the waveguide to sense the electric field, as Figure 4 shows. This causes a microwave signal to be induced at the probe output. The crystal detector detects this signal and produces a proportional DC voltage. This voltage is available at the BNC output of the probe holder.

A thumbscrew allows you to adjust the depth of the probe and, therefore, the magnitude of the DC voltage at the BNC output. The marks and the pointer provide an indication of the depth of the probe.

The voltage produced at the BNC output of the Slotted Line decreases as the probe is withdrawn from the waveguide; conversely, the voltage increases as the depth of penetration of the probe is increased.



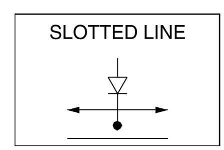


Figure 3. The Lab-Volt Slotted Line and its symbolic representation.

Standing Waves

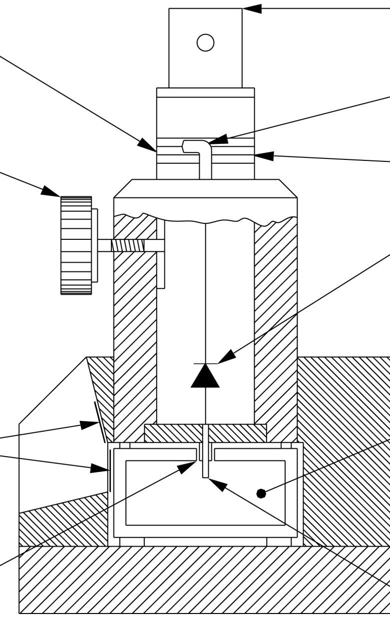


Figure 4. Cut-away view of the Lab-Volt Slotted Line.

Microwave Frequency Measurements and Standing Wave Measurements

The Lab-Volt Slotted Line can be used with the SWR Meter of LVDAM-MW to perform microwave frequency measurements and standing wave measurements.

To do this, the Slotted Line is connected to the input of the Data Acquisition Interface (DAI) that is dedicated to the SWR Meter: MULTI-FUNCTION INPUT 3. This connection is usually made via the Lab-Volt 60-dB Amplifier, Model 9593, to obtain the maximum dynamic range.

The SWR Meter is set to read power. Its power reading is directly related to the DC voltage at the Slotted Line output and, therefore, to the magnitude of the electric field in the waveguide.

When the carriage is moved along the waveguide, the position of the probe changes, causing the DC voltage produced by the crystal detector to change as a function of the variation in magnitude of the electric field along the waveguide.

Two positioning scales on the waveguide and the carriage indicate the location of the carriage. This allows you to locate the minima and the maxima in the standing wave produced by various loads, and to measure the wavelength and the frequency of the microwave signal in the waveguide.

The measurements made with a slotted line are limited by the scale graduations. The accuracy of measurement decreases as the frequency of the guided signal is increased.

Standing Waves

Startup Procedure to Follow When Using the Lab-Volt Slotted Line and the SWR Meter of LVDAM-MW

Before using the Lab-Volt Slotted Line and the SWR Meter, the following startup procedure must be performed. This procedure allows you to obtain the maximum dynamic range on the SWR Meter, while operating the crystal detector of the Slotted Line in its square-law region to obtain valid SWR Meter readings.

1. The microwave signal injected into circuit is amplitude modulated by a 1-kHz square wave, provided by the Gunn Oscillator Power Supply. The microwave signal is then attenuated in order for the crystal detector of the Slotted Line to operate in its square-law region and the SWR Meter to provide valid readings.

2. The Slotted Line's probe is located close to the maximum nearest the load in order for the Slotted Line output voltage to be maximum. This voltage is applied to MULTI-FUNCTION INPUT 3 of the DAI (input dedicated to the SWR Meter of LVDAM-MW).

3. The depth of the Slotted Line's probe is set to the initial default position of 1/3 of maximum.

4. With the minimum sensitivity (0-dB gain) on Input 3, the frequency of the SWR Meter's amplifier is tuned to obtain the maximum signal level on the SWR Meter.

5. The Slotted Line's probe depth is then adjusted so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale.

6. The Slotted Line's probe is accurately positioned over the maximum, and the probe depth is fine tuned, if necessary, to obtain the maximum signal level on the SWR Meter.

7. The reference level (0.0 dB) is set on the SWR Meter.

Particular attention must be paid to the adjustment of the probe depth inside the Slotted Line. If the probe penetrates too deep into the Slotted Line, the field distribution can be distorted, especially when the SWR is high. Moreover, the probe's crystal detector is then more likely to operate outside of its square-law region, causing the measurements to be erroneous.

To obtain a good accuracy of measurement, **the central frequency of the SWR Meter must be readjusted** whenever the microwave circuit is modified or used for a prolonged period of time, as the central frequency drifts over time. The drift in the central frequency of the SWR Meter is due, among other things, to variations in ambient temperature and equipment temperature.

Similarly, the SWR Meter's reference may vary slightly over time. Small drifts are acceptable. However, it is recommended that you verify the reference from time to time and readjust it to 0.0 dB, to maintain a good accuracy of measurement.

Standing Waves

Procedure Summary

In this exercise, you will measure the guided wavelength and the frequency of a microwave signal, using the Slotted Line and the SWR Meter.

You will then plot the standing-wave patterns for a short circuit, an attenuator and short-circuit load, and a matched load.

> **Note:** *For detailed information on how t use the SWR Meter of LVDAM-MW to perform SWR measurements, please refer to Section 3 of the Lab-Volt User Guide "Microwave Data Acquisition and Management", part number 85756-E.*

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix F of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

System Setup

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as showninFigure 5.

The Slotted Line must be connected, via the 60-dB Amplifier, to the analog input of the Data Acquisition Interface (DAI) that is dedicated to the SWR Meter of LVDAM-MW: MULTI-FUNCTION INPUT 3.

The supply cable of the 60-dB Amplifier must be connected to the DB-9 connector on the bottom of the Data Acquisition Interface.

☐ 2. Referring to the attenuation-versus-blade position curve (or the corresponding Data Table) of the Lab-Volt Variable Attenuator obtained in figure 6 below , determine the attenuator blade's position required for this attenuator to provide an attenuation of 20 dB approximately.

Set the Variable Attenuator's blade to this position, which will limit the microwave signal incident to the Slotted Line's crystal detector to make it operate in its square-law region.

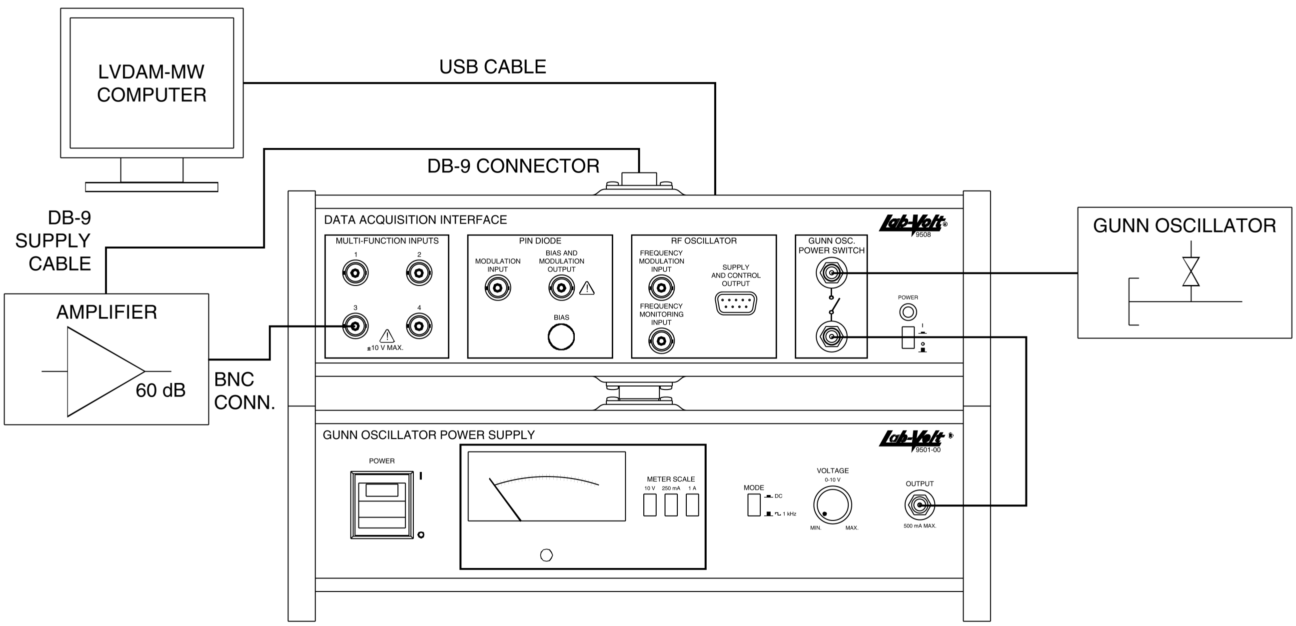
Attenuator blade's position: ______ mm

☐ 3. Make the following settings on the Gunn Oscillator Power Supply:

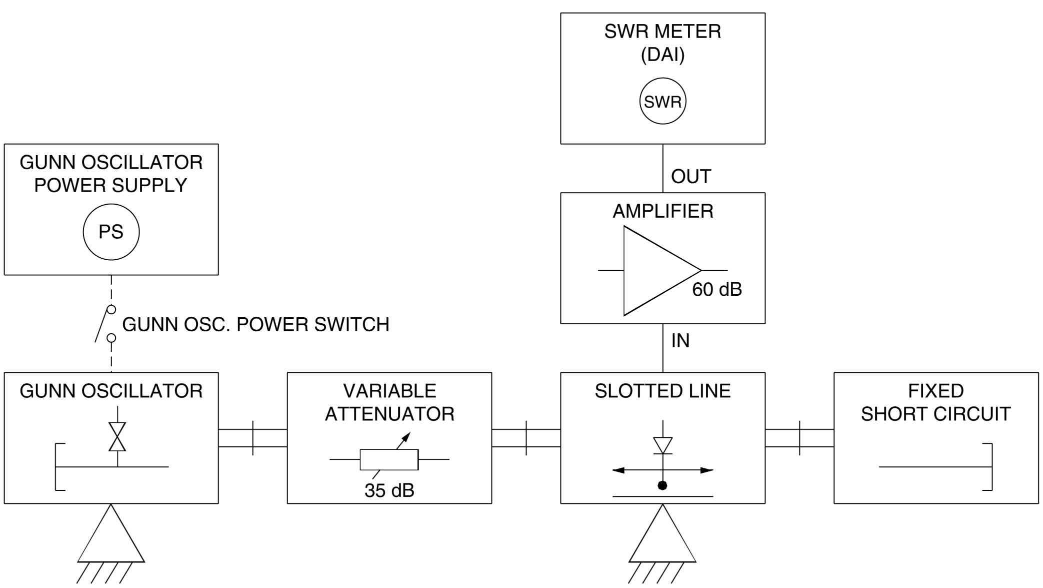
VOLTAGE . . . . MIN.
MODE . . . . 1 kHz
METER SCALE . . . . 10 V

☐ 4. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Set the Gunn Oscillator supply voltage to 8.5 V. Wait for about 5 minutes to allow the modules to warm up.



(a)



(b)

Figure 5. Computer and module arrangement (showing electrical connections to microwave components), and microwave setup.

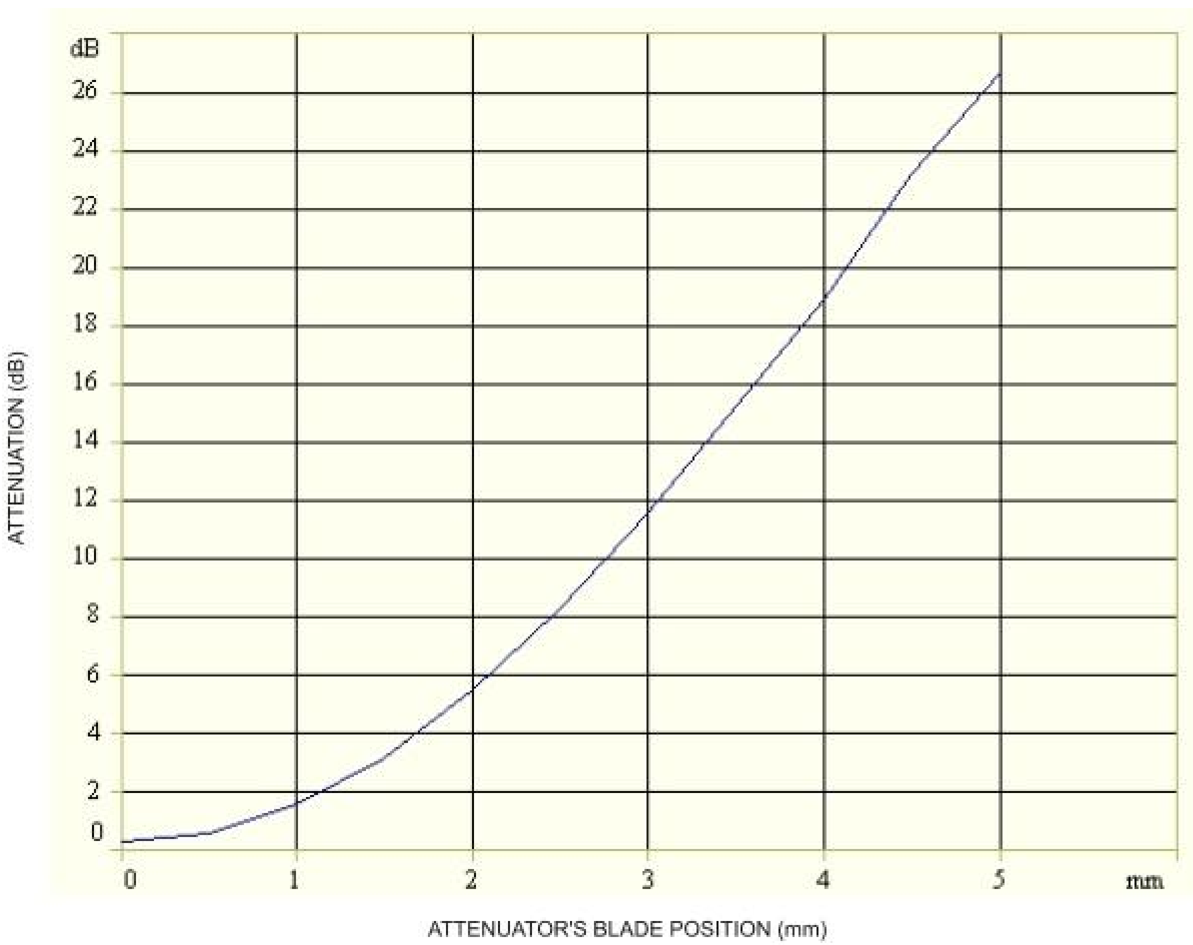


Figure 6**. Calibration curve of the Variable Attenuator.**

Preliminary Adjustment of the Slotted Line and SWR Meter

☐ 5. Move the probe of the Slotted Line along the waveguide and set it over the 45-mm position. (The 45-mm mark on the waveguide scale intersects the rightmost ("0") mark on the carriage scale, as Figure 7 shows).

The 45-mm position approximately corresponds to the location of the standing wave maximum nearest the load.

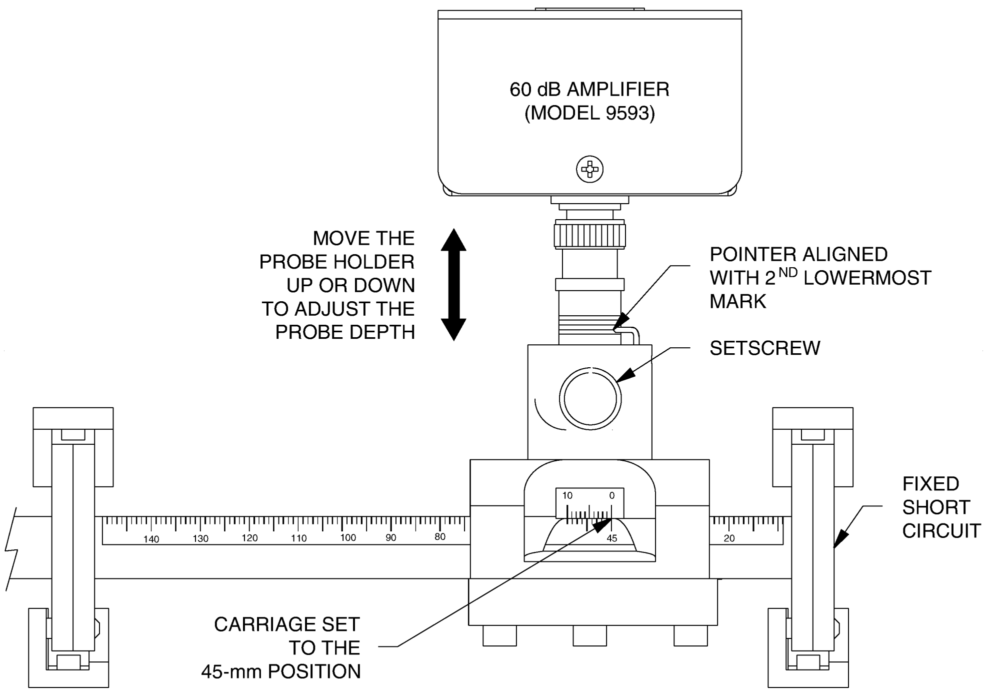


Figure 7. Locating the Slotted Line's probe over the 45-mm position and adjusting the probe's depth to 1/3 of maximum (pointer aligned with the second lowermost mark).

☐ 6. On the Slotted Line, loosen the thumbscrew of the sliding carriage and partially withdraw the probe holder (by gently pulling up on the 60-dB Amplifier connected to the probe holder).

Adjust the depth of the Slotted Line's probe to approximately 1/3 of maximum (the Slotted Line's pointer must be aligned with the second lowermost mark approximately, as Figure 7 shows); then tighten the thumbscrew.

> **Note:** *Particular attention must be paid to the adjustment of the probe depth inside the Slotted Line. If the probe penetrates too deep into the Slotted Line, the field distribution can be distorted, especially when the SWR is high. Moreover, the probe's crystal detector is then more likely to operate outside of its square-law region, causing the measurements to be erroneous.*

☐ 7. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Input 3 Gain . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

☐ 8. In LVDAM-MW, start the SWR Meter and set it to display decibels (dB).

☐ 9. Tune the frequency of the SWR Meter's amplifier: using the cursor of the SWR Meter, scan through the frequency tuning range of this meter (from 900 to 1100 Hz) to find the frequency at which the Signal Level (indicated as a percentage below the horizontal indicator bar of the meter) is maximum.

a. If the maximum signal level obtained on the SWR Meter is between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 10.

Note: *To obtain the maximum dynamic range of measurement on the SWR Meter (once its amplifier has been tuned), a maximum level between 70 and 90% on the SWR Meter with Input 3 Gain set to 0 dB is ideal.*

b. If the maximum signal level obtained on the SWR Meter is between 10% and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

Make sure not to insert the probe too deep inside the Slotted Line, otherwise the measurements may be erroneous. Instead slightly readjust the attenuation provided by the Variable Attenuator if the maximum reachable Signal Level stays below 70% of full scale, until this signal is within 70 and 90% of full scale.

Note: *The adjustment process may be tedious at first, since a small change in probe depth results in a significant change in the SWR Meter's signal level, however it will become easier with practice.*

c. If you are unable to tune the SWR Meter's amplifier because the maximum signal level exceeds the measurement scale (the horizontal indicator bar of the meter turns to red), loosen the thumbscrew of the Slotted Line. Readjust the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (a signal level of, for example, about 25% of full scale, once the thumbscrew of the Slotted Line has been re-tightened since its tightening will cause the signal level to change slightly). Then, tune the frequency of the SWR Meter to obtain the maximum signal level on this meter. If this level is not between 70 and 90% of full scale, very slightly readjust the depth of the Slotted Line's probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar never turns from green to red) once the thumbscrew of the Slotted Line has been re-tightened.

d. If the maximum signal level stays null or too low (below 10% of full scale with a blue indicator bar or no bar displayed) when trying to tune the SWR Meter's amplifier, slightly decrease the attenuation produced by the Variable Attenuator in order to obtain a significant level on the SWR Meter (a signal level of, for example, about 25% of full scale). Then, tune the meter frequency in order to obtain the maximum signal level on this meter. If the maximum signal level is not between 70 and 90% of full scale, slightly readjust the Variable Attenuator for the signal to be within this range.

Note: *The voltage produced by the Slotted Line decreases as the probe is withdrawn from the waveguide; conversely, the voltage increases as the depth of penetration of the probe is increased. The probe needs to be partially withdrawn from the Slotted Line's waveguide to obtain valid measurements on the SWR Meter and a good dynamic range. The probe must not be fully inserted into the Slotted Line's waveguide, otherwise its crystal detector may not operate in the square-law region, causing the SWR Meter readings to be erroneous.*

☐ 10. Very slightly move the probe of the Slotted Line around the 45-mm position on the graduated waveguide, while observing the Signal Level on the SWR Meter; locate the probe over the maximum (if not already there) to obtain the maximum Signal Level on the SWR Meter.

Note: *If this causes the Signal Level to become lower than 70% or higher than 90% of full scale, very slightly readjust the depth of the Slotted Line's probe to bring the Signal Level back to 70-90% of full scale, with a green bar that never turns to red, when the probe is at the maximum.*

☐ 11. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

Measuring the Guided Wavelength and the Microwave Signal Frequency

☐ 12. Move the Slotted Line's probe along the waveguide to locate the minima and the maxima. Record the position of each of them in Table 1. Do not modify any equipment setting, except Gain Input 3 when necessary.

– To locate the maxima, set Gain Input 3 to 0 dB and find the probe locations for which the signal level is maximum on the SWR Meter.

– To locate the minima, set Gain Input 3 to 20 dB and then 40 dB to find the probe locations for which the signal level is minimum on the SWR Meter—this level will be approximately null, causing jerky and small irregular moves of the SWR Meter's indicator bar in the blue (lowest) range area.

Note: *When the Slotted Line's probe is at a minimum and the indicator bar of the SWR Meter turns to blue, the indicated level is very low and fluctuates continuously. In this case, take the approximate meter value, as it is not possible to perform an accurate measurement.*

MINIMUM	DISTANCE FROM THE LOAD (mm)	MAXIMUM	DISTANCE FROM THE LOAD (mm)
m_1 (nearest from load)		M_1 (nearest from load)	
m_2		M_2	
m_3		M_3	
m_4		M_4	

Table 1. Location of minima and maxima when the load consists of a short circuit.

☐ 13. Based on the data recorded in Table 1, evaluate the distance, d, between two successive minima.

d = ______ mm

Multiply the distance, d, by 2 to obtain the wavelength of the signal in the waveguide, λ_g.

λ_g = 2d = ______ mm

Based on the obtained wavelength, λ_g, calculate the frequency of the signal in the waveguide, f, using the formula below.

$$f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$$

where
c = velocity of propagation of the signal in free space ($3.0 \cdot 10^8$ m/s);
λ_g = wavelength of the signal in the waveguide (m);
a = width of the waveguide, equal to 0.0229 m;
f = frequency of the signal in the waveguide (Hz).

____

____

Standing Wave Produced Along the Slotted Line when the Waveguide Is Short-Circuited

☐ 14. In LVDAM-MW, select the Data Table function and enter the column titles and figures already recorded in Table 2 below. Save your Data Table.

DISTANCE FROM THE LOAD (mm)	SWR METER READING (dB)	$E/E_{MAX.}$
45	0	1
47		
49		
51		
53		
55		
57		
59		
61		
63		
65		
67		
69		
71		
73		

Table 2. $E/E_{MAX.}$ ratios along the Slotted Line when the waveguide is short-circuited.

☐ 15. Set the Gain on Input 3 to 0 dB.

Locate the Slotted Line's probe over the maximum nearest the load (around the 45.0-mm position) in order to obtain the maximum signal level on the SWR Meter.

Verify that the frequency of the SWR Meter is properly tuned for the Signal Level displayed on the SWR Meter to be maximum. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 16. Fill in your Data Table: by moving the Slotted Line's probe away from the load in steps of 1.0 mm, set this probe to each of the locations listed in the Data Table and, for each location, perform the steps below.

a. Record the SWR Meter power reading under the column "SWR METER READING" (increase or decrease Gain Input 3 as necessary, but do not change the Reference on the SWR Meter).

b. Using the SWR Meter reading recorded in step a., use the equation below to calculate the ratio $E/E_{MAX.}$. Record your result under the column "$E/E_{MAX.}$". Save your table.

$$\frac{E}{E_{MAX.}} = 10^{\frac{\text{SWR Meter Reading (dB)}}{20}} = \text{antilog}\ \frac{\text{SWR Meter Reading (dB)}}{20}$$

where

E = Voltage of the standing wave at the current probe location (V);

$E_{MAX.}$ = Voltage of the standing wave at the location of the maximum (V);

SWR Meter Reading = Ratio of the standing wave voltage, E, to the maximum voltage, $E_{MAX.}$ of this wave, in decibels (dB).

☐ 17. In LVDAM, select the Graph function of the Data Table and plot the $E/E_{MAX.}$-versus-distance from the load curve: select "DISTANCE FROM THE LOAD" for the X-Axis and "E/E max" for the Y-Axis.

Have the X-Axis coordinates of your graph graduated like the Slotted Line's ruler (right-to-left increase) by making the following settings in the Graph window:

X-Axis Coordinates
- Inversion . . . . ON

Scale
- X-Axis Scale . . . . Manual
- X Interval 10
- X Max 150
- X Min 0

Your graph should show part of the standing-wave pattern, as Figure 8 shows. Print your graph, then plot the rest of the standing wave freehand based on the minima and the maxima recorded in Table 1. Remember that a standing wave repeats itself every half-wavelength. The distance between the minima and maxima remains constant.

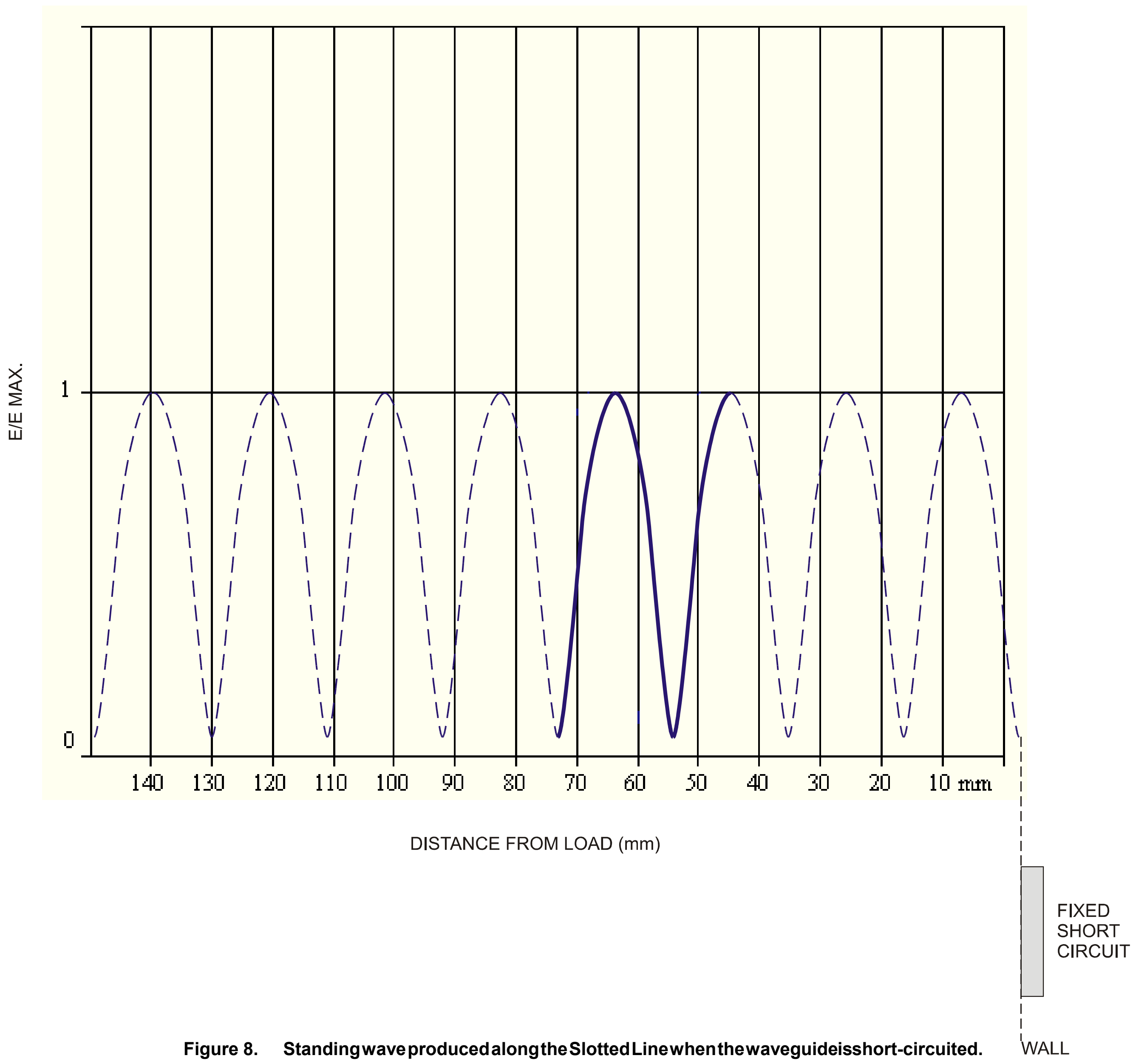


Figure 8. Standing wave produced along the Slotted Line when the waveguide is short-circuited.

Standing Wave Produced Along the Slotted Line with a Matched Load

☐ 18. Save and close your Data Table.

☐ 19. In the Settings panel of LVDAM-MW, set the Gunn Oscillator/VCO Power to OFF.

☐ 20. **Taking care not to modify the adjustment of the Variable Attenuator and Slotted Line's probe**, modify your microwave circuit in order to obtain the circuit shown in Figure 11.

Leave the rest of the equipment connected and set as before.

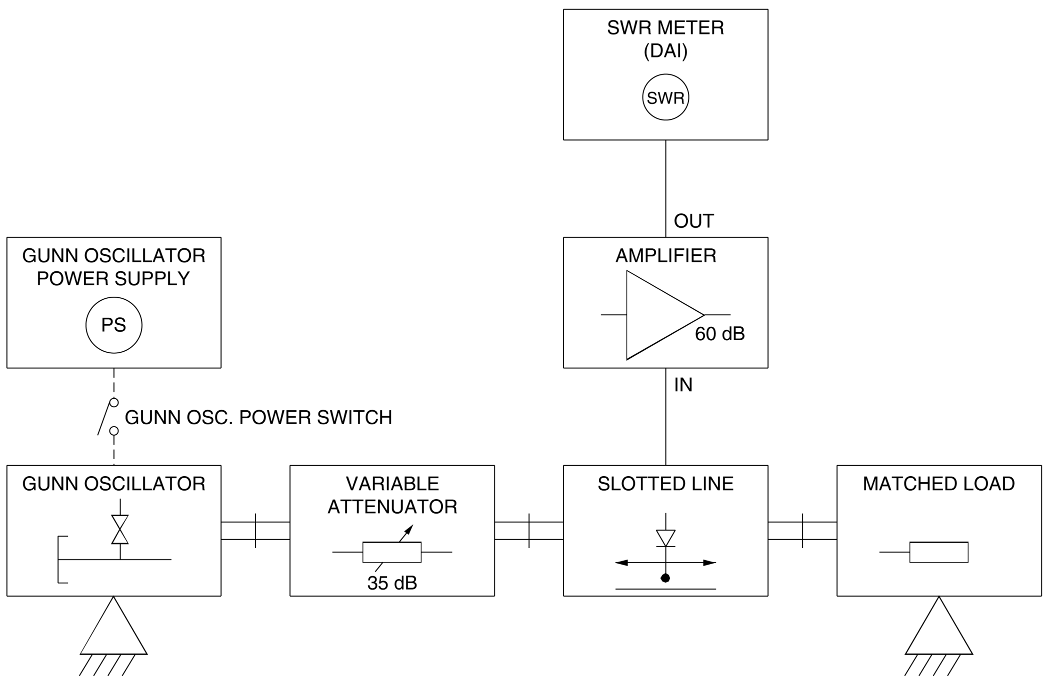


Figure 11. Modified microwave circuit to plot the standing-wave pattern with a matched load.

☐ 21. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Input 3 Gain . . . . 0 dB

☐ 22. In LVDAM-MW, select the Data Table function and enter the column titles and figures already recorded in Table 3 below. Save your Data Table.

PROBE LOCATION (mm)	SWR METER READING (dB)	$E/E_{MAX.}$
40	0	1
50		
60		
70		
80		
90		
100		
110		

Table 3. $E/E_{MAX.}$ ratios along the Slotted Line with a matched load.

☐ 23. Locate the Slotted Line's probe over the 40-mm position.

Verify that the frequency of the SWR Meter is properly tuned for the Signal Level displayed on the SWR Meter to be maximum. If this level is below 70% of full scale, very slightly readjust the attenuation provided by the Variable Attenuator or the depth of the Slotted Line's probe so that the maximum level is between 70 and 90% of full scale.

Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 24. Fill in your Data Table: by moving the Slotted Line's probe away from the load, set this probe to each of the locations listed in the Data Table and, for each location, perform the steps below.

a. Note the SWR Meter power reading and record it under the column "SWR METER READING".

Note: *When the SWR Meter's Signal Level fluctuates, approximate this level.*

b. Using the SWR Meter reading recorded in step a., use the equation below to calculate the ratio E/E_{MAX}. Record your result under the column "$E/E_{MAX.}$" Save your table.

$$\frac{E}{E_{MAX.}} = 10^{\frac{\text{SWR Meter Reading (dB)}}{20}} = \text{antilog}\,\frac{\text{SWR Meter Reading (dB)}}{20}$$

where E = Voltage of the standing wave at the current probe location (V);

$E_{MAX.}$ = Voltage of the standing wave at the location of the maximum (V);

SWR Meter Reading = Ratio of the standing wave voltage, E, to the maximum voltage, $E_{MAX.}$ of this wave, in decibels (dB).

☐ 25. In LVDAM, select the Graph function of the Data Table and plot the $E/E_{MAX.}$-versus-distance from the load curve.

Have the X-Axis coordinates of your graph graduated like the Slotted Line's ruler by making the following settings in the Graph window:

X-Axis Coordinates
 Inversion . . . . ON
Scale
 X-Axis Scale . . . . Manual
 X Interval 10
 X Max 150
 X Min 0

Your graph should resemble that shown in Figure 12.

Observe that the amplitude of the standing wave stays nearly constant around a ratio $E/E_{MAX.}$ of 1, since the impedance of the load is matched to the characteristic impedance of the waveguide.

☐ 26. Save and close your Data Table.

☐ 27. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 28. Close the LVDAM-MW software.

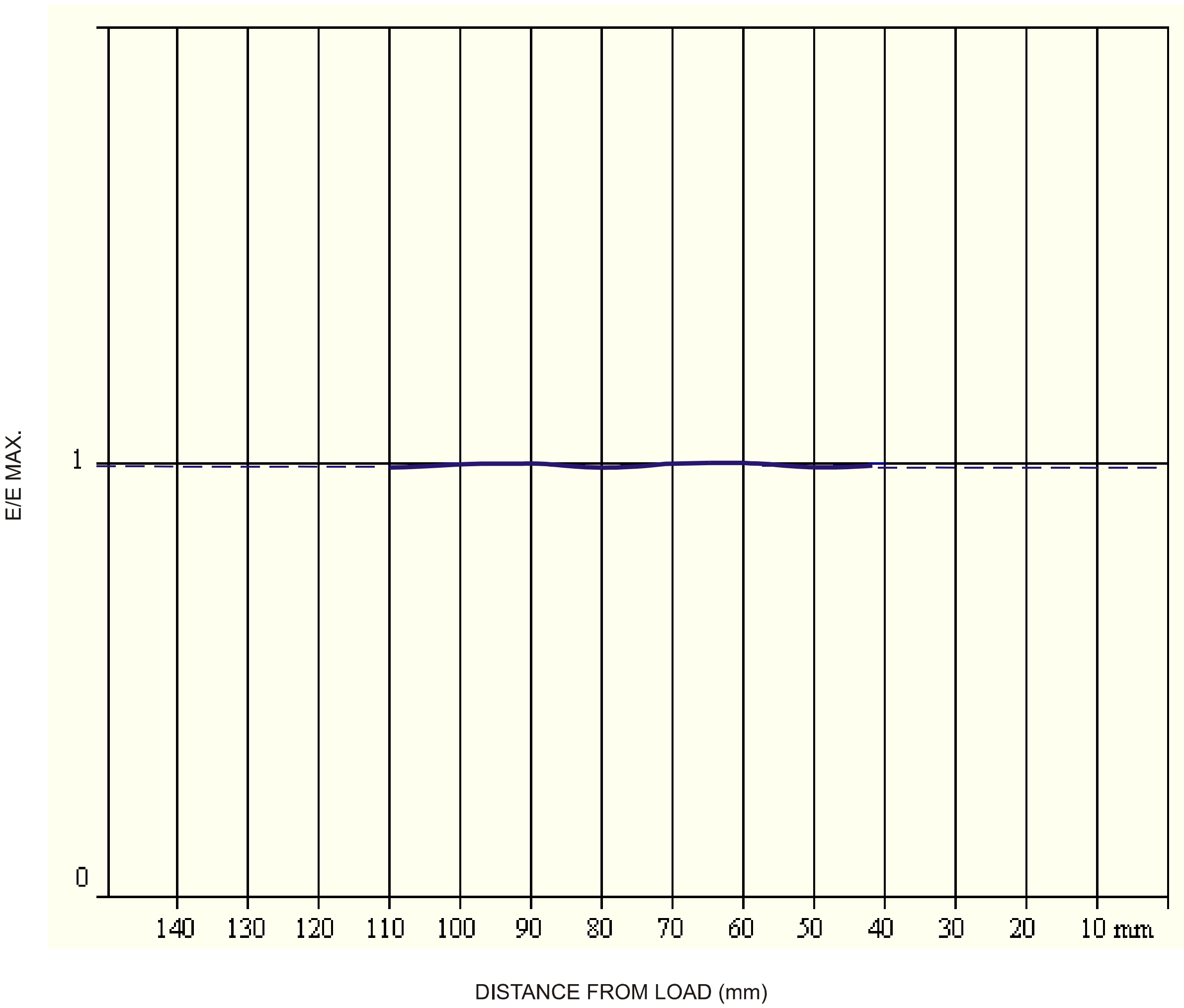


Figure 12. Standing wave produced along the Slotted Line with a matched load.

CONCLUSION

In this exercise, the concepts of characteristic impedance, reflected waves, and standing-waves were introduced. You became familiar with the use of a slotted line by evaluating the guided wavelength and the frequency of a microwave signal. You also determined the standing-wave patterns for a short circuit, an attenuator and short-circuit load, and a matched load.

REVIEW QUESTIONS

1. What does a standing-wave pattern represent?

____

____

Standing Waves

2. What is the distance, in terms of wavelengths, between successive minima in a standing-wave pattern?

3. What causes a maximum on a standing-wave?

4. Explain how to determine a microwave signal's frequency with a slotted line.

5. What physical parameter does a slotted line measure?

Exercise 2

The Directional Coupler

EXERCISE OBJECTIVES

When you have completed this exercise, you will be familiar with the operating principles of a directional coupler. You will be able to define and measure the coupling factor and the directivity of a directional coupler.

DISCUSSION

Introduction to Directional Couplers

A directional coupler is a device which allows the sampling of a known fraction of a microwave signal propagating in a given direction without greatly disturbing the signal.

In general, directional couplers consist of two waveguide sections joined together to form a four-arm junction. This junction permits a small portion of the microwave signal propagating in one waveguide to couple to the microwave signal propagating into the other waveguide. The direction of propagation of the coupled signal depends upon the direction of the signal in the first waveguide.

Directional couplers are commonly used to measure parameters such as the power of a transmitted or reflected signal, and the coefficient of reflection, without disturbing the transmission. They are also used, along with additional circuitry, to regulate the output of microwave signal generators.

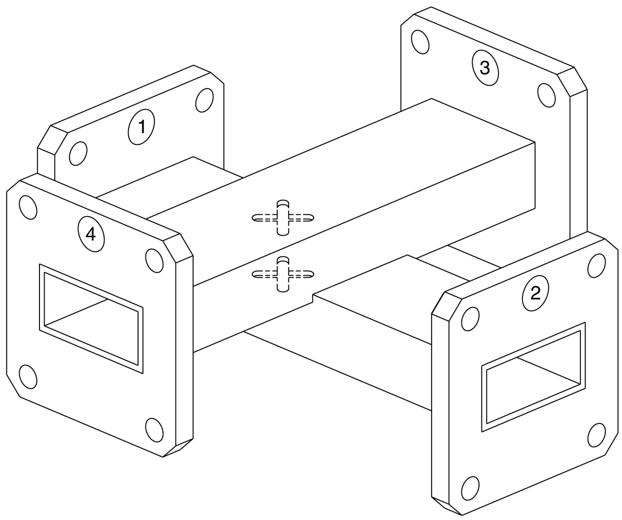
Construction and Operation of a Cross-Guide Directional Coupler

Waveguide directional couplers come in several different types. The Lab-Volt Directional Coupler, for example, is of the cross-guide type. Figures 13 and 14 show this directional coupler:

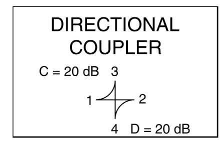
- It is formed by the superposition of two crossed waveguides sharing a common wall;
- The waveguides are at right angles to each other;
- Two cruciform openings are made in the common wall; they are located a quarter-wavelength ($\lambda_g/4$) apart. These openings allow the microwave signal to couple from one guide into the other.

Cruciform openings are preferred to circular openings because the discontinuity caused by a cruciform is smaller than that caused by a circle for the same degree of coupling.

The Directional Coupler



(a)



(b)

Figure 13. The Lab-Volt Directional Coupler and its symbolic representation.

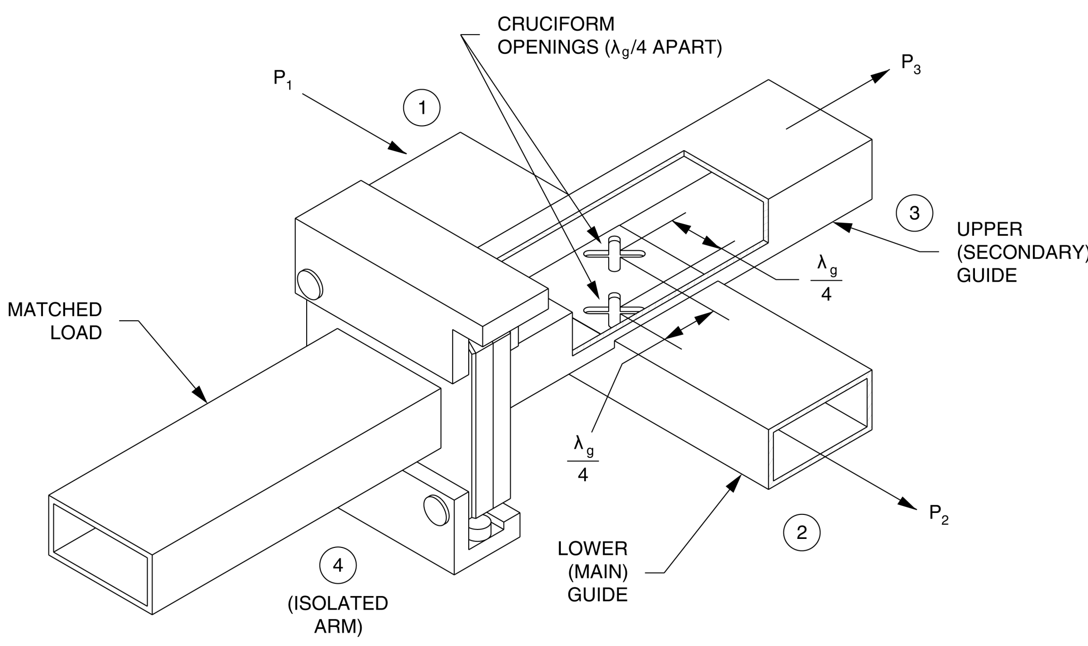


Figure 14. Construction of the cross-guide directional coupler.

Figure 15 shows how the directional coupler works.

- If a microwave signal is fed into arm ①, (signal P_1), part of this signal will be coupled into the upper guide section through the first cruciform opening.

This coupled signal will propagate in both directions: towards arms ③ and ④ of the upper guide.

- Another part of the signal fed into arm ① will couple into the upper guide through the second cruciform opening.

  This coupled signal will also propagate in both directions: towards arms ③ and ④ of the upper guide. Therefore, there will be two coupled signals propagating in each direction in these arms.

- At any point along arm ③, the two signals will have traveled the same distance, so that they will add together (combine) in phase.

- In arm ④ however, the signal from the second opening will have traveled half a wavelength further than the signal from the first opening, so they will cancel out each other. The result is a coupled signal in arm ③ and no signal in arm ④ the latter being often called the isolated arm.

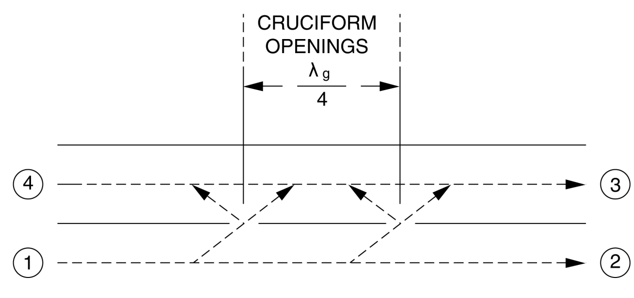


Figure 15. How the cross-guide directional coupler works.

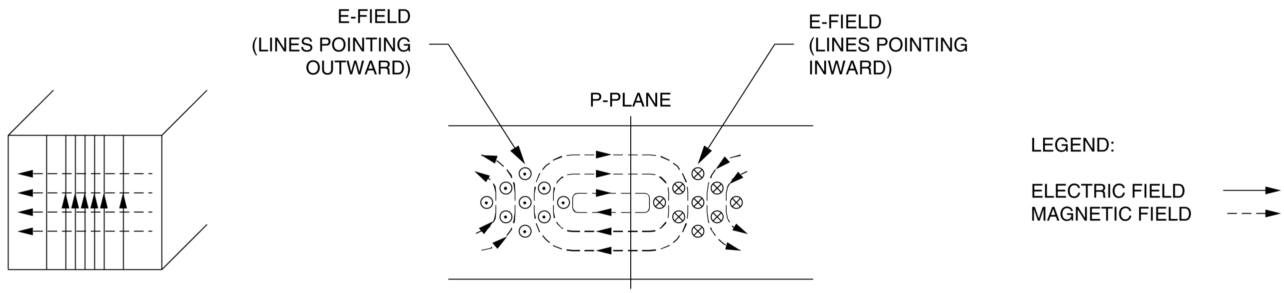
Electric and Magnetic Field Distributions Inside a Waveguide

To better understand the operating principle of the cross-guide directional coupler, consider the distribution of the electric and magnetic fields inside a rectangular waveguide. Figure 16 shows this distribution in the fundamental mode of propagation (mode TE_{10}).

As the figure shows, the electric field has only one component parallel to the shorter sides of the guide. The intensity of the electric field is maximum at the center of the guide, and null at the side walls.

The magnetic field has a component across the width of the guide, and another component in the direction of propagation of the signal.

The Directional Coupler



(a) Cross Section (b) Top View

Figure 16. Distribution of the electric and magnetic fields inside a waveguide in the fundamental mode of propagation.

In any plane, P, perpendicular to the direction of propagation, the component of the magnetic field parallel to the plane is in the same direction from one side of the guide to the other.

The component of the magnetic field parallel to the direction of propagation changes polarity from one side of the guide to the other. However, the polarity of each component of the magnetic field changes every half-wavelength.

Orientation of the Components of the Magnetic Field in a Cross-Guide Directional Coupler

Figure 17 shows the orientation of the magnetic field components, H_X and H_Z, in each arm of a cross-guide directional coupler. The incident signal is fed into arm ①. Since coupling of this signal in the coupler is due essentially to the magnetic field, the electric field is not illustrated in the figure.

Consider the component of the magnetic field which is **in the direction of propagation of the signal**: component $\mathbf{H_z}$.

- The two cruciform openings, A and B, are located so that the component H_z coupled through opening B is 180° out of phase with the signal coupled through opening A.
- However, the signal coupled through opening B and propagating along arm ③ must travel a half-wavelength further than the signal coupled through opening A. This adds an extra 180° phase shift to the phase difference between the two signals, thereby bringing these signals back into phase. These signals therefore add together to form one signal that propagates along arm ③.
- For their part, the coupled signals propagating along arm ④ travel the same distance and end up out of phase: they therefore cancel each other so that no signal propagates along arm ④.

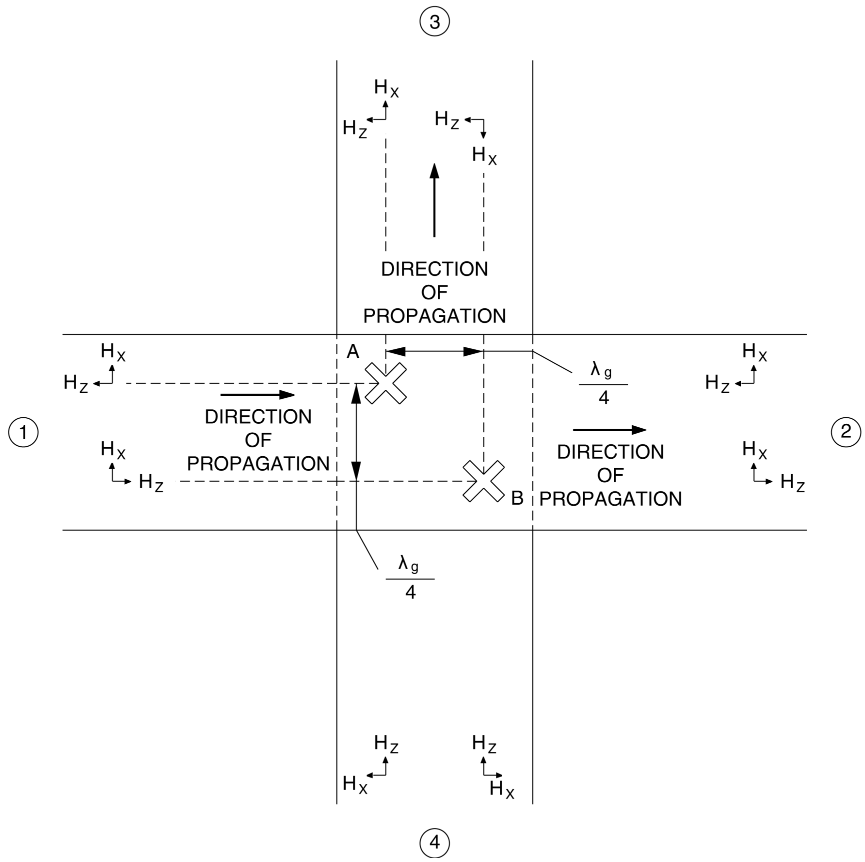


Figure 17. Figure orientation of the components of the magnetic field in a cross-guide directional coupler.

Coupling Factor

The power of the coupled signal in the secondary waveguide is a function of the dimensions of the openings. The ratio of the incident power to the power of the coupled signal at the sampling arm is called the coupling factor, and is denoted C.

If the signal is fed into arm ①, while arm ③ is the sampling, or coupled arm, then the coupling factor may be calculated as:

$$C_{(dB)} = 10 \log \frac{P_1}{P_3}$$

where C = Coupling factor (dB);
P_1 = Power of the incident signal (W);
P_3 = Power of the coupled signal in arm ③ (W).

It should be remembered that the power at arm ② will be less than the power fed into arm ①, due to the coupling of a certain amount of power into the secondary waveguide. This difference may be neglected when the coupling factor is high. The directivity of a cross-guide coupler is generally greater than 15 dB.

Directivity

As already mentioned, most of the coupling into a coupler is attributed mainly to the magnetic field.

However, a small amount of coupling also occurs due to the electric field. The electric field component does not experience the same 180° phase shift and cancellation. Consequently, a small part of the coupled signal propagates through the isolated arm (arm ④).

Directivity (or isolation) can be defined as the ratio of the power at arm ③ to the power at the isolated arm ④, when the incident signal is fed into arm ①.

By symmetry, the directivity can also be defined as the ratio of the power at arm ③ when the incident signal is fed into arm ①, to the power at arm ③ when the incident signal is fed into arm ②. Therefore, the directivity, D, can be calculated as:

$$D_{(dB)} = 10 \log \frac{P_{3\,(1\rightarrow 2)}}{P_{4\,(1\rightarrow 2)}} = 10 \log \frac{P_{3\,(1\rightarrow 2)}}{P_{3\,(2\rightarrow 1)}}$$

where D = Directivity (dB);
$P_{3\,(1\rightarrow 2)}$ = Power at arm ③ when the incident signal is fed into arm ① (W);
$P_{4\,(1\rightarrow 2)}$ = Power at arm ④ when the incident signal is fed into arm ① (W);
$P_{3\,(1\rightarrow 2)}$ = Power at arm ③ when the incident signal is fed into arm ① (W);
$P_{3\,(2\rightarrow 1)}$ = Power at arm ③ when the incident signal is fed into arm ② (W);

The directivity of a cross-guide directional coupler is generally greater than 15 dB. It can vary between 20 to 40 dB approximately, depending on the frequency.

Couplers requiring higher directivities can be obtained by using multi-hole opening designs. Nowadays, it is common to find multi-opening directional couplers with a bandwidth on the order of an octave and a directivity higher than 40 dB.

Procedure Summary

In this exercise, you will measure the coupling factor and the directivity of the Directional Coupler, using the Crystal Detector and the SWR Meter.

You will first set up the system and adjust the maximum power of the incident signal to a known level (0 dBm). You will then attenuate this signal by 30 dB, in order for the Crystal Detector to operate in its square-law region and the SWR Meter to provide valid readings.

You will then determine the coupling factor of the Directional Coupler by measuring the attenuation between the Directional Coupler's input arm and coupled arm.

Similarly, you will determine the directivity of the Directional Coupler by measuring the attenuation between its coupled and isolated arms.

PROCEDURE

System Setup

Setting the Maximum Power to 0 dBm on the Power Meter

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as shown in Figure 18.

> **Note:** *Before connecting the Thermistor Mount, unscrew the matching screws so that they do not penetrate into the waveguide; the screws do not need to be removed from the posts.*

☐ 2. Make the following settings:

On the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . DC
METER SCALE . . . . 10 V

On the variable Attenuator:

Blade Position . . . . 10 mm

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position. Set the Gunn Oscillator supply voltage to 8.5 V.

Wait for about 5 minutes to allow the modules to warm up.

☐ 4. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 4 . . . . Power Meter
Gain Input 4 . . . . 20 dB

The Directional Coupler

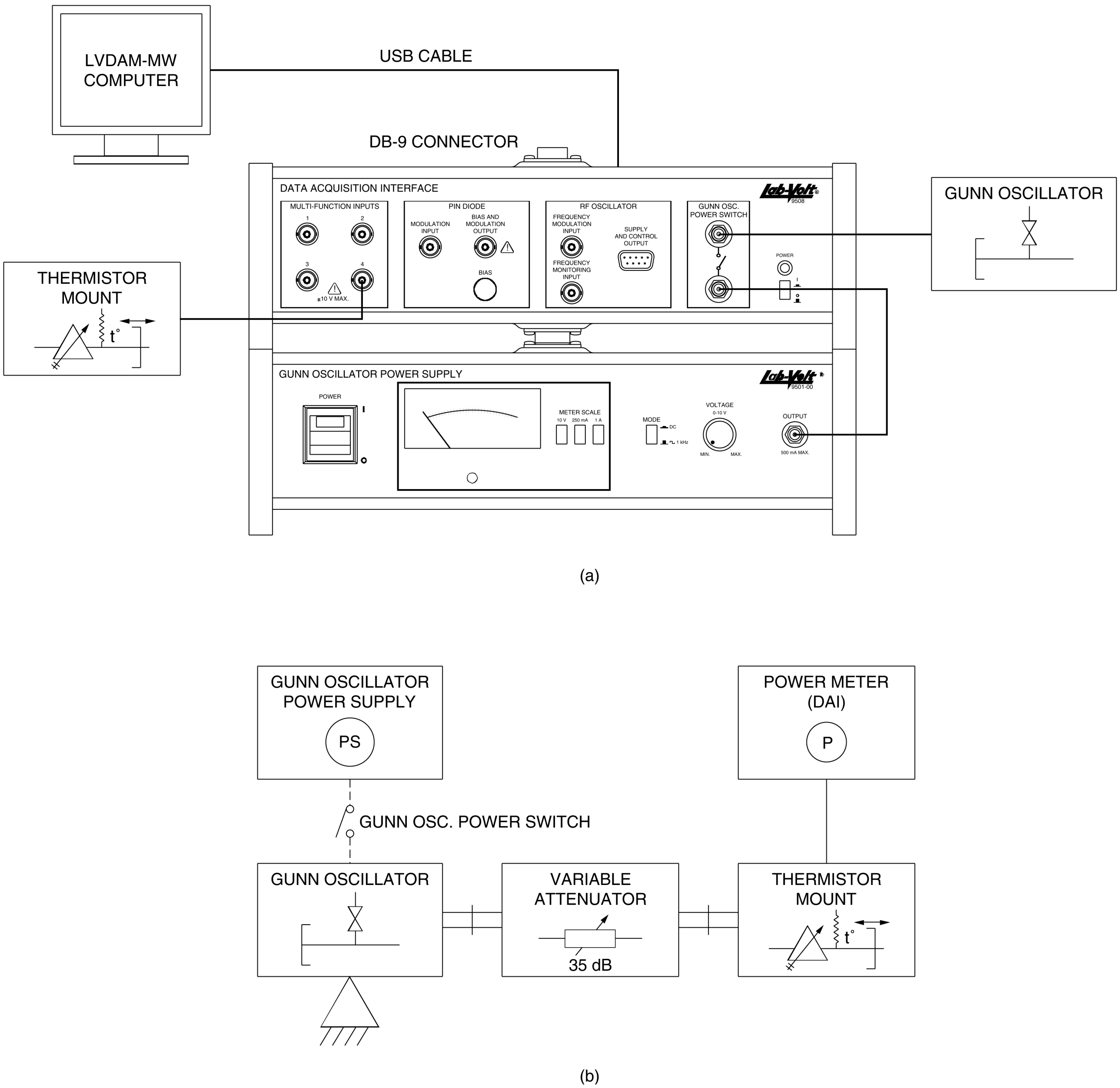


Figure 18. Computer and module arrangement (showing electrical connections to microwave components), and microwave setup.

☐ 5. In LVDAM-MW, start the Power Meter and set it to display dBm readings. Then, perform zeroing of the Power Meter.

☐ 6. Decrease the attenuation provided by the Variable Attenuator (turn adjustment screw counterclockwise) to obtain a reading of about -3 dBm on the Power Meter.

On the Thermistor Mount, loosen the knurled lock-nut that holds the moveable short circuit in place. Slowly pull out the plunger of this short circuit and observe the Power Meter reading, which alternately decreases and increases, as minima and maxima positions are encountered. Adjust the short circuit to the position nearest the waveguide which gives a maximum reading on the Power Meter. Then, adjust each matching screw of the Thermistor Mount to maximize the power reading. Fine tune if necessary. Finally, lock the moveable short circuit into position.

Now adjust the position of the Variable Attenuator's blade to obtain a reading of 0.0 dBm on the Power Meter (upper end of the current measuring scale, just before the green indicator bar turns from green to red). Record below the position of the Variable Attenuator's blade as a reminder.

Variable Attenuator's blade position: ______ mm.

Close the Power Meter.

Setting the Reference on the SWR Meter

☐ 7. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF, so that there is no microwave signal injected into the waveguide.

☐ 8. **Taking care not to modify the Variable Attenuator adjustment**, so as to keep this attenuator adjusted for an output power of 0 dBm, set up the modules and assemble the microwave components as shown in Figure 19.

In this setup, a 30-dB Fixed Attenuator is connected to the output of the Variable Attenuator. Since the Variable Attenuator was set for a maximum output power of 0 dBm, the addition of the 30-dB Fixed Attenuator will limit the level of the signal incident to the Crystal Detector to -30 dBm approximately.

☐ 9. On the Gunn Oscillator Power Supply, set the MODE switch to 1 kHz.

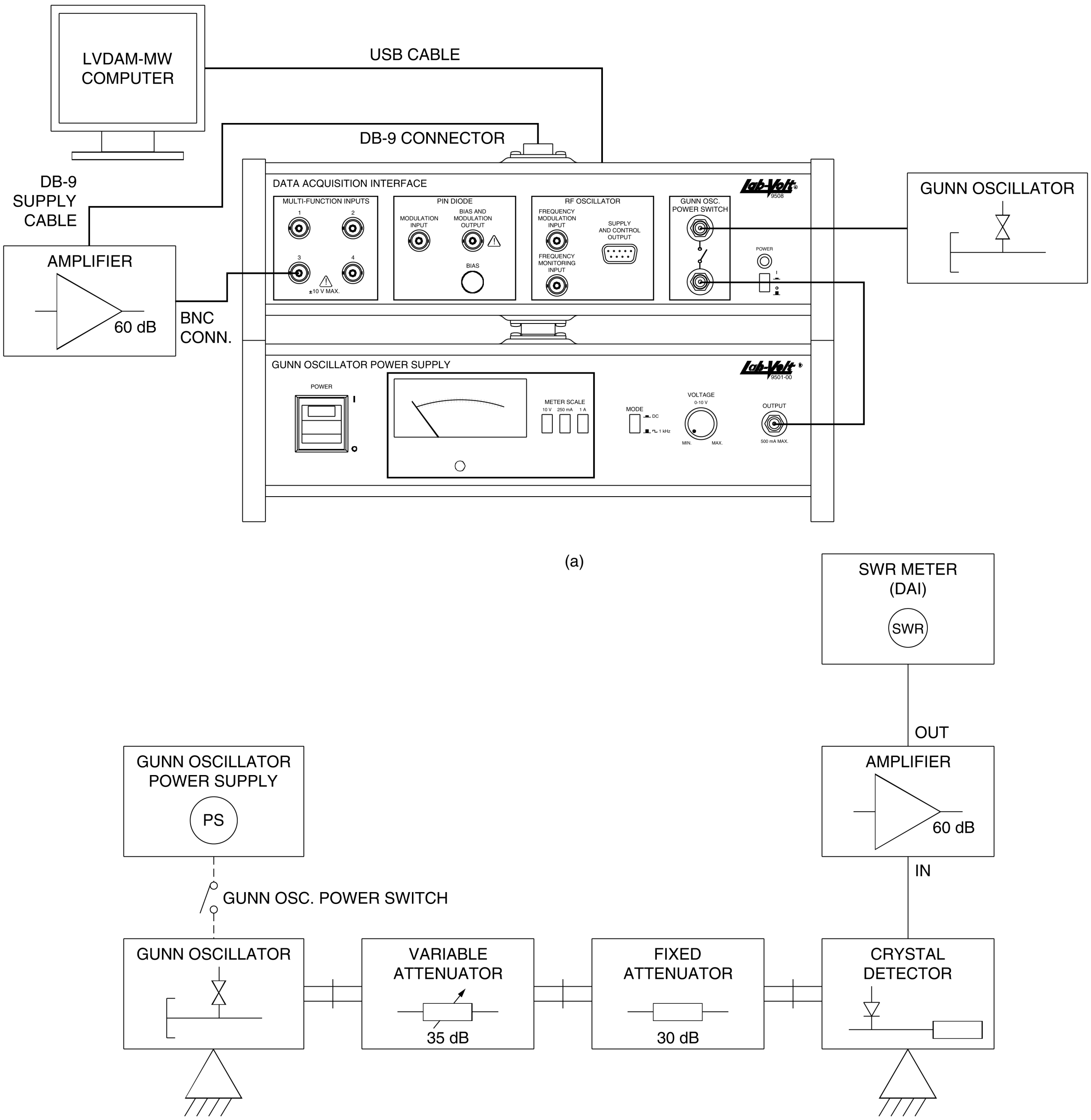
☐ 10. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Input 3 Gain . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

Wait for about 5 minutes to allow the modules to warm up.

☐ 11. In LVDAM-MW, start the SWR Meter and set it to display decibels (dB).

The Directional Coupler



(b)

Figure 19. Computer and module arrangement (showing electrical connections to microwave components) and microwave setup.

☐ 12. Using the cursor of the SWR Meter, scan through the frequency range of this meter (from 900 to 1100 Hz) to find the frequency at which the Signal Level (indicated as a percentage below the green indicator bar of the meter) is maximum. Set the cursor to this frequency.

Note: *If the signal level indicated by the SWR Meter stays null or too low (below 10% of full scale, with a blue indicator bar or no bar displayed) while trying to tune the SWR Meter frequency, increase Gain Input 3 to 20 dB in order to obtain a significant signal level on the SWR Meter (that is, a signal level of 10% of full scale or higher, and a green horizontal bar). Then tune the meter frequency in order to obtain the maximum signal level on this meter.*

Conversely, too high a gain causes the meter indicator bar to be fully red. If the meter indicator bar stays fully red when the Gain on DAI Input 3 is set to 0 dB, remove the 60-dB Amplifier from the microwave circuit, and connect the Crystal Detector output directly to MULTI-FUNCTION INPUT 3 of the DAI. Then, set the field 60 dB Ampli on Input 3 to OFF and Gain Input 3 to the proper value (40 dB) in order to be able to tune the meter frequency and obtain the maximum signal level on this meter.

☐ 13. Once the SWR Meter has been tuned to obtain the maximum signal level, click on the REFERENCE button of the SWR Meter.

Measuring the Coupling Factor of the Directional Coupler

☐ 14. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF, so that there is no microwave signal injected into the waveguide.

☐ 15. **Taking care not to modify the Variable Attenuator adjustment**, modify your microwave circuit in order to obtain the circuit shown in Figure 20.

Leave the rest of the equipment connected as before.

The Directional Coupler

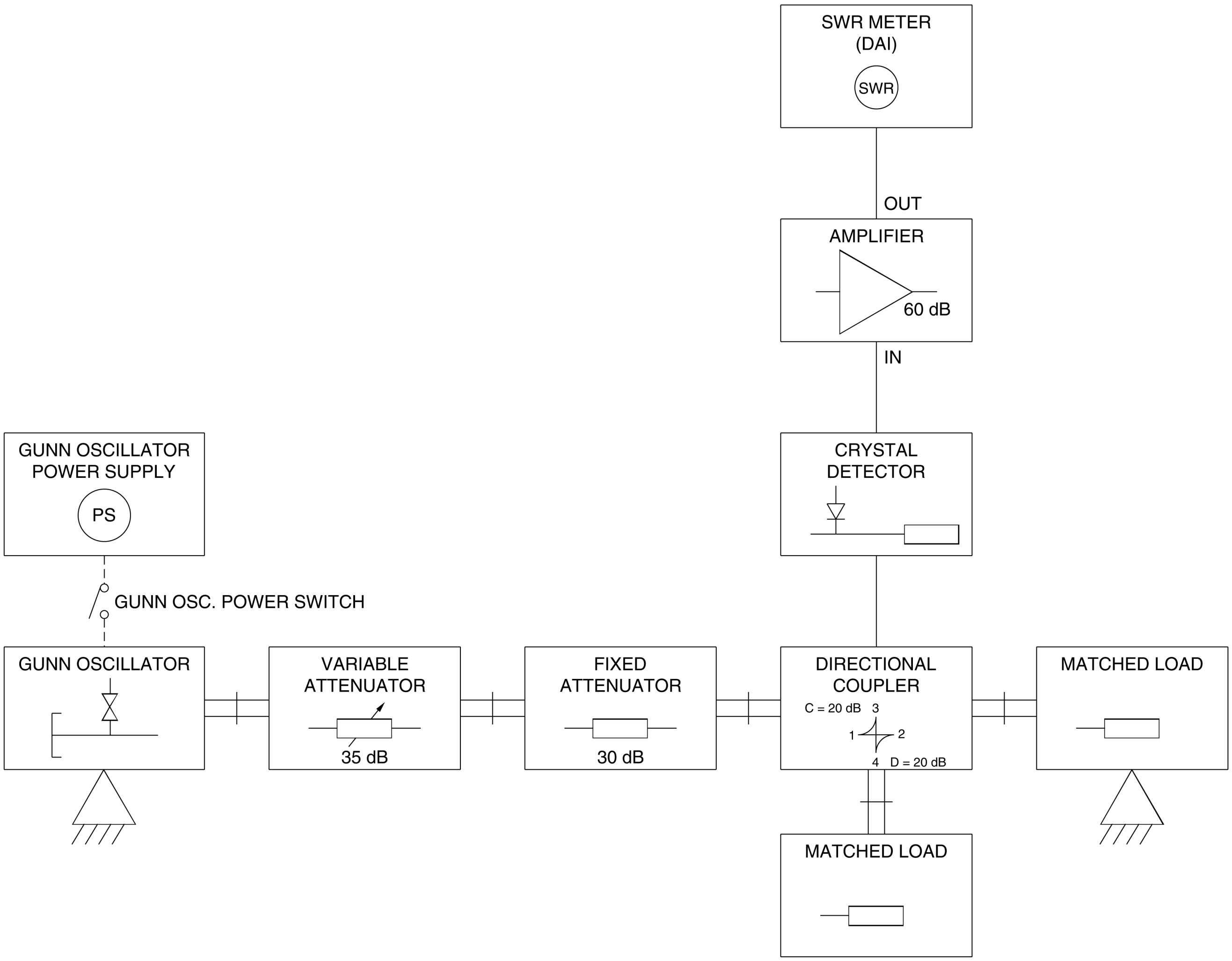


Figure 20. Modified microwave circuit for the measurement of the coupling factor.

☐ 16. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Input 3 Gain . . . . 40 dB

Do not modify the reference of the SWR Meter. Wait for about 5 minutes to allow the modules to warm up.

☐ 17. Record below the SWR Meter reading (absolute value). This reading (absolute value) corresponds to the coupling factor, C, of the Directional Coupler.

Coupling Factor, C: ______ dB

Measuring the Directivity of the Directional Coupler

☐ 18. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF, so that there is no microwave signal injected into the waveguide.

☐ 19. **Taking care not to modify the Variable Attenuator adjustment**, modify your microwave circuit in order to obtain the circuit shown in Figure 21.

Leave the rest of the equipment connected as before.

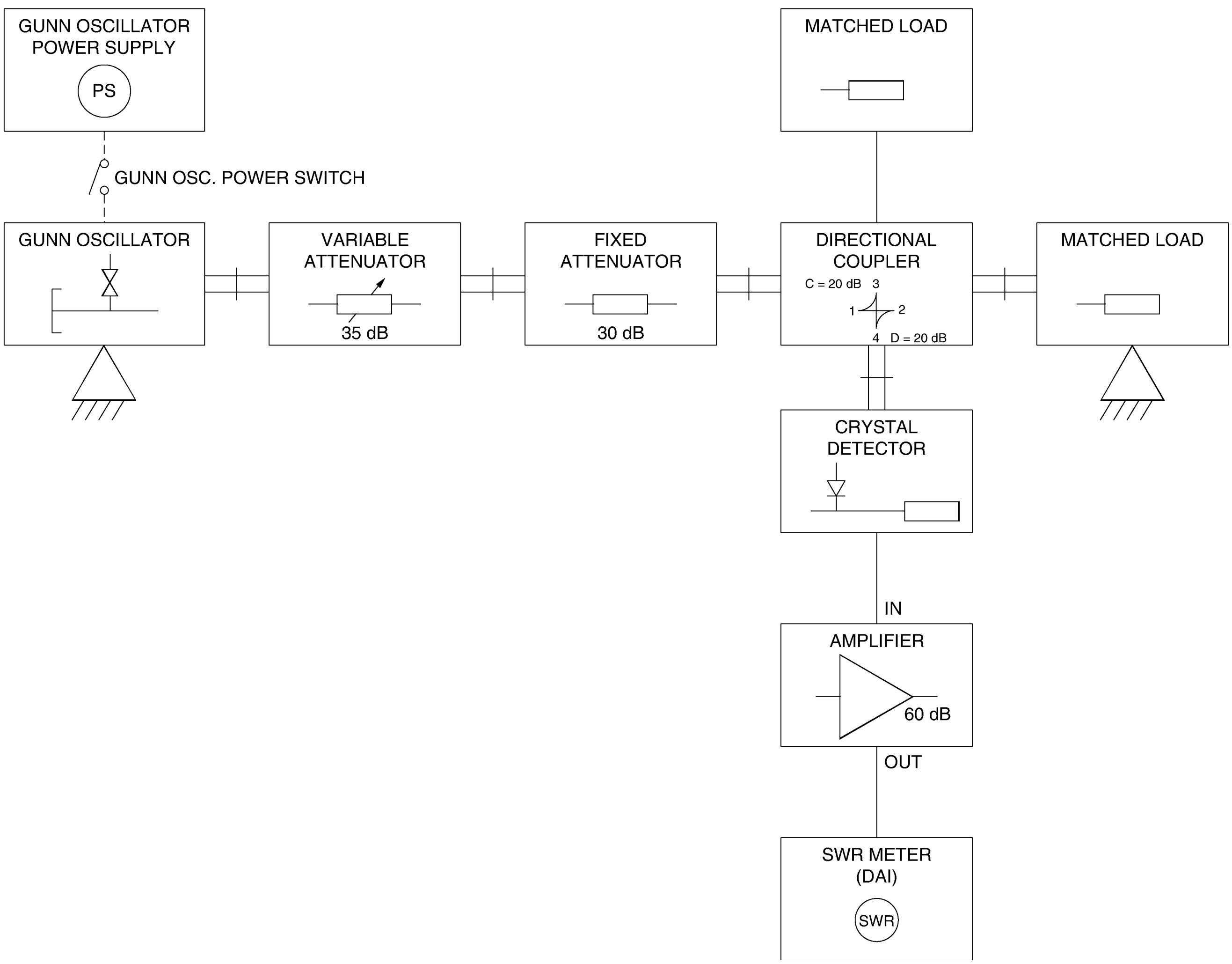


Figure 21. Modified microwave circuit for the measurement of the directivity.

☐ 20. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Input 3 Gain . . . . 40 dB

Do not modify the reference of the SWR Meter. Wait for about 5 minutes to allow the modules to warm up.

☐ 21. Record the SWR Meter reading (absolute value) below. This reading corresponds to the directivity, D, of the Directional Coupler.

> **Note:** *If the signal level indicated by the SWR Meter is null or too low (below 10% of full scale, with a blue indicator bar or no bar displayed), set the field Gunn Oscillator/VCO Power to OFF. Remove the 30-dB Fixed Attenuator from the microwave circuit: connect the Variable Attenuator's output directly to arm 1 of the Directional Coupler. Then, set the field Gunn Oscillator/VCO Power to ON and Gain Input 3 to 40 dB (or the proper scale to obtain a significant signal level of 10% of full scale or higher on the SWR Meter, and a green horizontal bar) and repeat this step.* ***Do not*** *modify the reference on the SWR Meter. Subtract 30 dB from the SWR Meter reading to account for the removal of the 30-dB Fixed Attenuator and record your result below, in absolute value.*

SWR meter , $10 \log \frac{P_1}{P_4}$: ______ dB

$$D = 10 \log \frac{P_3}{P_4} = 10 \log \frac{P_3}{P_1} + 10 \log \frac{P_1}{P_4}$$

☐ 22. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 23. Close the LVDAM-MW software.

CONCLUSION

In this exercise, you learned the operating principles of a directional coupler. You became familiar with the concept of the coupling factor and the directivity as they apply to directional couplers. You also used a simple technique to measure these parameters.

The Directional Coupler

REVIEW QUESTIONS

1. What is a directional coupler?

2. Briefly explain the operating principles of a two-opening superimposed-waveguide directional coupler.

3. Briefly explain what are the main parameters used to compare directional couplers: the coupling factor and the directivity.

4. What would be the directivity of an ideal directional coupler?

5. (Refer to Figure 14.) Determine the power at arms 2, 3 and 4 (P_2, P_3, and P_4) if the incident power at arm 1 (P_1) is 1 mW, given a coupling factor C of 20 dB, and a directivity D of 20 dB.

Exercise 1

Helical Antennas

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with circular polarization and the characteristics of helical antennas operating at 10 GHz.

DISCUSSION

Circular polarization

All of the antennas seen so far in this manual are linear polarization antennas. In the case of the straight-wire antennas, such as dipoles, folded dipoles, and monopoles, the related electric field has the same orientation as the physical wire. With a transmitting horizontal dipole, for example, the E field is in the horizontal plane and the H field is in the vertical plane. The same antenna best receives waves whose E field is in the horizontal plane.

The loop antenna is also linearly polarized. For example, a vertical full-wave loop antenna fed from the bottom behaves somewhat like a horizontal dipole and produces a horizontally polarized wave. If we move the feed from the bottom to the left or right side, the wave will be vertically polarized.

A rectangular waveguide also transmits a linearly polarized wave. While performing E- and H-plane measurements in previous exercises, you verified that both the transmitting and receiving antennas must use the same polarization. If both transmitting and receiving antennas are aligned and adjusted for the same polarization, the signal will be received well. However, if one antenna is then rotated by 90°, only a weak signal will be received due to cross-polarization isolation. In theory, cross-polarization isolation should be infinite and no signal should be received, but in practice, cross-polarization isolation is not perfect.

The polarization of an antenna can also be elliptical or circular. **Elliptical polarization** results from the combination of two electric field vectors (you can think of these two vectors as two linearly polarized waves) which are perpendicular to each other, have the same frequency, and are travelling in the same direction. The phase relation between these two waves as well as their amplitudes can have different values. If the amplitudes of the two vectors are identical and if they are exactly 90° out of phase, we have **circular polarization**. If one vector or the other has a zero amplitude, the polarization is linear. Linear and circular polarizations are special cases of elliptical polarization.

In order to have circular polarization, the electric field must be made to rotate rapidly. There are a number of ways this can be accomplished.

One way is to transmit both a vertically polarized wave and a horizontally polarized wave 90° out of phase. This is somewhat analogous to tracing a Lissajous figure of a perfect circle on an oscilloscope by sending sinusoidal waves 90° out of phase into the X- and Y-axis inputs.

Helical Antennas

Another way is to send an electric wave along a helix of appropriate dimensions. As the wave travels along the helix, it produces a rapidly rotating electric field. This principle is used in helical antennas.

The rotation of the electric field can be either clockwise or counterclockwise. If the fingers of your right hand curl in the direction of rotation when the thumb points in the direction of propagation, the polarization is said to be **right-hand circular polarization**. The opposite sense of rotation gives rise to **left-hand circular polarization**.

With circular polarization, the effect of cross-polarization isolation is very marked. A right-hand circularly polarized antenna cannot receive a left-hand circularly polarized signal, and vice versa. Each antenna can, however, receive with some attenuation a linearly polarized signal in any orientation.

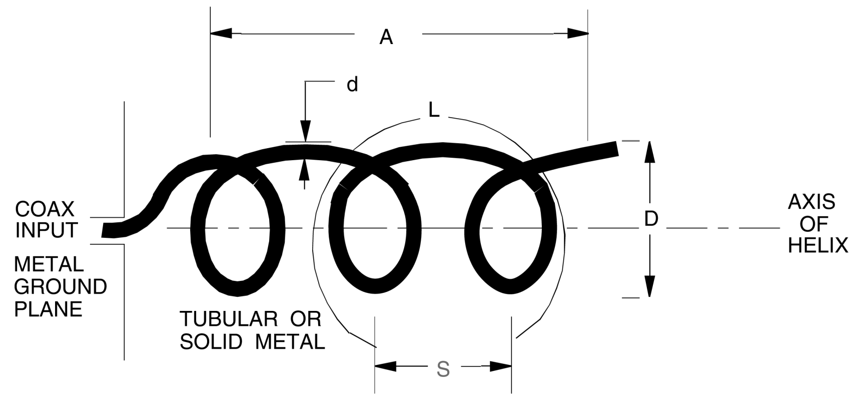
Although linear polarization is perfectly adequate for many situations, circular polarization is very useful in certain types of communications. One example is satellite communications where it is difficult to maintain a constant antenna orientation. Excessive fading would result if linear polarization were used. With circular polarization, the strength of the received signal is fairly constant regardless of the satellite antenna orientation.

Helical antennas

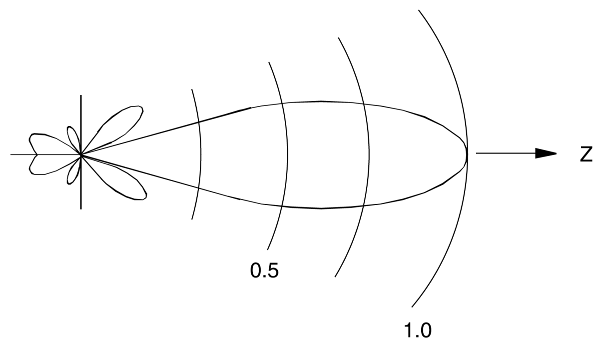
Figure 1 illustrates a typical axial-mode helical antenna, that is, a helical antenna which is designed to have a pencil-beam radiation pattern oriented along the axis of the helix away from the ground plane.

Helical antennas of this type are useful for a number of applications. Besides their very desirable radiation pattern, they offer a large bandwidth and an input impedance of 120 to 140 Ω.

Helical Antennas



(a)



(b)

Figure 1. Axial-mode helical antenna: (a) geometry (b) pencil-beam radiation pattern

The symbols used to describe the helix are as follows:

N = number of turns
S = spacing between turns = C tan α
A = axial length = NS
D = diameter of helix
d = diameter of conductor
C = circumference = πD
L = length of one turn
α = pitch angle = $\tan^{-1}(S/C)$

The helix will radiate in the axial mode when the circumference of the helix is in the order of magnitude of one wavelength. A fairly wide range of frequencies can be used. This range corresponds to

$$\frac{3}{4}\lambda < C < \frac{4}{3}\lambda \tag{1}$$

The sinusoidal wave travels along the helix from the ground plane towards the opposite end. For this reason, the helical antenna is called a **travelling-wave antenna**.

To understand how the helical antenna operates, consider one loop of a helix of circumference λ, as shown in Figure 2.

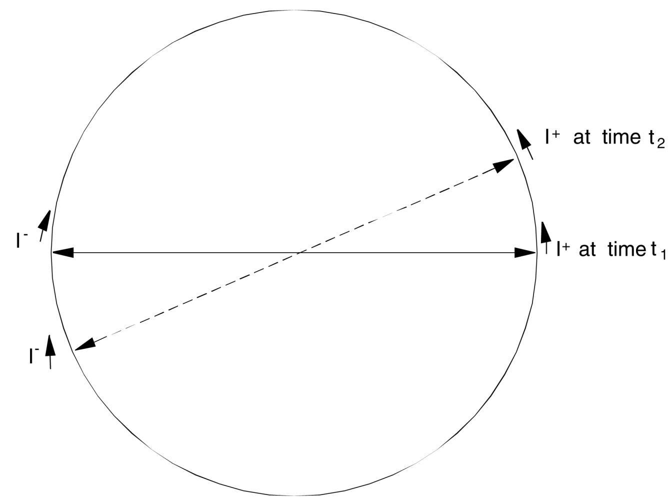


Figure 2. One loop of a helical antenna (C = λ)

At a given instant of time t_1, the current is positive on one side of the loop and negative on the opposite side, since the circumference of the loop is λ. This is shown in the figure by the fact that the arrows at I^+ and I^- point in the same geometrical direction. This gives rise to a kind of dipole.

A very short time later, at time t_2, the current has travelled a short distance down the helix. The dipole has now rotated slightly. The dipole effectively rotates at a frequency equal to that of the transmitted wave.

The radiation pattern towards the sides of Figure 2 will be zero. The radiation will be along the axis of the helix.

It would be reasonable to think that if the fields of each loop forming the helix were all superposed and in phase, they would add up to give a strong radiation pattern along *both* ends of the axis of the helix, as shown in Figure 3. However, this is not the case. Propagation delays along the helix cause phase differences which modify the radiation pattern, giving it one lobe in the axial direction instead of two, as in Figure 1(b). The helical antenna can be modeled as an endfire array which, because of the position of its elements and the phases of the currents, has only one lobe in the endfire direction.

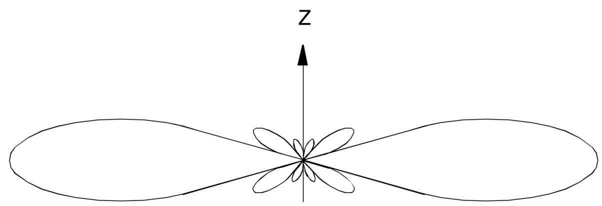


Figure 3. Fan beam radiation pattern

The direction of the winding of the helix determines the direction of polarization. When viewing the helix from the ground-plane end, a clockwise winding produces right-hand circular polarization, and a counterclockwise winding produces left-hand circular polarization.

Axial ratio and gain

While receiving a circularly polarized signal, the response of a helical antenna should, ideally, remain constant as the electric field of the signal rotates.

To illustrate this, imagine a linearly polarized antenna, such as a dipole, used for transmission and a helical antenna used for reception. The polarization of the transmitted signal could be changed by rotating the dipole by a certain angle. An ideal helical antenna would produce the same response for all orientations of the dipole, that is, for all polarizations. Since the helix is of finite length, however, it is slightly asymmetric. It therefore responds to some polarizations slightly better than others.

The measure of the response of a helix to different polarizations is called the **axial ratio**, also known as the **circularity**. This is defined as the ratio of the amplitude with the polarization that gives the maximum response to the amplitude with the polarization that gives the minimum response. An antenna which responds equally to all polarizations has an axial ratio of 1.0 (or 0 dB).

The axial ratio is given by

$$AR = \frac{2N + 1}{2N} \tag{2}$$

where AR is the axial ratio
N is the number of turns in the helix.

The axial ratio can be measured by transmitting between a linearly polarized antenna and the helical antenna. By rotating one of the antennas and measuring the maximum and minimum amplitudes, the axial ratio can be calculated directly as the ratio of these two amplitudes.

Ideally, a helical antenna has an axial ratio between 1 and 1.1 (0 and 0.83 dB). To obtain such results, however, the open end of the helix should be tapered. In practice, for a constant diameter helix, it is not uncommon to encounter axial ratios around 1.12 (1 dB).

The gain of the helical antenna can be expressed empirically as

$$G \approx 8.3 \left(\frac{\pi D}{\lambda}\right)^{[(N+2)^{1/2}-1]} \cdot \left(\frac{NS}{\lambda}\right)^{0.8} \cdot \left[\frac{\tan(12.5°)}{\tan(\alpha)}\right]^{(N/2)^{1/2}} \qquad (3)$$

Normal mode of radiation

It is possible to make a helical antenna with an entirely different radiation pattern, as shown in Figure 4. This helical antenna operates in the normal mode of radiation, that is, the direction of maximum radiation is normal to the axis of the antenna.

For normal mode operation, the circumference of the helix must be small compared to the wavelength. This makes the current distribution nearly uniform in amplitude and phase along the helix. This type of helix is electrically small and its efficiency is low.

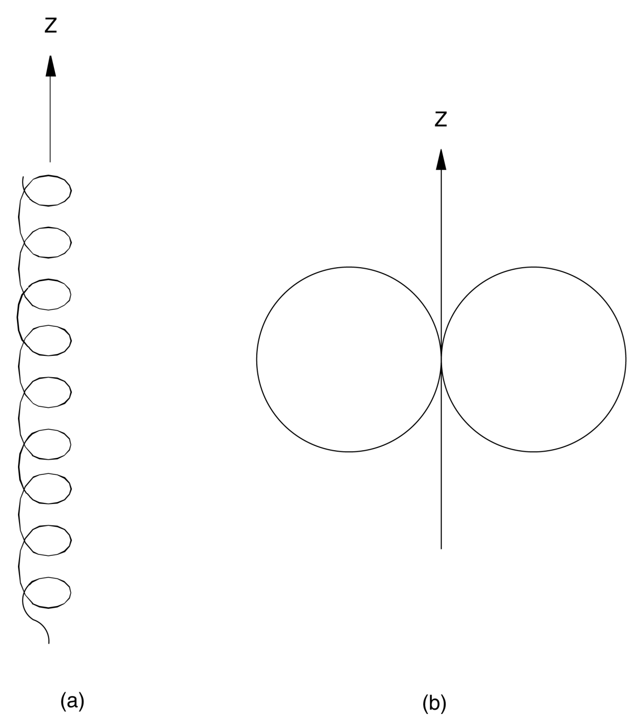


Figure 4. Normal-mode helical antenna: (a) geometry (b) radiation pattern

Radomes

The helical antennas included in the Antenna Training and Measuring System are protected by a **radome**. Radomes, or radar domes, are protective housings for millimeter-wave or microwave antennas. They are shaped to cover the antenna and are usually made of low-loss dielectrics of thickness much smaller than a wavelength.

Because of reflections, refractions, and losses, a radome modifies the electrical characteristics of the antenna it covers. These changes usually result in some distortion of the radiation pattern. The gain, beamwidth, sidelobe levels, and polarization characteristics may be altered. In the case of the helical antennas in the Antenna Training and Measuring System, the presence of the radome reduces the half-power beamwidth slightly and increases the levels of the side lobes.

Procedure Summary

In this exercise you will learn to differentiate between a right-hand (RHP) and a left-hand (LHP) polarized helical antenna. You will plot the radiation patterns of these two antennas and evaluate their half-power beamwidth. You will measure the gain of the helix and compare your results with the calculated theoretical value. Finally, you will complete this exercise by evaluating the axial ratio, also called the circularity, of the helical antenna.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Insert the antenna mast with locking ring into the transmission support. Couple a large horn antenna onto the waveguide-to-coax adapter. Using the plastic holder, attach the horn antenna to the mast, polarized horizontally. Install the long SMA cable on the 10 GHz OSCILLATOR OUTPUT of the RF Generator, then connect the antenna.

☐ 3. Place the other antenna mast with locking ring on the sliding support of the Antenna Positioner. Attach the small horn antenna to the mast, making sure that it is in line with the rotation centre of the Antenna Positioner and oriented for an E-plane acquisition.

Using the intermediate SMA cable, connect the receiving antenna to the RF input on top of the Antenna Positioner.

☐ 4. Position the antennas a distance of r = 1.5 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 5. Make the following adjustments:

On the RF Generator

10 GHz OSCILLATOR MODE . . . . 1 kHz
10 GHz OSCILLATOR RF POWER . . . . OFF
1 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 6. Set the 10 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

CAUTION!

For your own safety, never look directly into the horn antenna while the RF POWER switch is ON.

☐ 7. Using the Attenuation control, optimize reception of the signal. Start your first acquisition.

Store the radiation pattern in a new document (Document1). Orient the pattern so that the MSP is at 0°.

☐ 8. Remove the receiving antenna. Replace the receiving mast with the one that has horizontal clips. Fasten to the mast one of the two right-hand polarized (RHP) helical antennas supplied with the system. Ensure that the antenna is in line with the rotation centre of the Antenna Positioner and oriented as shown in Figure 5.

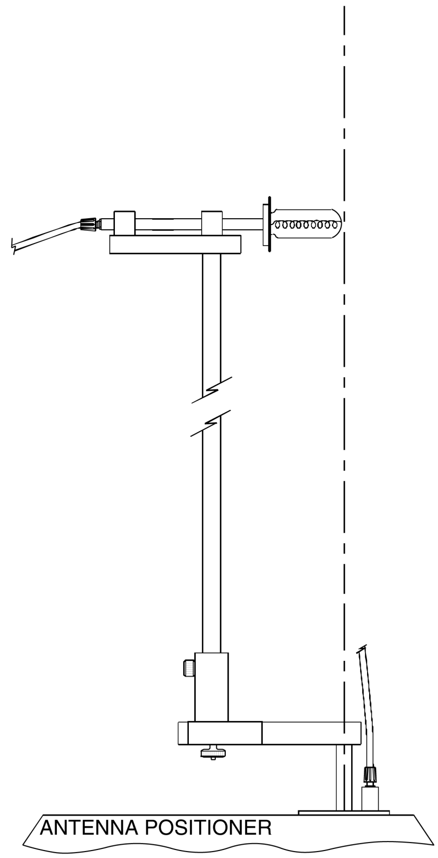


Figure 5. Set-up of the RHP helical antenna

Connect the receiving antenna to the RF input on top of the Antenna Positioner.

☐ 9. Referring to Figure 6, make sure that the antennas are at a distance of r = 1.5 m apart.

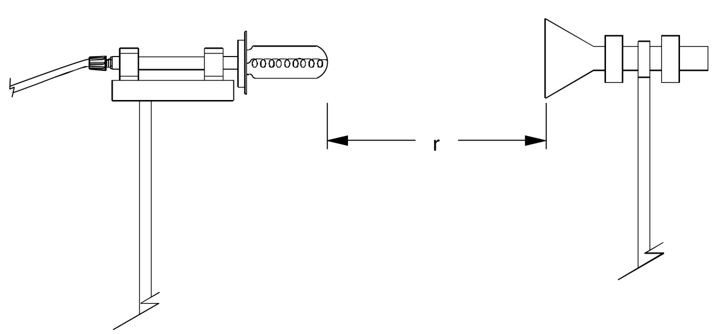


Figure 6. Distance r between the antennas

Helical Antennas

☐ 10. Keep the same attenuation level as for the horn antenna and perform an acquisition. Store the radiation pattern as the E-plane of a new document (Document2) and orient the pattern so that its MSP is at 0°.

☐ 11. Rotate the transmission horn antenna by 90° so that it is oriented for an H-plane acquisition.

Do not change the attenuation level. Perform another acquisition. Store this new pattern as the H-plane in Document2 and adjust its MSP to 0°.

☐ 12. Compare the E and H-planes in Document2; do you observe a significant difference in their maximum amplitudes? Considering that the receiving antenna has not been rotated to perform the H-plane acquisition, explain this result.

____

____

____

☐ 13. Remove the receiving antenna and replace it with the left-hand polarized (LHP) helical antenna. Referring to the preceding steps, make the correct set-up and perform acquisitions of the E and H-planes of this antenna. Keep the same attenuation level used for the RHP helix. Store the radiation patterns in a new document (Document3).

☐ 14. Save the data stored in the Document2 and Document3, then print the 3-D representations of these two antennas. Note the similarity between the radiation patterns of the RHP and LHP helical antennas.

HPBW and gain of a helical antenna

☐ 15. Evaluate the half-power beamwidth of the helical antennas.

RHP helix: $HPBW_E$ = ______° $HPBW_H$ = ______°

LHP helix: $HPBW_E$ = ______° $HPBW_H$ = ______°

☐ 16. Use the following equation to calculate the gain of the helical antennas given the following dimensions:

D = 8.4 mm
N = 15 turns
S = 6.1 mm
α = 13°

$$G = 8.3\left(\frac{\pi D}{\lambda}\right)^{[(N+2)^{1/2}-1]} \cdot \left(\frac{NS}{\lambda}\right)^{0.8} \cdot \left[\frac{\tan(12.5°)}{\tan(\alpha)}\right]^{(N/2)^{1/2}}$$

G = ______

G (dB) = 10 log G = ______dB

☐ 17. Using the small horn antenna as a reference, measure the gain of the helical antennas.

G_horn=10log(26000/(HPBW_E * HPBW_H))

Record the following values:

$MSL_{E\text{-}plane}$ of the RHP helix : P_{RHP} _______ dB

$MSL_{E\text{-}plane}$ of the LHP helix : P_{LHP} _______ dB

$MSL_{E\text{-}plane}$ of the horn: P_{Ref} _______ dB

Referring to the gain of a small horn (G_{Ref}), calculate the gain of the helical antennas.

Note: *When a linearly polarized antenna is used to acquire a circularly polarized signal (or vice-versa), a part of the signal is not received; half of the power can be observed to be lost. Therefore, to obtain the real gain of a helical antenna evaluated in such a manner, 3 dB must be added to the result.*

$G_{RHP} = P_{RHP} + G_{Ref} - P_{Ref} + 3$ dB = ______ dB

$G_{LHP} = P_{LHP} + G_{Ref} - P_{Ref} + 3$ dB = ______ dB

Note: *This measurement could also have been performed using the H-plane.*

Circularity and axial ratio

☐ 18. Remove the two antennas. Replace the transmission mast with the one that has horizontal clips, then attach an RHP helix to it. Install the other RHP helical antenna on the receiving mast. Position the antennas a distance of 1 m apart, facing each other. Optimize the attenuation level, then make an acquisition. Replace the E-plane radiation pattern in Document1 by this new one.

Replace the transmission antenna with the LHP helix, then perform a new acquisition. Store this pattern as the H-plane of Document1.

☐ 19. Compare the two patterns in Document1. Were you expecting this result? Explain.

____

____

____

☐ 20. An important parameter of the helical antenna is the circularity of its polarization. This is known as the axial ratio.

Using the following equation, calculate the theoretical axial ratio of the helix antennas.

$$AR = \frac{2N + 1}{2N}$$

where N = the number of turns in the helix

AR = ______

AR (dB) = 20 log (AR) = ______ dB

☐ 21. One way to measure the axial ratio of a helical antenna is to rotate a linearly polarized antenna through 360° in a plane perpendicular to the axis of the transmitting helix as shown in Figure 7. The ratio of the maximum to minimum received signal is the axial ratio. An abbreviated version of this measuring method is used in the following steps.

☐ 22. Remove the receiving antenna and the mast with horizontal clips. Place a mast with locking ring on the sliding support and attach a large horn antenna to this mast. Make sure that the receiving and transmitting antennas are facing each other. Adjust the signal level approximately 5 dB under the saturation level and note the exact value of this signal ($Signal_1$).

Rotate the horn antenna by 90°, as if to acquire a pattern in the other plane. Make sure that both antennas are still facing each other. Do not modify the attenuation level. Now record the received signal ($Signal_2$).

$Signal_1$: ______ dB $Signal_2$: ______ dB

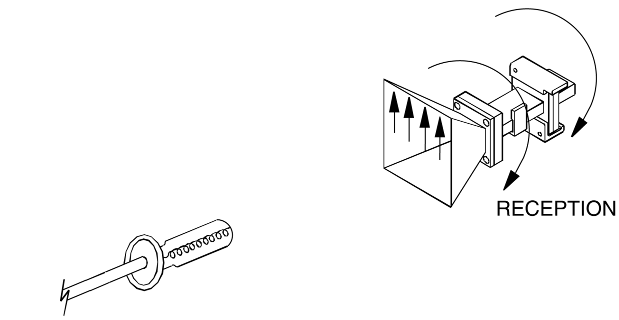


Figure 7. Rotation of the linearly polarized antenna in a plane perpendicular to the axis of a helix.

☐ 23. Using the centre line of the radome as reference, rotate the helix by 45°, as shown in Figure 8, while maintaining the alignment with the receiving horn.

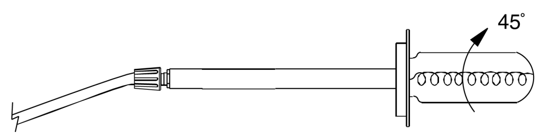


Figure 8. Rotation of the helix by 45°

Do not modify the attenuation level. Note the signal received in this plane, then, after having again rotated the horn antenna by 90°, record the signal received in the other plane.

$Signal_3$: ________dB $Signal_4$: ________dB

☐ 24. Taking the highest of these four values as the maximum and the lowest as the minimum, establish the axial ratio of the helical antenna.

$$\frac{Signal_{max}}{Signal_{min}} = Signal_{max}(dB) - Signal_{min}(dB)$$

______ – ______ = ______ dB

☐ 25. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you observed that the gain of a helical antenna is similar in both the E and H-planes due to the circularity of its polarization. Using the 3-D option, you visualized the representation in space of this type of antenna. Using the small horn gain as a reference, you measured the gain of an RHP and an LHP helix. Finally, the results of the cross-polarization experiment and the measured axial ratio allowed you to assess the efficiency of the circularity of the helical antenna's polarization.

REVIEW QUESTIONS

1. Define circular polarization.

2. What is the relation between elliptical, linear and circular polarizations?

3. Could a 4-turn helical antenna be considered as a good antenna to receive different linear polarizations? Explain.

4. Explain the main difference between the normal and axial modes of a helical antenna.

5. What is the purpose of a radome? Does it influence the electrical characteristics of an antenna?

Exercise 2

Parasitic Array (Yagi-Uda) Antennas

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with parasitic array antennas of the Yagi-Uda type. You will have constructed such antennas in different configurations and measured their characteristics.

DISCUSSION

Few antennas are as common as the ubiquitous Yagi antenna, also called the Yagi-Uda antenna. This antenna is named after the researcher S. Uda and the professor H. Yagi who experimented with these parasitic array structures in Japan in the 1920's.

In several previous exercises, reference has been made to antennas which can be considered to be made up of multiple elements, where each element has its own current distribution. The radiation pattern of such an antenna is the result of the addition or cancelling of the current distributions.

it was shown that, in a folded dipole, the current distributions of the two parallel wires close together add up to enhance the radiation pattern in certain directions. and it was shown that the current distributions in loop antennas, in different parts of the loop located the same distance from each other, add up or cancel to produce the radiation pattern. Finally, in Exercise 1 on the helical antenna, you saw that the effects of the travelling wave add up from loop to loop in the helix to produce a pencil beam-radiation pattern.

These are all examples of **active antenna array effects**, that is, effects due to antenna elements which are connected to a feed network of some kind. An antenna composed of discrete elements is called an **antenna array**.

An array effect can also be obtained using **parasitic antenna elements** or **parasites**—metallic structures or wires which are not connected to a feed network. In this case, the array effect can be considered as being due to the current induced by the electromagnetic field in the parasitic antenna element. These elements receive their excitation by near-field coupling from the driven elements.

An example of this phenomenon was seen in a vertical folded dipole located at a λ/4 spacing from the vertical metallic mast showed an increase in gain of a few dB in the direction opposite to the mast. The mast in this case acts as a reflector element in a parasitic antenna array.

Parasitic Array (Yagi-Uda) Antennas

Basic principle of Yagi antennas

Figure7-9 illustrates a six-element Yagi antenna.

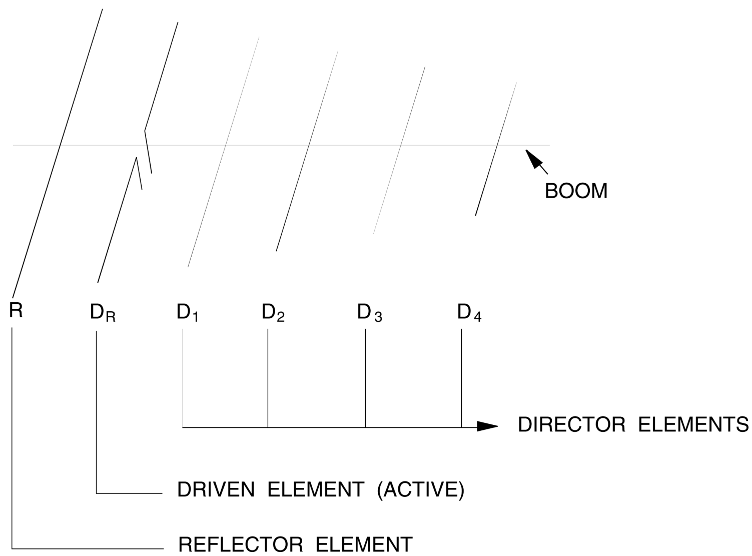


Figure 9. Six-element Yagi antenna

A Yagi antenna consists of the following elements:

- an **active antenna element** or **driver** element connected to a feed network. This can be a half-wave dipole as in Figure 9, but it can also be another type of element such as a folded dipole or a loop antenna.

- a **reflector** element on one side of the active element. As the name implies, this reflects radiated power back towards the active element. In principle, there can be more than one reflector element located on the same side of the driver and with similar lengths and spacings. In practice, however, there is very little benefit from having more than one reflector element.

- one or more **director** elements on the other side of the active element which tend to concentrate the radiated power.

The reflector element is typically about 5% longer than the active element whereas the first director is about 5% shorter than the active element. The optimum spacing, for maximum directivity, is from 0.15λ to 0.25λ between the active element and the reflector, with the same spacing between the active element and the first director.

When several directors are used, successive elements usually become somewhat shorter and spaced further apart. The spacing of the reflector and first director are the most important as they determine the spacing for the other directors and have the greatest effect on the matching. However, the spacing of the elements is not highly critical.

Parasitic Array (Yagi-Uda) Antennas

The effect of the active element on the parasitic elements very near to it is to induce current in these elements so that their electric field is more or less equal in amplitude and opposite in phase to the incident field. Computer simulations show that increasing the length of the reflector and decreasing the length of the director, compared to that of the active element, introduces the directivity effect.

There is significant benefit in having more than one director element as this increases the gain of the antenna. However, the benefit diminishes gradually as the number of director elements increases. This is because, as the parasitic director elements get farther away from the active element, their induced current decreases and consequently so does their contribution to the antenna gain. This is illustrated in Figure 10 and Table 1.

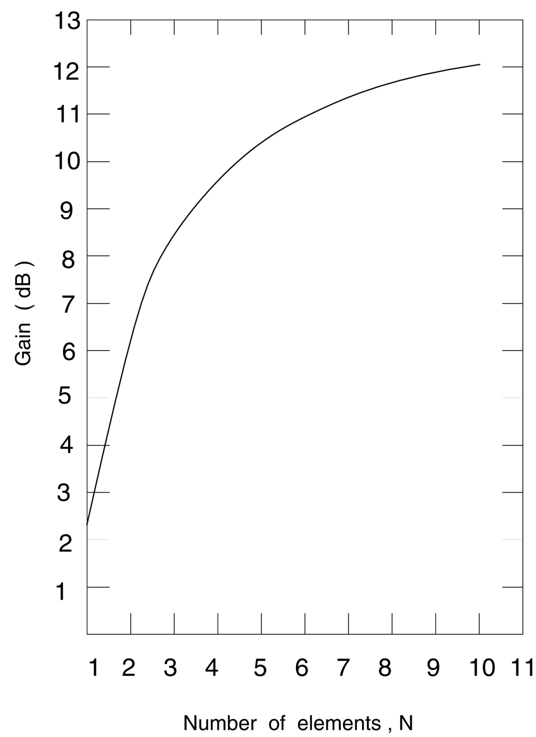


Figure 10. Graph of gain versus the total number of elements of a typical Yagi antenna

ELEMENTS	GAIN
3	8,7
4	9,9
5	10,5
6	11,1

Table 1. Gain of a Yagi antenna for different numbers of elements (spacing = 0.15λ)

Parasitic Array (Yagi-Uda) Antennas

The input impedance of a Yagi antenna is a function of the input impedance of the driver element, but is greatly influenced by the parasitic elements. A theoretical value of about 25 Ω for a three-element dipole array can be established. The variation of the input impedance with the antenna configuration is rather large and values from 20 Ω to 100 Ω are often quoted in literature on the subject.

As the above discussion implies, the term Yagi is more indicative of a type of antenna structure than of a specific antenna model. In fact, there are many variations of the Yagi antenna.

It should be noted that since there is no easy analytical method to analyse a Yagi antenna, the analysis and optimization of these antennas is usually done using computer calculations and simulations.

Fortunately, many experimental and numerical studies have been performed and their results are widely available in papers, handbooks, and textbooks (see the Bibliography of this manual).

Procedure Summary

In this exercise you will study the construction of a Yagi-Uda antenna. You will observe the variations in different parameters when you increase the number of its elements. Using radiation patterns, you will study the gain, the half-power beamwidth and the front-to-back ratio characteristics.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/ Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission support. Clip the Yagi antenna onto the mast, so it is horizontally polarized, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator using the long SMA cable.

☐ 3. Set up a λ/2 dipole antenna. Using the screw-on 90˚ adapter, attach the dipole to the aluminum boom. Place the mast with horizontal clips on the sliding support of the Antenna Positioner. Clip the antenna onto the mast, as shown in Figure 11.

Using the sliding support, make sure that the dipole is in line with the rotation centre of the Antenna Positioner. Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the intermediate SMA cable.

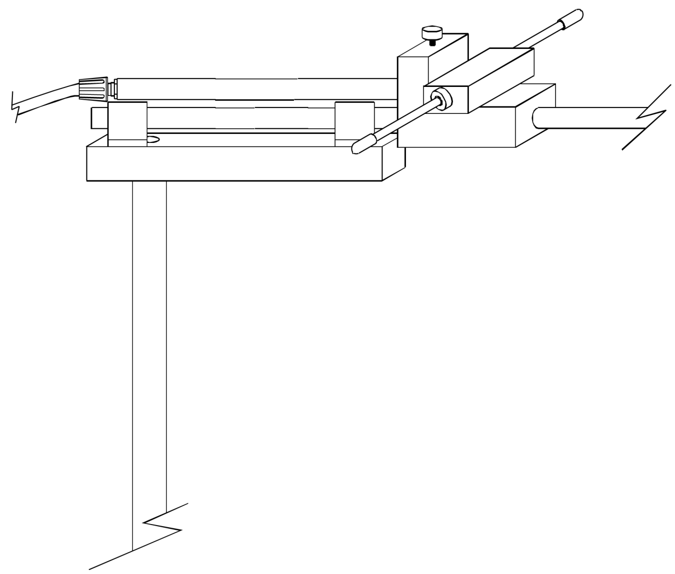


Figure 11. Set-up of the dipole attached to the aluminum boom

☐ 4. Position the transmitting Yagi antenna and the receiving dipole a distance of r = 1.5 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 5. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 6. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

Optimize the attenuation to produce a signal level of 13 dB under the saturation point (you should maintain this attenuation throughout the exercise). Start your acquisition and store the radiation pattern as the E-plane of a new document (Document1).

☐ 7. Save the pattern stored in the antenna1 data box. You will use it as a reference in the following steps.

☐ 8. Use the wire having a length of 178 mm as a reflector by placing it at an approximate distance of A = 0.15λ to 0.25λ behind the dipole, as shown in Figure 12.

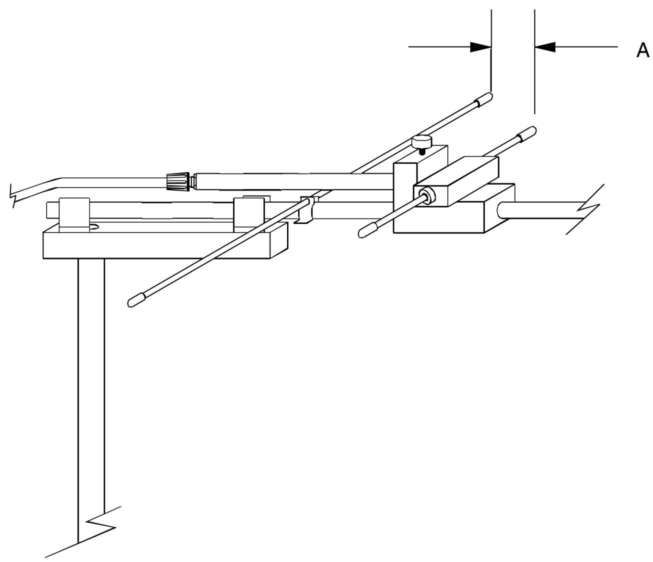


Figure 12. Set-up of the antenna using only a reflector

Make sure that the dipole is still aligned with the rotation centre of the Antenna Positioner. Start an acquisition and store the pattern as the E-plane of a new document (Document2).

☐ 9. Remove the reflector from the boom, then clip a 146 mm director at a distance of A = 0.15λ to 0.25λ in front of the dipole. Acquire the pattern and store it as the H-plane of Document2 (even it is an E-plane pattern).

Parasitic Array (Yagi-Uda) Antennas

☐ 10. For a better understanding of the roles of the reflector and the director, compare these two patterns with the one saved in the first data box. Describe your observations.

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Save the data stored in Document2 if you expect to use them in the future, then close this file.

☐ 11. Set up a three-element Yagi-Uda antenna using the 178 mm and the 146 mm wires as a reflector and a director respectively, and the dipole as the driven element. Space the elements 0.15λ apart.

Perform an acquisition and store it as the E-plane of a new document (Document3).

> **Note:** *The set-up of an efficient Yagi-Uda antenna requires exact measurement of the wire lenghts and their spacing; it can be a tedious process if you are not using some reliable software. The following steps will allow you to observe the behaviour of this type of antenna, when the number of elements is increased according to the correct pattern of adjustment.*

☐ 12. To improve the efficiency of your three-element Yagi antenna, refer to Figure 13 and to the following values to adjust the distance between the elements.

Length of the wires:

A = 178 mm   C = 146 mm
B = 154 mm

Spacing between the wires:

1 = 87 mm
2 = 61 mm

Parasitic Array (Yagi-Uda) Antennas

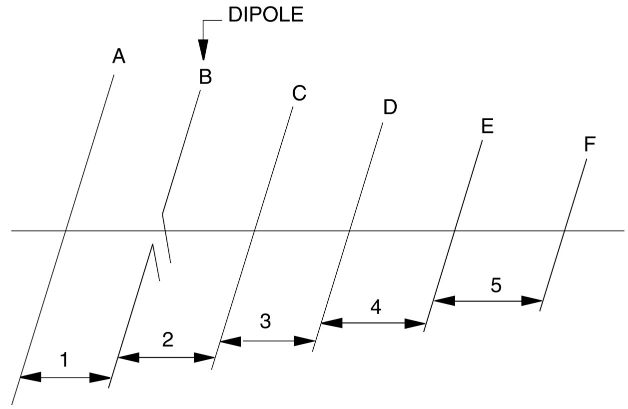

Figure 13. Set-up of the Yagi-Uda antenna

Start an acquisition and store the pattern as the H-plane of Document3. Compare this result with the previous one, and notice the effect of the correct spacing between the elements.

☐ 13. Using Table 2, record the gain in dBd (referenced to the dipole pattern stored in the first data box) and in dBi (use the λ/2 dipole gain), the HPBW and the front-to-back ratio (F/B) of the adjusted three-element Yagi.

NUMBER OF ELEMENTS	**$HPBW_E$ (°)**	**GAIN (DBi)**	**GAIN (DBd)**	**F/B**
3				
4				
5				
6				

Table 2. Parameters of different Yagi-Uda antenna set-ups

$$Approximated\ Gain\ in\ DBi = \frac{30000}{(HPBW_E)^2}$$

☐ 14. Using the following values and referring to Figure 13, set up a four-element Yagi-Uda antenna.

Length of the wires:

A = 178 mm C = 146 mm
B = 154 mm D = 144 mm

Spacing between the wires:

1 = 88 mm 3 = 85 mm
2 = 66 mm

Perform an acquisition and store the pattern as the E-plane of a new document (Document4).

Repeat Step 13 for the four-element Yagi antenna.

☐ 15. Refer to Figure 13 and use the following values to set up a five-element Yagi antenna.

Length of the wires:

A = 178 mm C = 146 mm E = 142 mm
B = 154 mm D = 144 mm

Spacing between the wires:

1 = 94 mm 3 = 100 mm
2 = 75 mm 4 = 108 mm

Perform an acquisition and store the pattern as the H-plane of Document4.

Repeat Step 13 for the five-element Yagi antenna.

☐ 16. Refer to Figure 13 and use the following values to set up a six-element Yagi antenna.

Length of the wires:

A = 178 mm C = 146 mm E = 142 mm
B = 154 mm D = 144 mm F = 140 mm

Spacing between the wires:

1 = 66 mm 3 = 105 mm 5 = 120 mm
2 = 70 mm 4 = 110 mm

Perform an acquisition and store the pattern as the E-plane of a new document (Document5).

Repeat Step 13 for the six-element Yagi antenna.

☐ 17. Print the 2-D representation of the 3-, 4-, 5- and 6-element Yagi E-plane on the same sheet.

Comment on the gain progression of the different set-ups considering the theoretical values given in the discussion.

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☐ 18. Rotate the transmitting and receiving antennas and perform an acquisition of the six-element Yagi H-plane. Store this pattern in Document5.

☐ 19. Orient the MSP of the six-element Yagi patterns to 0°, then observe the spatial representation of this antenna using the E-H and 3-D tabs.

☐ 20. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you observed the role of the reflector and director elements on a Yagi-Uda antenna. You plotted the radiation patterns of antennas having an increasing number of elements and evaluated their HPBW, their front-to-back ratio and, with reference to a λ/2 dipole, their gains. You saw the influence of the increase in the number of elements on the gain enhancement of this type of antenna.

REVIEW QUESTIONS

1. Explain the relation between a folded dipole, a loop antenna, a helical antenna and a Yagi-Uda antenna.

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2. How does the Yagi antenna differ from the three other antennas mentioned in Question 1?

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3. Explain the purpose of each element of a Yagi-Uda antenna.

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4. Explain the relationship between the number of elements in a Yagi antenna and its gain.

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Parasitic Array (Yagi-Uda) Antennas

5. Why does the benefit derived from adding directors gradually decrease as the number of elements increases?

Part 1
Transformer Matching

Objectives of this Part

Having completed this part you will be able to:

- Describe how a quarter wavelength long line can be used to match impedances.
- Describe how a half wavelength long line can be used to match a line, which would otherwise be mismatched.
- Investigate transformer matching using the Transmission Line Trainer.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.
- Function Generator.

7.1.1 Transformer Matching with a Quarter Wavelength Line

In the last chapter we considered the effect of standing waves.

Consider a line that is one quarter wavelength long. We have already seen that if the line has a short circuit termination the input will be at a maximum and if the line has an open circuit termination the input will be a minimum.

It was noted before that the input impedance of the line depends on whether the voltage at the input is higher or lower than for the matched line.

This suggests if the impedance of the quarter wavelength line could be measured at different points along its length, it would be found to vary from one point to the next. This is indeed the case, and it means that a quarter wavelength long line can act as a transformer to match two different impedances.

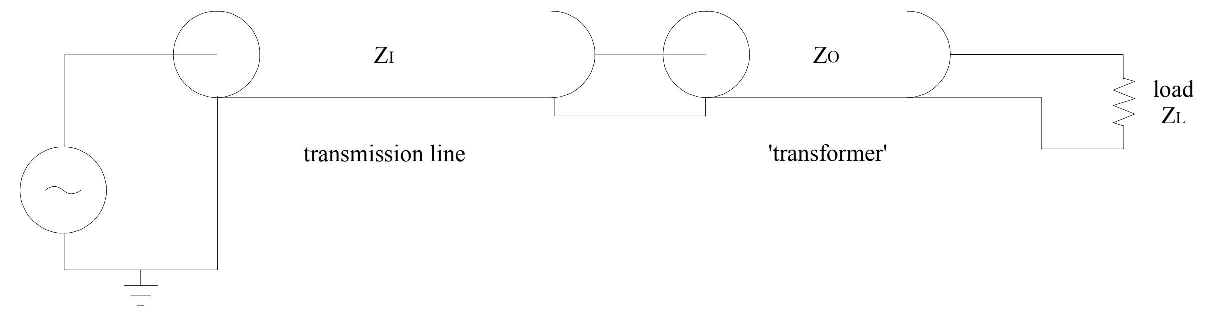

Figure 1

The formula that describes how the impedance is changed for a quarter wave line used as a transformer is:

$$Z_I = \frac{Z_O^2}{Z_L}$$

Where Z_O is the characteristic impedance of the line used as a transformer, Z_L is the load impedance and Z_I is the input line impedance, that is, the impedance of the line connected to the generator.

For the practical exercises in this chapter, the 70 ohm simulated line will be used as the transformer and the 50 ohm simulated line will be used as the input line.

This formula is sometimes expressed in the form:

$$Z_O = \sqrt{Z_L Z_I}$$

The above formula is used when a line (the transmission line in Figure 1) has tobe matched to a load, which does not have the same value as the characteristicimpedance of the line. The formula will tell you the characteristic impedance ofthe 'transformer' line that is required to make a quarter wave matching section.

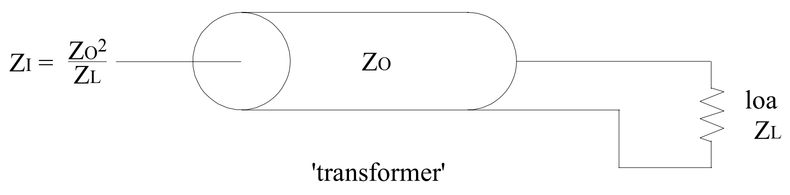

Figure 2

The disadvantage with using a quarter wave (or indeed a half wave) matching section is that it only works at one frequency, but in practice a narrow band around this frequency can be used. This frequency corresponds to the frequency at which the 'transformer' line being used as a quarter wave matching section is a quarter wavelength long.

The frequency at which a line is a quarter wavelength long is:

$$f = \frac{0.25}{m\sqrt{LC}}$$

where m is the length in meters, L is the inductance per meter and C is the capacitance per meter.

7.1.1a In transmission line theory, what is transformer matching?

- [a] Finding two compatible transformers.
- [b] The use of a transmission line to match two different impedances.
- [c] Transforming a match to a mismatch.
- [d] Replacing a transmission line with one that is a quarter wavelength long.

7.1.1b You wish to match a 600 ohm load to a 50 ohm line using transformer matching. Calculate and enter the value of characteristic impedance of the 'transformer' line needed to make a quarter wave matching section.

Notes:

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7.1.2 Practical Exercise

In this practical exercise we will see the effect of transformer matching on the oscilloscope display.

- Connect the power supply to the Transmission Line Trainer as in Figure 16 (EXP.1 Introduction to Transmission line).
- Ensure all switched faults are off.
- Switch the Pulse Generator off.
- Connect the Function Generator to the input of the simulated 50 ohm line via the Summing Amplifier, using settings as described in Practical Exercise 8.4.
- Switch on the power supply.
- Using channel 2 of the oscilloscope, set the function generator to give a 4 volt peak-to-peak sinewave, frequency 100kHz at the input of the simulated transmission line.
- Connect channel 1 of the oscilloscope to **TPA**. The oscilloscope should display a square wave. Trigger the oscilloscope with the negative edge of this signal.
- Set the timebase so that the negative going edge of this square wave is on the left most graticule and the next positive going edge is on the right most graticule. In other words, half the square wave should be displayed on the oscilloscope display.
- As the square wave is only used for setting up the oscilloscope it can be moved out of view.
- Use a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit.
- Connect channel 2 of the oscilloscope to examine the output of the Standing Wave Display at **TPB**.

You should recall that the X axis of the oscilloscope display now displays distance along the line instead of time. The first 24 sections are the simulated 50 ohm line and the next 8 sections are the simulated 70 ohm line.

■ Calculate the value of termination resistor required at the end of the 70 ohm line, if this line is to be used to match the termination resistor to the simulated 50 ohm line. Do this by using the formula below:

$$R = \frac{Z_O^2}{Z_I}$$

Where Z_O is the characteristic impedance of the line used as a transformer and Z_I is the input line impedance, that is, the impedance of the line connected to the generator. Make a note of this value in your workbook.

7.1.2a Enter the value of resistance you calculated to give a match to the simulated 50 ohm line.

■ Set variable resistor R to the resistance you calculated. Remember to switch off the power supply while measuring this resistance.

■ Calculate the frequency at which the simulated 70 ohm line is a quarter wavelength long, using the formula below:

$$f = \frac{0.25}{n\sqrt{LC}}$$

Where n is the number of sections, L is the inductance per section and C is the capacitance per section. Note that for the simulated 70 ohm line, L = 10μH and C = ZnF. Make a note of this value in your workbook.

■ Set the function generator to the frequency you calculated.

The simulated 50 ohm line will not be matched in this configuration.

■ Now move the 4mm lead from variable resistor R to the input of the simulated 70 ohm line, so that the output of the simulated 50 ohm line is connected to the input of the simulated 70 ohm line.

■ Use a 4mm lead to connect the output of the simulated 70 ohm line to variable resistor R in the Termination Unit.

The simulated 50 ohm line should now be matched and you should be able to notice the quarter wave on the simulated 70 ohm line. A small adjustment of the function generator frequency may be necessary to see this effect. Sketch this display.

■ Switch off the power supply.

7.1.3 Transformer Matching with a Half Wavelength Line

If the 'transformer' line is one half of a wavelength long, then the impedance reflected back to its input is the same as the load impedance.

That is:

$Z_I = Z_L$

where Z_I is the input line impedance and Z_L is the load impedance.

The input line can be matched if the line being used as a transformer is terminated using a resistor with the same value as the characteristic impedance of the input line. In other words, the characteristic impedance of the line used as a transformer is unimportant, all that is necessary is that it is half a wavelength long at the frequency in question.

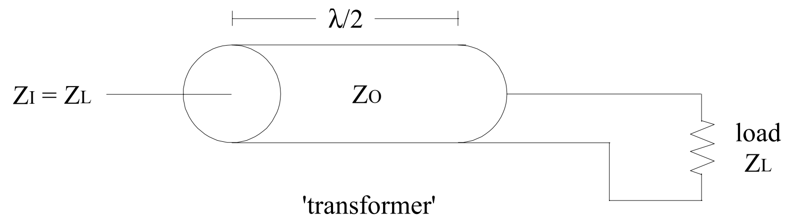


Figure 3

This could be used where a cable of the wrong characteristic impedance had to be used as an extension cable but is only required to operate over a narrow band of frequencies.

7.1.4 Practical Exercise

In this practical exercise we will see the effect of transformer matching using a half wavelength long line.

- Connect and set up the Transmission Line Trainer as in Practical Exercise 7.1.2.
- Set resistor R in the Termination Unit to the characteristic impedance of the simulated 50 ohm transmission line. Ensure that the power supply is switched off while doing this.
- Switch on the power supply.
- Calculate the frequency at which the simulated 70 ohm line is a half wavelength long using the formula below:

$$f = \frac{0.5}{n\sqrt{LC}}$$

Where n is the number of sections, L is the inductance per section and C is the capacitance per section. Make a note of this value in your workbook.

7.1.4a Enter the frequency at which the 70 ohm line is a half wavelength long.

- Set the function generator to the frequency you calculated.
- View the Standing Wave Display on the oscilloscope. You should be able to see that the simulated 50 ohm line is matched and observe the half wave on the 70 ohm simulated line. A small adjustment of the function generator frequency may be necessary to see this effect. Sketch this display.
- Switch off the power supply.

7.1.5 Summary of Practical Exercises

This chapter has shown the effect of transformer matching using quarter waves and half waves.

i) A line can be matched to a load that is not equal to its characteristic impedance by using another line at one particular frequency. This frequency is equal to the frequency at which the line being used as a transformer is a quarter wavelength long.

ii) A line can be matched to a load that is equal to its characteristic impedance by using a line with an incorrect characteristic impedance, provided the line with the incorrect characteristic impedance is a half wavelength long.

You may think that operation at one, or a narrow band of frequencies is a problem, but in some cases this is acceptable. One example of this could be Amplitude Modulation (AM) where the bandwidth is small compared with the carrier frequency.

It may be that you cannot change the frequency at which the matching must take place in a particular application. However, by changing the length of the cable that is to be used as the transformer, it is possible to achieve a match at the required frequency.

Student Assessment 7.1

1. **To match a cable to a load of the wrong impedance using transformer matching we need to use:**

   [a] a long length of cable.

   [b] a cable which is one wavelength long.

   [c] a cable which is a half wavelength long.

   [d] a cable which is a quarter wavelength long.

2. **A mismatched quarter wavelength line has along its length:**

   [a] constant voltage.

   [b] constant impedance.

   [c] variable impedance.

   [d] variable frequency.

3. **Transformer matching to match a cable to an incorrect load using another cable is accomplished by putting the cable to be used as a transformer:**

   [a] before the input line.

   [b] between the input line and load.

   [c] after the load.

   [d] in place of the load.

4. **The disadvantage with using a half wave matching section is:**

   [a] it is expensive.

   [b] it only works over a narrow band of frequencies.

   [c] it needs special connectors.

   [d] adjusting the cable length has no effect on the frequency of operation.

5. **When a line is being used as a half wavelength long transformer:**

   [a] it reflects an impedance equal to half the load resistance back to its input.

   [b] it can be used over a wide band of frequencies.

   [c] the load resistance is unimportant.

   [d] its impedance is unimportant, as long as the load is matched to the input line.

6. **To demonstrate transformer matching, the Transmission Line Trainer uses:**

   [a] A built in sinewave generator.

   [b] The 600 ohm line.

   [c] The simulated 70 ohm line as the transformer.

   [d] The simulated 50 ohm line as the transformer.

Part 2
Time Domain Reflectometry

Objectives of this Part

Having completed this part you will be able to:

- Explain the principles of TDR.
- Use the principles of TDR to find faults that have been switched into the Transmission Line Trainer.

Equipment Required for this Part

- CT30 Transmission Line Trainer.
- Power Supply.
- Set of 4mm leads.
- Oscilloscope.

7.2.1 Time Domain Reflectometry (TDR)

This chapter builds on the work completed in assignment 1 part 3&4

In assignment 1 part 3 we saw that a pulse input took a finite length of time between input and output. In assignment 1 part 4 we saw that if a transmission line was not terminated with an impedance equal to the characteristic impedance, then there would be a reflected pulse which would travel back down the line. In TDR these characteristics are exploited to make measurements on a cable. For TDR to work reliably in predicting where a fault is, the propagation velocity has to be uniform along the length of the transmission line. This is normally the case.
For example, if the transmission line is left deliberately disconnected (open circuit) and a short pulse is sent periodically down the line, the time between the transmitted and reflected pulses can be measured. This will give the time taken for a pulse to travel down the line, be reflected at the other end and travel back down the line. If the propagation velocity of the line is known, the length of the line can be calculated:

length = velocity x time

Now let us suppose a fault is suspected along the line. Whether the fault is a short circuit or an open circuit can be determined by examining the polarity of the pulse (non-inverted for open circuit or inverted for short circuit).

Now let us also suppose that the time delay between the transmitted pulse and the reflected pulse, at the start of the transmission line, is t seconds:

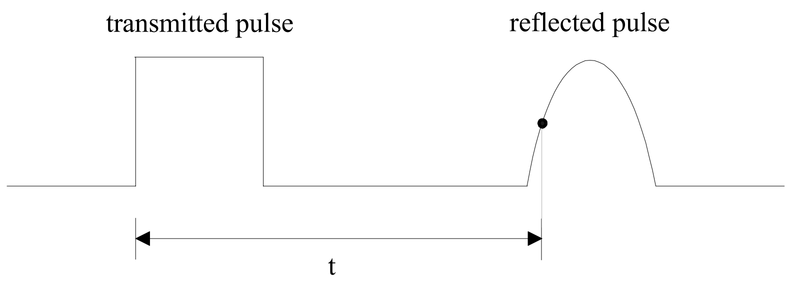


Figure 4

As the pulse is reflected along the line to the fault and back again, the time for the transmitted pulse to reach the fault will be:

$$\text{time} = \frac{t}{2}$$

The distance from the start of the transmission line to the fault will therefore be:

$$\text{distance} = \text{velocity x time} = \frac{v.t}{2}$$

Where t is the measured delay between transmitted and reflected pulses at the start of the line (in seconds), and v is the propagation velocity of the line.

If a fault had to be found on a cable that had just been installed, the cable's propagation velocity would have to be determined either by looking up the specifications for that cable or by cutting a section of the same type of cable to a known length and measuring the delay.

An alternative way to determine where the fault is, is to measure the reflected pulse delay when the line is unfaulted and terminated in an open circuit (obviously this must be done before a fault develops!), then compare this with the reflected pulse delay when the fault is present. If the length of the complete line is known, then you can calculate how far the fault is from the start of the line:

$$\text{distance} = \frac{t}{T} \cdot L$$

Where t is the reflected pulse delay when the fault is preset, T is the reflected pulse delay with no fault present and an open circuit termination, and L is the length of the complete line.

Calculating the fault position in this way helps to minimize measurement errors and errors introduced by the tolerance of cables and components. We will use this method in the practical exercise that follows.

7.2.1a If TDR is to be used to reliably predict the location of a fault on a transmission line:

a the line must have a matched termination.

b the end of the transmission line must be deliberately left disconnected.

c the fault must be a short circuit.

d the propagation velocity has to be uniform along the length of the line.

7.2.2 Practical Exercise

In this practical exercise we shall measure the delay between transmitted and reflected pulses at the input to the simulated 50 ohm line, under unfaulted and faulted line conditions.

- Connect the power supply to the Transmission Line Trainer as in Figure 16 (EXP.1 Introduction to Transmission Line).
- Ensure all switched faults are off.

- Switch the Pulse Generator ON and set the speed to fast (F).

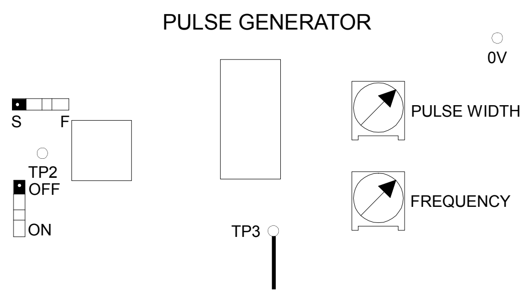


Figure 5

■ Use a 4mm lead to connect the output of the Summing Amplifier to the input of the simulated 50 ohm line.

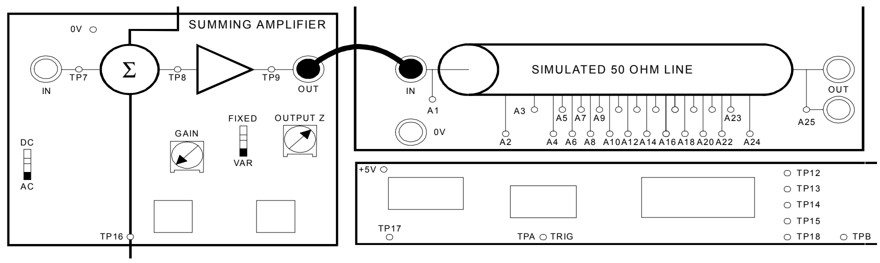


Figure 6

■ Set the Summing Amplifier coupling to DC.

■ Set the Summing Amplifier output impedance to FIXED.

■ Set the Summing Amplifier gain to minimum (fully counter-clockwise).

■ Set the Noise Generator AMPLITUDE control to minimum (fully counter-clockwise).

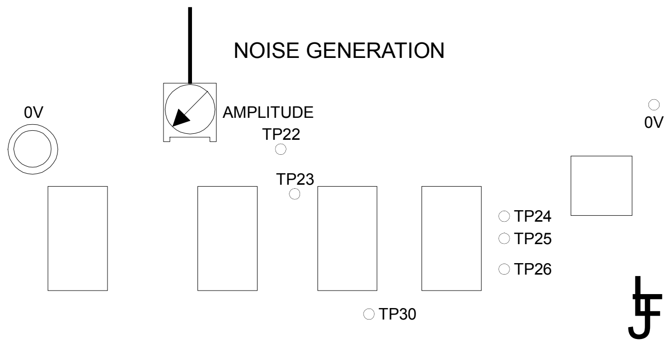


Figure 7

■ Switch on the power supply.

■ Connect channel 1 of the oscilloscope to examine the input of the simulated 50 ohm line at test point **A1**.

■ Connect your oscilloscope's external trigger to **TP2** and switch the oscilloscope to external triggering.

- Adjust the GAIN control on the Summing Amplifier to give a pulse amplitude of 2 volts at the input of the simulated 50 ohm line (transmitted pulse).
- Set the PULSE WIDTH control to give a 1µs pulse and set the oscilloscope to see the delay between the transmitted and received pulses (remember to leave the output of the simulated 50 ohm line open circuit).
- Measure the delay between the leading edge of the transmitted pulse and the leading edge of the reflected pulse. The easiest way to do this is to determine the point on each leading edge where the voltage is half of the pulse amplitude (see diagram below), then measure the distance between these two points. This figure is the reflected pulse delay for the unfaulted line, which we will call T.

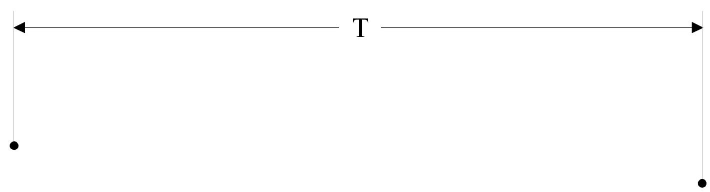


Figure 8

- Record your measured delay for the unfaulted line in your workbook.

7.2.2a Enter the delay between the transmitted and reflected pulses for the unfaulted simulated 50 ohm line.

- Use a 4mm lead to connect the output of the simulated 50 ohm line to variable resistor R in the Termination Unit. Set the resistor to its mid point.

  The line is now matched and you will observe that there is now no reflected pulse at the input of the line. You will now fault-find a transmission line.

- Ask your instructor to insert FAULT 1 on the transmission line, using the switched faults block.
- Measure the delay between the transmitted and reflected pulses in the same way as you did previously. We will call this time t_1.
- Estimate where you think the fault is by using the formula below for the simulated 50 ohm line. Record in your workbook your measured delay, whether the fault is open circuit or short circuit and your estimate of which section is at fault.

$$\text{section} = \frac{t_1}{T} \times 24$$

7.2.2b Enter your estimate of the section number in which FAULT 1 is to be found.

- Now ask your instructor to remove FAULT 1 and insert FAULT 2.
- Measure the delay between the transmitted and reflected pulses in the same way as you did previously. We will call this time t_2.
- Estimate where you think the fault is by using the formula below. Record in your workbook your measured delay, whether the fault is open circuit or short circuit and your estimate of which section is at fault.

$$\text{section} = \frac{t_2}{T} \times 24$$

7.2.2c Enter your estimate of the section number in which FAULT 2 is to be found.

- Finally, ask your instructor to remove FAULT 2 and insert FAULT 5.
- Measure the delay between the transmitted and reflected pulses in the same way as you did previously. We will call this time t_3.
- Estimate where you think the fault is by using the formula below. Record in your workbook your measured delay, whether the fault is open circuit or short circuit and your estimate of which section is at fault.

$$\text{section} = \frac{t_3}{T} \times 24$$

7.2.2d Enter your estimate of the section number in which FAULT 5 is to be found.

- Switch off the power supply.

7.2.3 Summary of Practical Exercise

Practical Exercise 7.2.2 has explored the principles and use of TDR. You have learned that:

i) Provided the propagation velocity is known, the position of the fault can be determined.

ii) The polarity of the reflected pulse determines the type of fault.

iii) The time delay of the reflected pulse determines the fault position.

This chapter has shown the basic principles of TDR. Sophisticated TDR instruments use mathematical techniques such as inverse Fourier transforms on the reflected pulse to give even more information about the type of fault. Such an instrument might display a graph of impedance against distance with a movable cursor, to allow the user to determine the position of a fault more accurately.

Student Assessment 7.2

1. **If a real cable had a non-uniform propagation velocity this would mean that:**
   - [a] it is not connected correctly.
   - [b] it is ideally suited to finding faults using TDR.
   - [c] it cannot be used reliably to determine faults using TDR.
   - [d] it has a non-standard characteristic impedance.

2. **The delay which the simulated 50 ohm line gives between a transmitted and reflected pulse when it has no faults applied is approximately:**
   - [a] 1.3µs
   - [b] 4.2µs
   - [c] 8.4µs
   - [d] 14.8µs

3. **While testing a transmission line using TDR, a non-inverted reflected pulse is observed with a delay that is half of the total delay for the line. This means that:**
   - [a] there is a short circuit fault halfway along the line.
   - [b] there is an open circuit fault halfway along the line.
   - [c] the line is matched.
   - [d] there is an open circuit fault one quarter of the way along the line.

4. **While testing a transmission line using TDR, an inverted reflected pulse is observed with a delay that is equal to the total delay for the line. This means that:**
   - [a] There is a short circuit fault at the end of the line.
   - [b] There is an open circuit fault halfway along the line.
   - [c] There is no fault on the line.
   - [d] The line is disconnected at its end.

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 8 Hybrid Tees

Hybrid Tees

EXERCISE OBJECTIVES

Upon completion of this exercise, you will be familiar with the construction and operation of hybrid tees. You will know how to characterize a hybrid tee. You will learn how a hybrid tee can be used to split or combine microwave signals. Finally, you will be able to name various applications for hybrid tees.

DISCUSSION

Introduction to Waveguide Tees

A waveguide tee is a section of waveguide that is used to split a microwave signal into two or more signals.

Waveguide tees come in two forms: the **H-plane tee** and the **E-plane tee**. These tees have tree arms.

- The **H-plane tee**, or shunt tee, is in the plane of the **magnetic** field (Figure 1). When a signal is fed into the central arm, it is split into two even signals that exit the tee, via the lateral arms, **in phase** with each other.

- The **E-plane tee**, or series tee, is in the plane of the **electric** field (Figure 2). When a signal is fed into the central arm, it is split into two even signals that exit the tee, via the lateral arms, **180° out of phase**.

  The E-plane tee is sometimes used for impedance matching. In that case, a piston, located along the central arm of the tee, is adjusted so as to reduce the standing waves to a minimum.

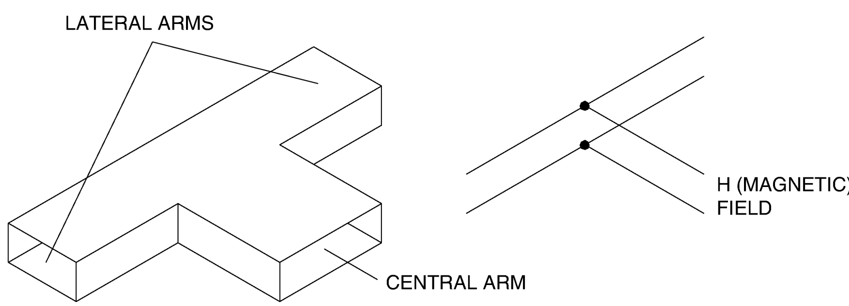


Figure 1. The H-plane tee, or shunt tee.

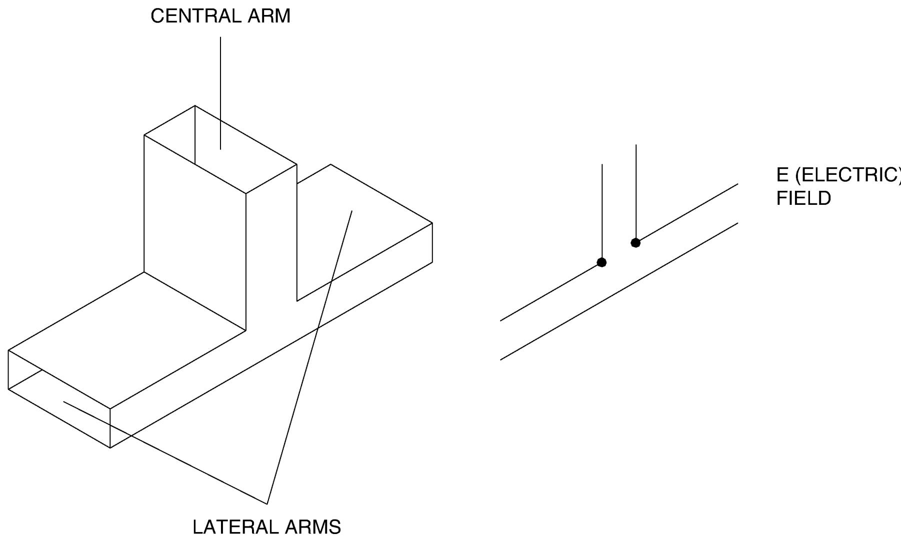


Figure 2. The E-plane tee, or series tee.

The Hybrid (Magic) Tee

The hybrid tee, also called magic tee, is a combination of the H-plane tee and the E-plane tee. As Figure 3 shows, the hybrid tee has four arms:

– The H-(Σ) plane arm, which is in the direction of the H (magnetic) field.

– The E-(Δ) plane arm, which is in the direction of the E (electric) field.

– Two lateral arms, 1 and 2. The lateral arms are disposed about an imaginary plane dividing the H- and E-plane arms symmetrically, as Figure 3 shows.

Hybrid Tees

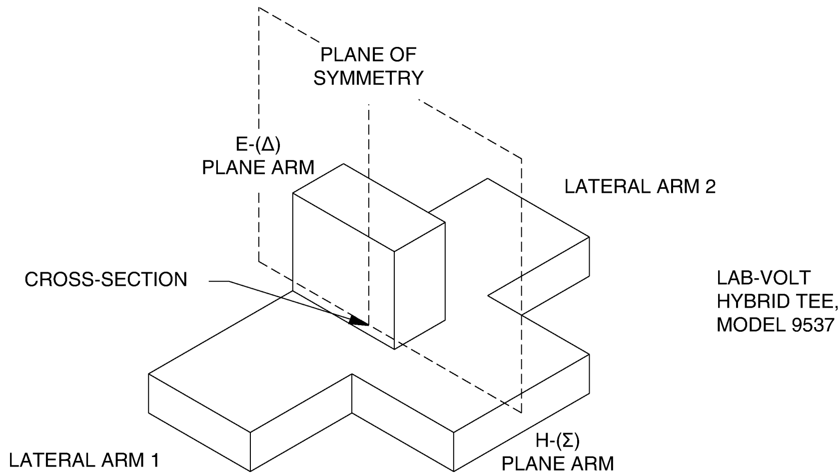


Figure 3. Hybrid tee.

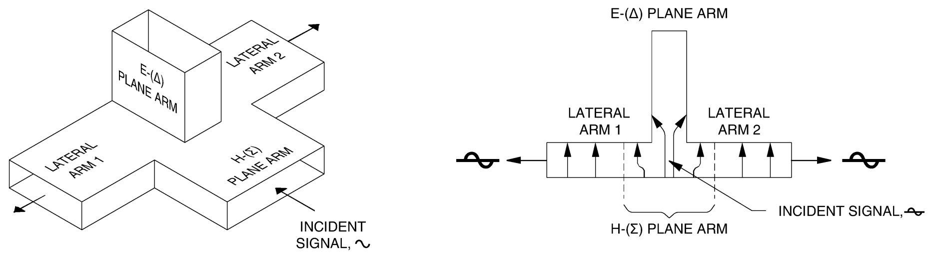
In the dominant mode of propagation (mode TE_{10}), a signal applied to the H- or E-plane arm of the tee will produce an electrical field (E-field) that is symmetrical about the midplane of the tee.

It can be demonstrated that, due to the symmetry of the E-field about the midplane of the tee, there is no coupling between the H- and E-plane arms, so that no signal propagation can occur between these arms. This statement assumes a perfect match at the junction of the H- and E-plane arms, and no reflection from the terminations of the four arms.

Using Hybrid Tees to Split Signals

Hybrid tees can be used to split a microwave signal into two even signals. To do this, the incident signal to split is fed into the H- or E-plane arm.

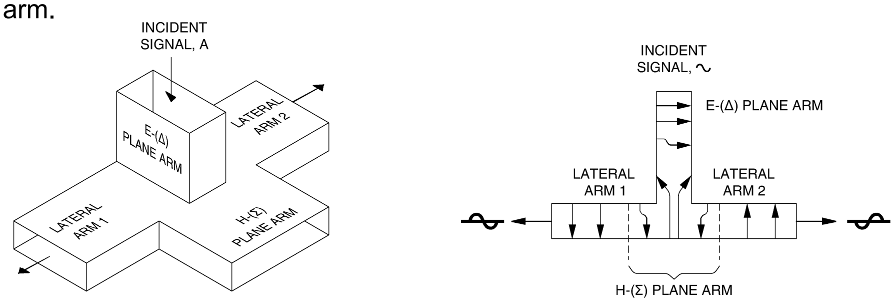
- When the incident signal to split is fed into the H-(Σ) plane arm (Figure 4), it divides into two signals that exit the tee via the lateral arms, in phase with each other. These signals are of even amplitude if the lateral arms are properly terminated. No signal propagates into the E-plane arm.



(a) 3D View (b) Lateral view

Figure 4. When the incident signal is fed into the H-plane arm, it divides into two even signals that exit the tee via the lateral arms in phase with each other.

- When the incident signal to split is fed into the E-(Δ) plane arm (Figure 5), it divides into two even signals that exit the tee via the lateral arms, 180°out of phase. These signals are of even amplitude if the lateral arms are properly terminated. No signal propagates into the H-plane arm.



(a) 3D View (b) Lateral view

Figure 5. When the incident signal is fed into the E-plane arm, it divides into two even signalsthat exit the tee via the lateral arms 180 out of phase .

Theoretical Versus Actual Attenuation and Isolation

The previous statements about signal splitting through either the H- or E-plane arm apply for the case of a perfect match at the tee junction, and no reflections from the terminations of each arm. In that ideal case,

- the signals exiting the lateral arms of the tee are attenuated by 3 dB relative to the signal fed into the H- or E-plane arm;

- the isolation between the H- and E-plane arms is infinite.

In practice, the attenuation of the signals exiting the lateral arms is greater than 3 dB, and the isolation between the H- and E-plane arms is typically between 20 and 40 dB.

Hybrid Tees

Matching devices can be used to obtain a better impedance match at the junction of the H- and E-plane arms and, therefore, reduce the reflections. However, these devices will often decrease the bandwidth of the tee.

Using Hybrid Tees to Couple Signals

Hybrid tees can be used to combine two microwave signals into a single signal. To do this, the two signals to couple are simultaneously fed into the H- and E-plane arms (Figure 6).

– In lateral arm 2, signals A and B (attenuated by a certain amount as they propagate through branches E→2 and H→2) will add together. The signal exiting lateral arm 2 is, therefore, the vectorial sum (Σ) of the two attenuated signals (A + B).

– In lateral arm 1, signals A and B (attenuated by a certain amount as they propagate through branches E→1 and H→1) will subtract from each other. The signal exiting lateral arm 2 is, therefore, the vectorial difference (Δ) of the two attenuated signals (A - B).

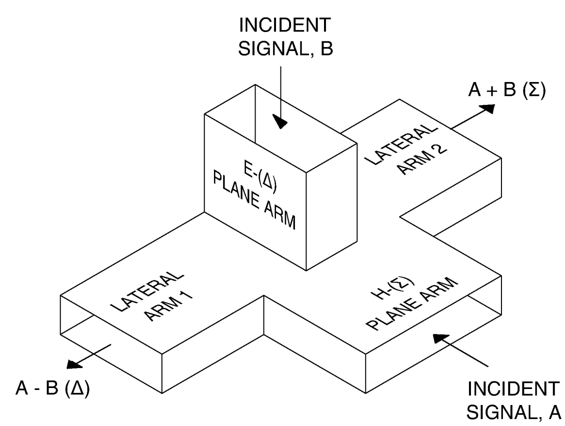


Figure 6. Combining two signals by feeding them into the H- and E-plane arms.

Another way of using hybrid tees for signal combining consists in feeding two in-phase signals into each lateral arm: the signals will add together in the H-plane arm, and subtract from each other in the E-plane arm. Therefore, the signal exiting the H-plane arm will be the vectorial sum (Σ) of the two signals, while the signal exiting the E-plane arm will be the vectorial difference (Δ) of the two signals.

Applications

Applications of the hybrid tee include, among others, power splitters, power combiners, monopulse radars, and single-ended mixers for millimetric waves.

Hybrid Tees

Figure 7 shows an application in which a hybrid tee is used to couple (mix) the signals at the front end of a radar receiver.

– The signal from the antenna is fed into the E-(Δ) plane arm;
– The signal from a local oscillator is fed into the H-(Σ) plane arm.

The signal exiting lateral arm 2 is the vectorial sum (Σ) of the antenna signal and local oscillator signal. This signal goes to the receiver input. Lateral arm 1, which is unused, is connected to a matching load to prevent reflections.

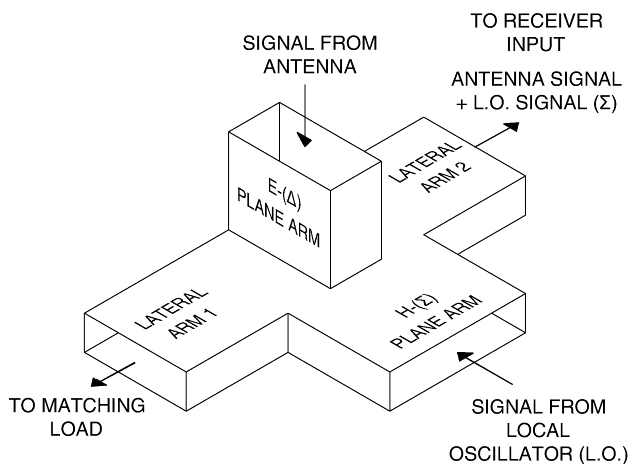


Figure 7. Hybrid tee used at the front end of a receiver mixer.

Figure 8 shows another application, in which four hybrid tees are used to determine the elevation and azimuth errors in a monopulse radar.

- The antenna has four feed horns: A, B, C, and D.
- The echo amplitude (Σ channel) is obtained by summing the four feeds.
- The azimuth error, Δ_A, is obtained by subtracting the sum of feeds C and D from the sum of feeds A and B.
- The elevation error, Δ_E, is obtained by adding the difference between feeds A and B to the difference between feeds C and D.

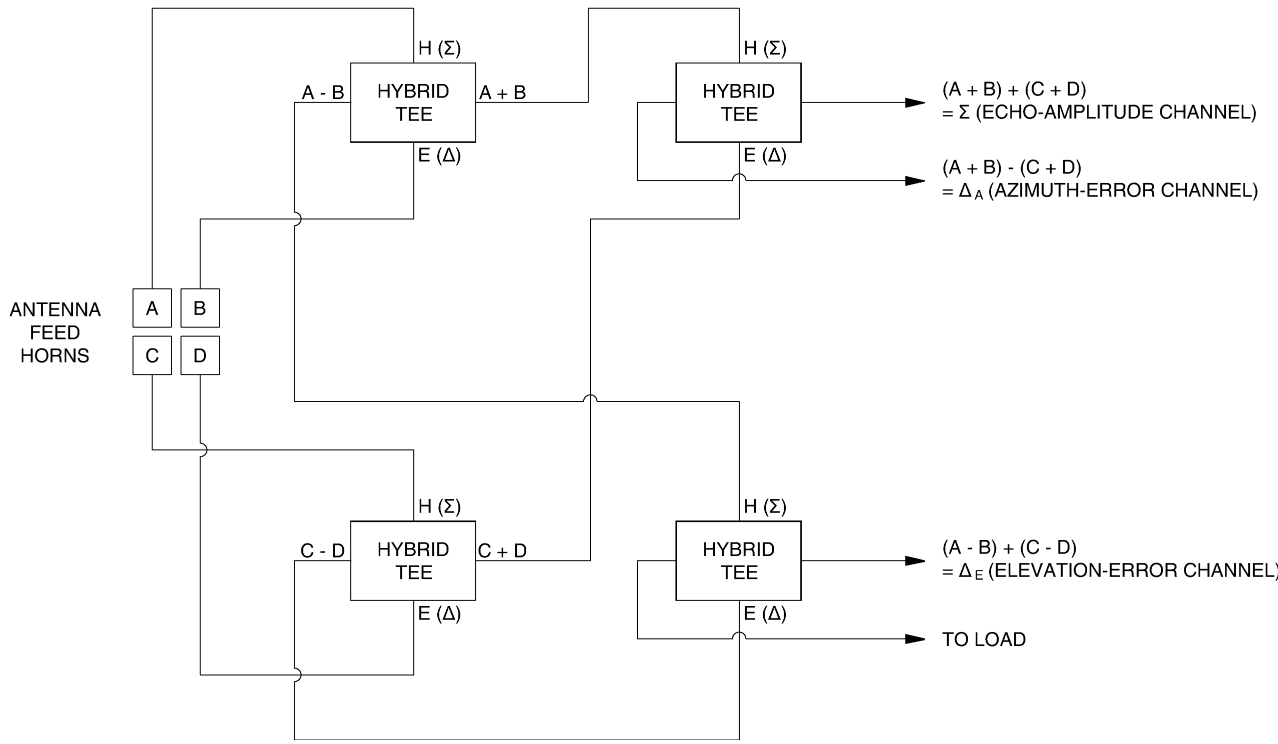


Figure 8. Four hybrid tees are used to determine the elevation and azimuth errors in a monopulse radar.

Procedure Summary

In the first part of this exercise, you will measure the attenuation of a microwave signal as it propagates through the H- and E-plane arms and the lateral arms of the Lab-Volt Hybrid Tee.

In the second part of the exercise, you will measure the isolation between the E- and H-plane arms of the Hybrid Tee.

In the third part of the exercise, you will verify that the signals propagating through the two branches connected to the E-plane arm are 180° out of phase.

In the last part of the exercise, you will measure the SWR in the Hybrid Tee when the E-plane arm is left unconnected. This will allow you to calculate the reflection loss and see why this loss causes the actual attenuation in the tee branches to be greater than 3 dB.

Hybrid Tees

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix F of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

System Setup

Setting the Maximum Power to 0 dBm

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as shown in Figure 9.

> **Note:** *Before connecting the Thermistor Mount, unscrew the matching screws so that they do not penetrate into the waveguide; the screws do not need to be removed from the posts).*

☐ 2. Make the following settings:

On the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . 1 kHz
METER SCALE . . . . 10 V

On the Variable Attenuator:

Blade Position . . . . 10 mm

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Set the Gunn Oscillator supply voltage to 8.5 V.

Wait for about 5 minutes to allow the modules to warm up.

☐ 4. Set the blade position of the Variable Attenuator to 2.5 mm approximately .

☐ 5. Once the SWR Meter has been tuned to obtain the maximum signal level, click on the REFERENCE button of the SWR Meter.

Setting the Reference on the SWR Meter

☐ 6. **Taking care not to modify the Variable Attenuator adjustment**, so as to keep this attenuator adjusted for an output power of 0 dBm, set up the modules and assemble the microwave components as shown in Figure 10.

In this setup, a 30-dB Fixed Attenuator is connected to the output of the Variable Attenuator, to limit the level of the signal incident to the Crystal Detector to -30 dBm.

Place the 60-dB Amplifier on the work surface instead of mounting it directly on the Crystal Detector. Get a BNC tee and connect it to the input of the 60-dB Amplifier. Then, connect the Crystal Detector to the BNC tee at the amplifier input. Connect the amplifier output to MULTI-FUNCTION INPUT 3 of the DAI.

☐ 7. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

Wait for about 5 minutes to allow the modules to warm up.

☐ 8. In LVDAM-MW, start the SWR Meter and set it to display decibels (dB).

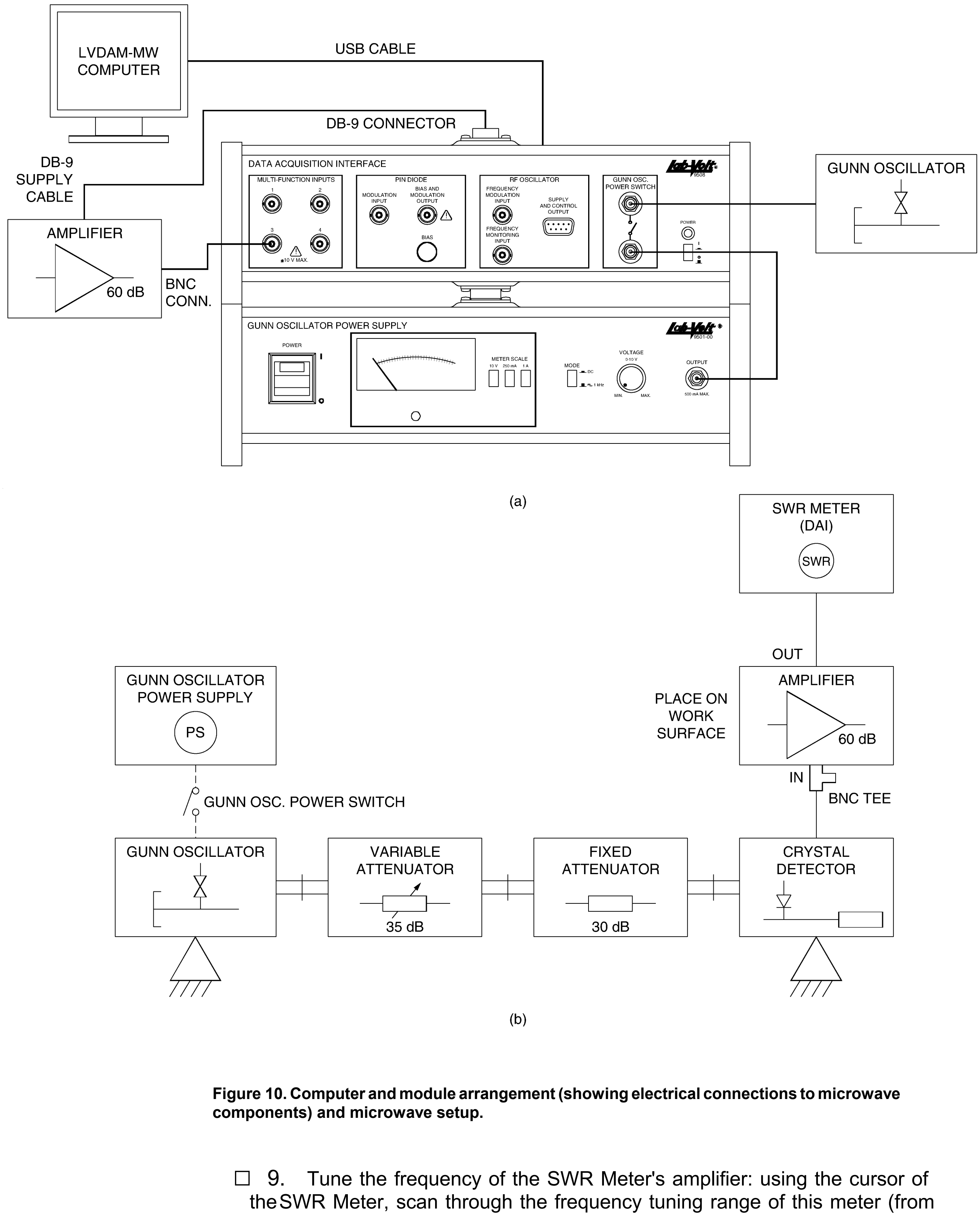


Figure 10. Computer and module arrangement (showing electrical connections to microwave components) and microwave setup.

☐ 9. Tune the frequency of the SWR Meter's amplifier: using the cursor of the SWR Meter, scan through the frequency tuning range of this meter (from 900 to 1100 Hz) to find the frequency at which the Signal Level (indicated as a percentage below the horizontal bar of the meter) is maximum. Set the cursor to this frequency.

> **Note:** *If the signal level indicated by the SWR Meter stays null or too low (below 10% of full scale, with a blue indicator bar or no bar displayed) while trying to tune the SWR Meter, increase Gain Input 3 to 20 dB in order to obtain a significant signal level on the SWR Meter (that is, a signal level of 10% of full scale or higher, and a green horizontal bar). Then, tune the meter frequency in order to obtain the maximum signal level on this meter.*
>
> *Conversely, too high a gain causes the SWR Meter's indicator bar to be fully red. If the meter indicator bar stays fully red when Gain Input 3 is set to 0 dB, remove the 60-dB Amplifier from the microwave circuit, and connect the Crystal Detector output directly to MULTI-FUNCTION INPUT 3 of the DAI. Then, set the field 60 dB Ampli on Input 3 to OFF and Gain Input 3 to the proper value (40 dB) in order to be able to tune the meter frequency and obtain the maximum signal level on this meter.*

☐ 10. Once the SWR Meter has been tuned to obtain the maximum signal level, click on the REFERENCE button of the SWR Meter.

The SWR Meter's reference corresponds to a signal level of -30 dBm approximately.

DO NOT modify the reference of the SWR Meter for the rest of the exercise.

Attenuation Between the H-Plane Arm and Lateral Arm 1

☐ 11. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF. Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 11.

Leave the rest of the equipment connected as before.

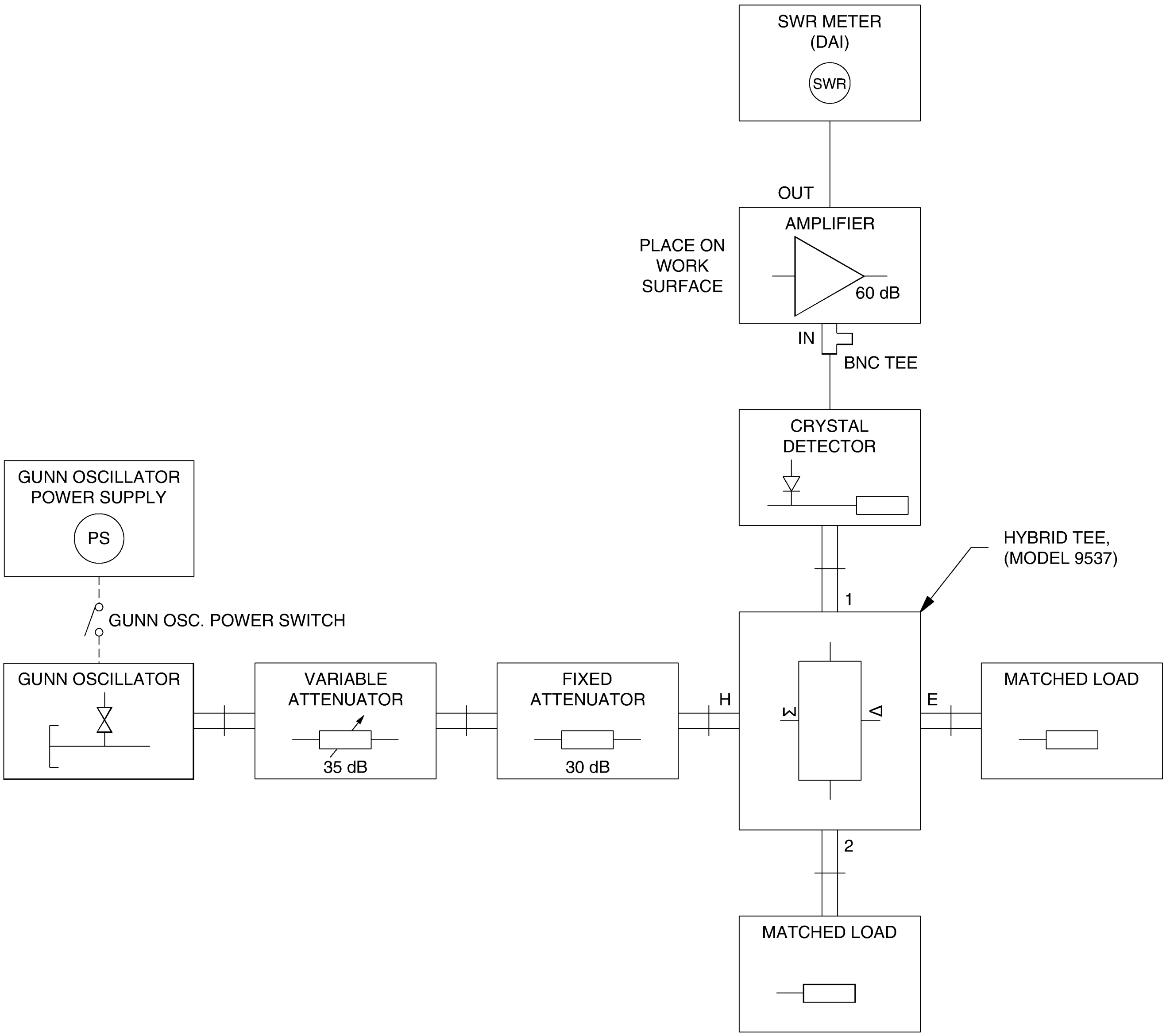


Figure 11. Setup used to measure the attenuation between the H-plane arm and lateral arm 1.

☐ 12. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Output Power to ON.

Wait for about 5 minutes to allow the modules to warm up.

☐ 13. The SWR Meter reading (absolute value) corresponds to the attenuation in signal level between the H-plane arm and lateral arm 1 of the Hybrid Tee, "**H→1**". Record this attenuation in the proper row of Table 1.

(If the SWR Meter reading is too low, DO NOT modify the reference of this meter. Instead increase Gain Input 3).

TEE BRANCH	SWR METER READING (ABSOLUTE VALUE) = ATTENUATION (dB)
H-PLANE ARM → LATERAL ARM 1 (H→1)	
H-PLANE ARM → LATERAL ARM 2 (H→2)	
E-PLANE ARM → LATERAL ARM 1 (E→1)	
E-PLANE ARM → LATERAL ARM 2 (E→2)	

Table 1. Attenuation measured between the H- and E-plane arms and the lateral arms of the Hybrid Tee.

Attenuation Between the H-Plane Arm and Lateral Arm 2

☐ 14. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.
Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 12.
Leave the rest of the equipment connected as before.

☐ 15. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Output Power to ON.

Wait for about 5 minutes to allow the modules to warm up.

☐ 16. The SWR Meter reading (absolute value) corresponds to the attenuation in signal level between the H-plane arm and lateral arm 2 of the Hybrid Tee, "**H→2**". Record this attenuation in the proper row of Table 1.

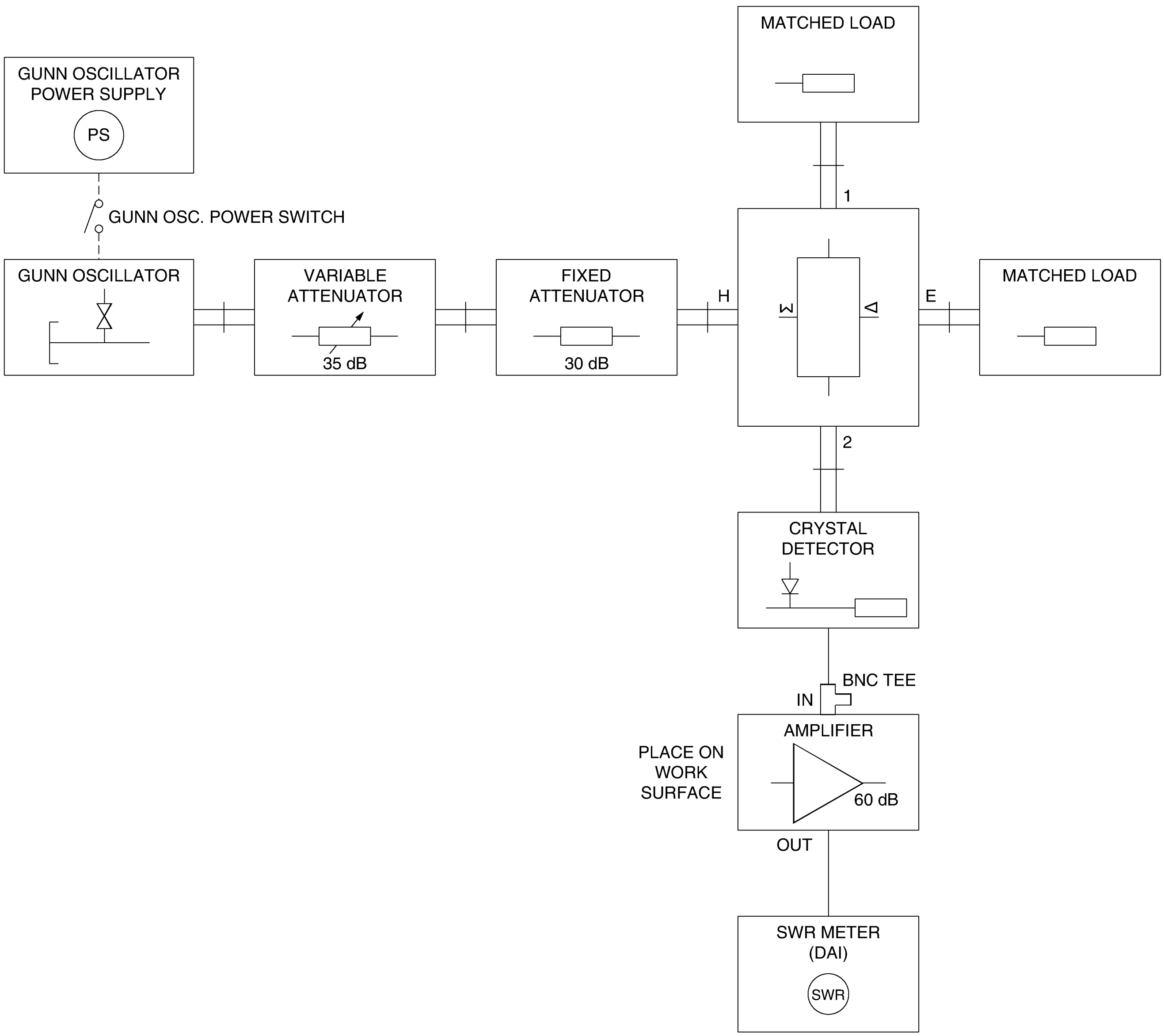


Figure 12. Setup used to measure the attenuation between the H-plane arm and lateral arm 2.

Attenuation Between the E-Plane Arm and Lateral Arm 1

☐ 17. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.

Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 13.

Leave the rest of the equipment connected as before.

Hybrid Tees

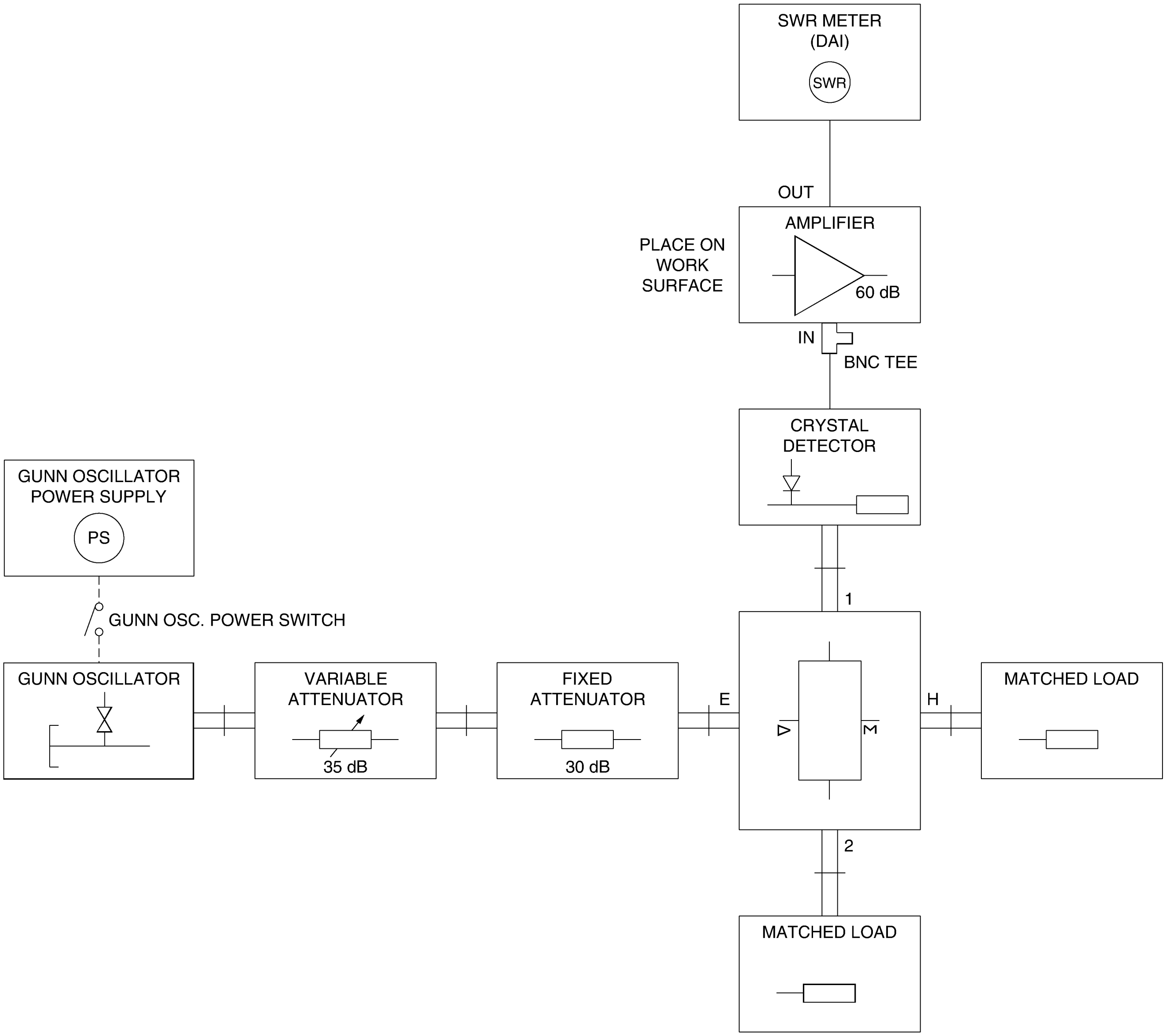


Figure 13. Setup used to measure the attenuation between the E-plane arm and lateral arm 1.

☐ 18. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Output Power to ON.

Wait for about 5 minutes to allow the modules to warm up.

☐ 19. The SWR Meter reading (absolute value) corresponds to the attenuation in signal level between the E-plane arm and lateral arm 1 of the Hybrid Tee, "**E→1**". Record this attenuation in the proper row of Table 1.

Attenuation Between the E-Plane Arm and Lateral Arm 2

☐ 20. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.

Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 14.

Leave the rest of the equipment connected as before.

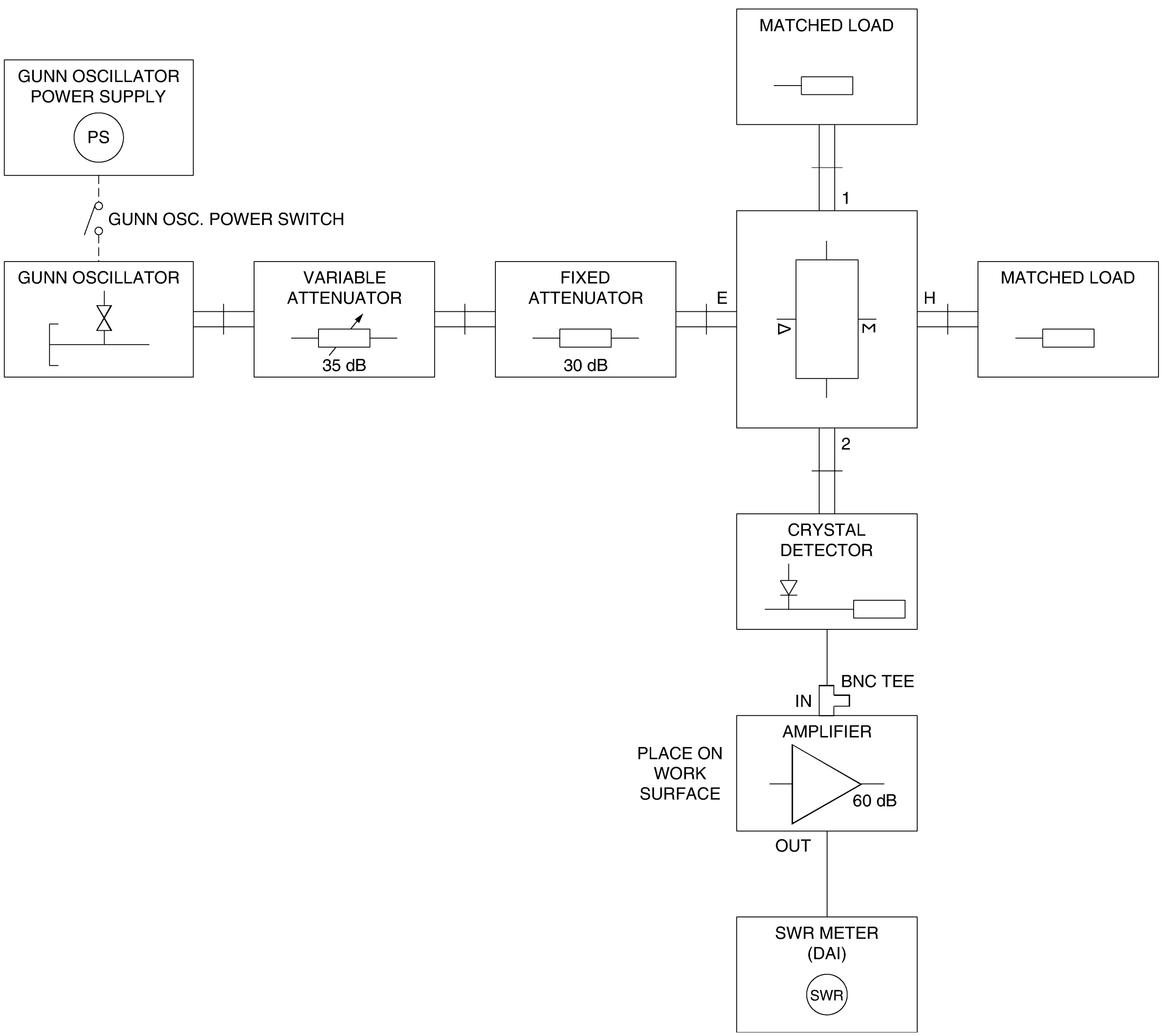


Figure 14. Setup used to measure the attenuation between the E-plane arm and lateral arm 2.

☐ 21. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Output Power to ON.

Wait for about 5 minutes to allow the modules to warm up.

☐ 22. The SWR Meter reading (absolute value) corresponds to the attenuation in signal level between the E-plane arm and lateral arm 2 of the Hybrid Tee, "**E→2**". Record this attenuation in the proper row of Table 1.

☐ 23. Examine the results recorded in Table 1.

Are the attenuations measured in each of the four branches greater than the theoretical figure of 3 dB? Why?

____

____

____

In Table 1, observe that the attenuations through branches **(H→1)** and **(H→2)** are approximately equal.

Also, observe that the attenuations through branches **(E→1)** and **(E→2)** are approximately equal (though not necessarily the same as for the H branches). Does this indicate symmetry of the electrical field about the midplane of the tee in both the E- and H-plane arms? Explain.

____

____

____

Measuring the Isolation Between the E- and H-Plane Arms of the Hybrid Tee

Note: *In this section of the exercise, the 30-dB Fixed Attenuator will not be present in the microwave circuits to allow you to measure very small power levels. Since the reference of the SWR Meter was set with this attenuator present in the circuit, you will have to subtract 30 dB from the SWR Meter reading to account for the removal of this attenuator.*

Isolation Between the E-Plane Arm and the H-Plane Arm (E→H)

☐ 24. In the Settings panel of LVDAM-MW, set the field

GunnOscillator/VCO Power to OFF.

Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 15.

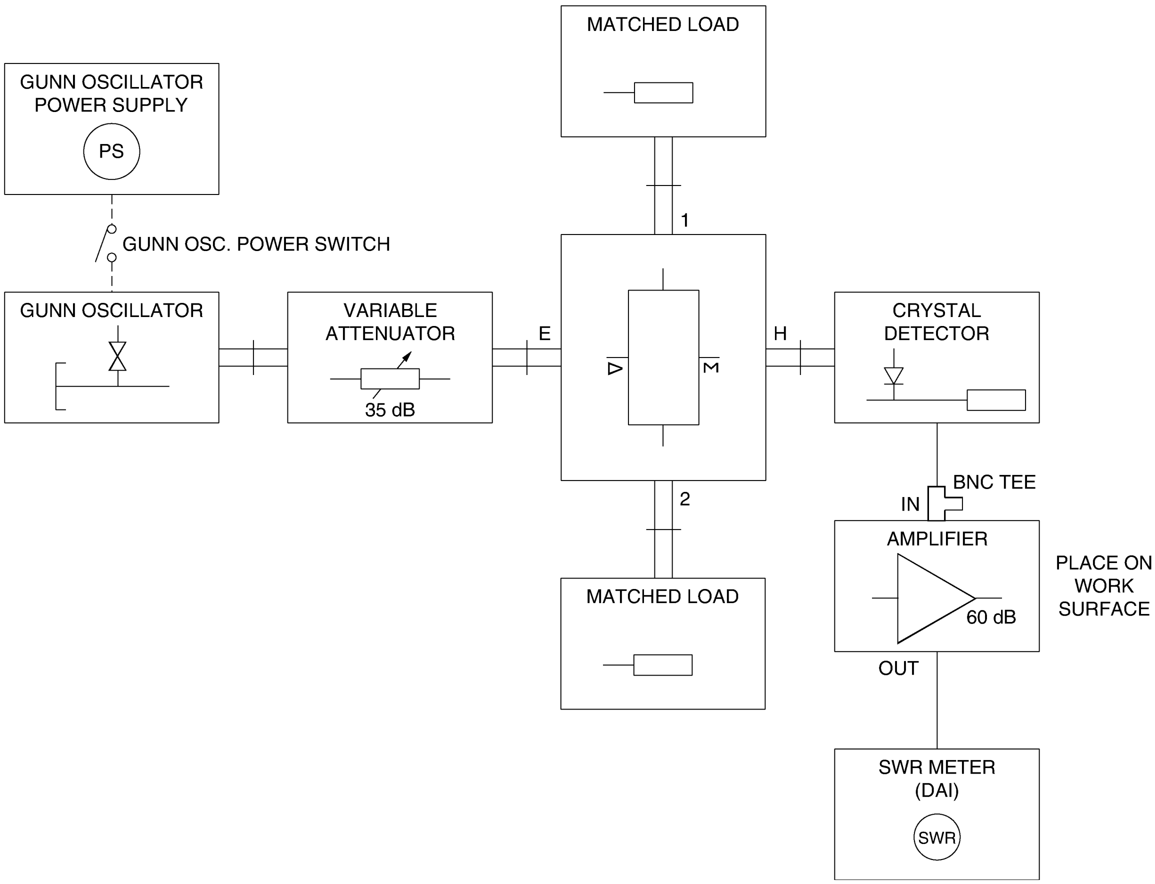


Figure 15. Setup used to measure the attenuation between the E-plane arm and the H-plane arm (E→H).

☐ 25. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Gain Input 3 . . . . 20 dB

Wait for about 5 minutes to allow the modules to warm up.

☐ 26. Record the SWR Meter reading (absolute value) below. If this reading is too low, set Gain Input 3 to 40 dB.

SWR Meter reading: ______ dB

Subtract 30 dB from the SWR Meter reading (to account for the removal of the 30-dB Fixed Attenuator). The result corresponds to the isolation between the E-plane arm and the H-plane arm.

E-PLANE ARM → H-PLANE ARM isolation, (E→H) =

SWR Meter reading - 30 dB = ______ dB

Isolation Between the H-Plane Arm and the E-plane Arm (H→E)

☐ 27. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.
Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 16.

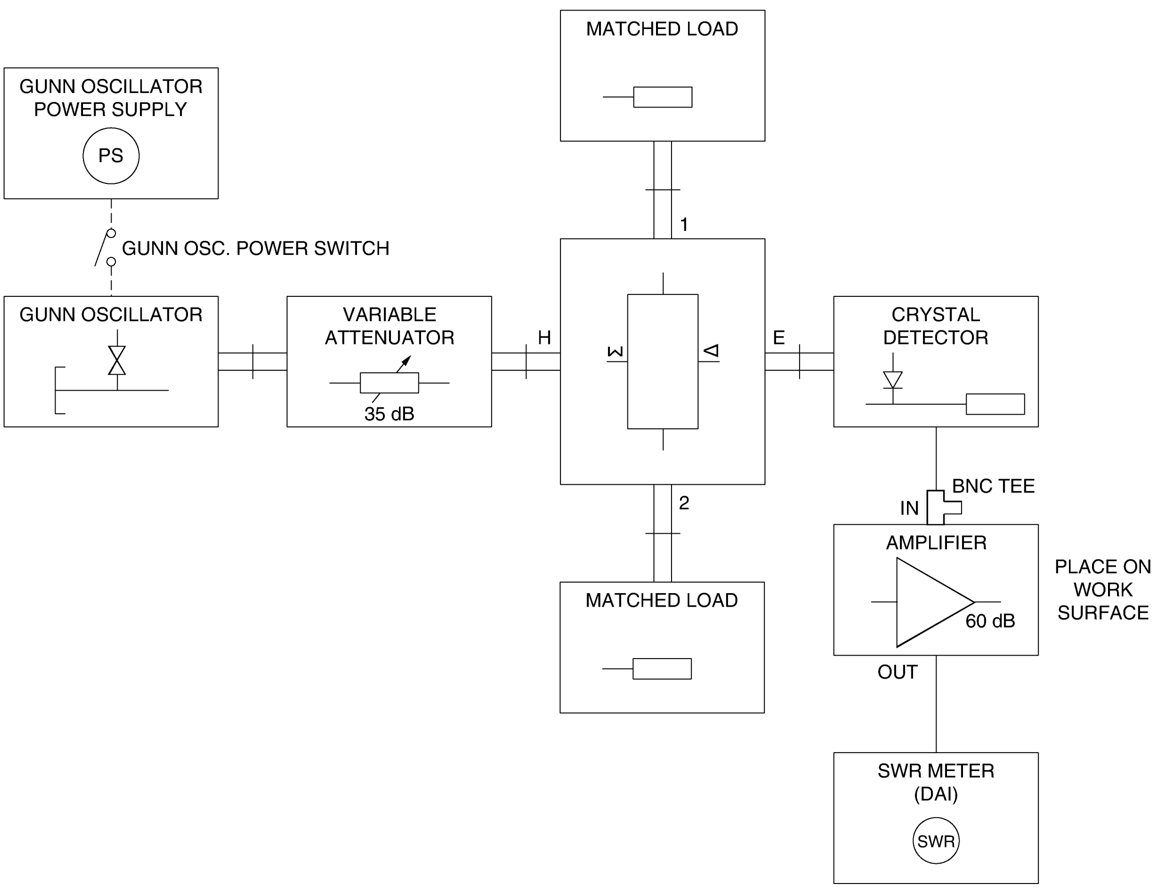


Figure 16. Setup used to measure the attenuation between the H-plane arm and the E-plane arm (H→E).

☐ 28. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Gain Input 3 . . . . 20 dB

Wait for about 5 minutes to allow the modules to warm up.

☐ 29. Record below the SWR Meter reading (absolute value). If this reading is too low, set Gain Input 3 to 40 dB.

SWR Meter reading: ______ dB

Subtract 30 dB from the SWR Meter reading. The result corresponds to the isolation between the H-plane arm and the E-plane arm.

H-PLANE ARM → E-PLANE ARM isolation, (H→E) =

SWR Meter reading - 30 dB = ______ dB

180*E* Phase Difference Verification

☐ 30. In the Settings panel of LVDAM-MW, set the field GunnOscillator/VCO Power to OFF. Taking carenottomodifytheVariableAttenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 17.

☐ 31. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Gain Input 3 . . . . 40 dB

Wait for about 5 minutes to allow the modules to warm up.

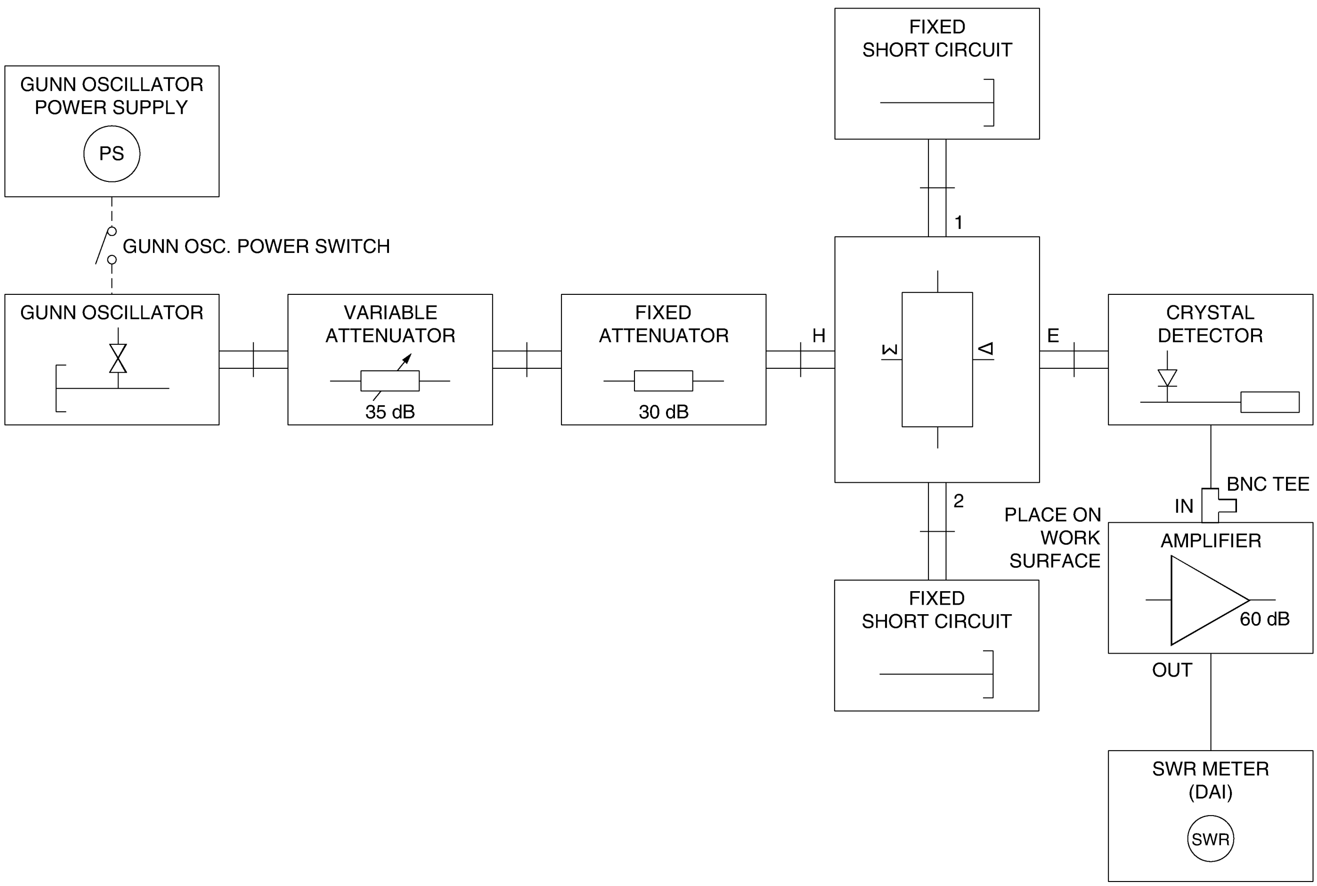


Figure 17. Setup used to verify that the signals propagating through the two branches of the E-plane arm (branches E→1 and E→2) are 180° out of phase, so that they cancel themselves out.

☐ 32. On the SWR Meter, observe that the E-plane arm signal level is very low. In fact, the signal level might be below the minimum measurable level.

This occurs because when the two split signals from the H-plane arm reach the short-circuits at arms 1 and 2, they are reflected back into these arms.

They then propagate into the E-plane arm. The phase of the signal propagating through branch E→1 stays unchanged. However, the phase of the signal propagating through branch E→2 is shifted by 180°.

These signals therefore have a relative phase difference of about 180° when they reach the E-plane arm, so that they practically cancel themselves out.

Record your observations below.

Calculating the Reflection Loss from the Measured SWR

☐ 33. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.
Taking care not to modify the Variable Attenuator adjustment, so as to keep this attenuator adjusted for an output power of 0 dBm, modify your microwave circuit in order to obtain the circuit shown in Figure 20.

☐ 34. Move the probe of the Slotted Line along the waveguide and locate it over the 45-mm position. (The 45-mm mark on the waveguide scale intersects the 0-mm (rightmost) mark on the carriage scale).

☐ 35. On the Slotted Line, loosen the thumbscrew of the sliding carriage and adjust the depth of the Slotted Line's probe to approximately 1/3 of maximum (the Slotted Line's pointer must be aligned with the second lowermost mark approximately), then tighten the thumbscrew.

☐ 36. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

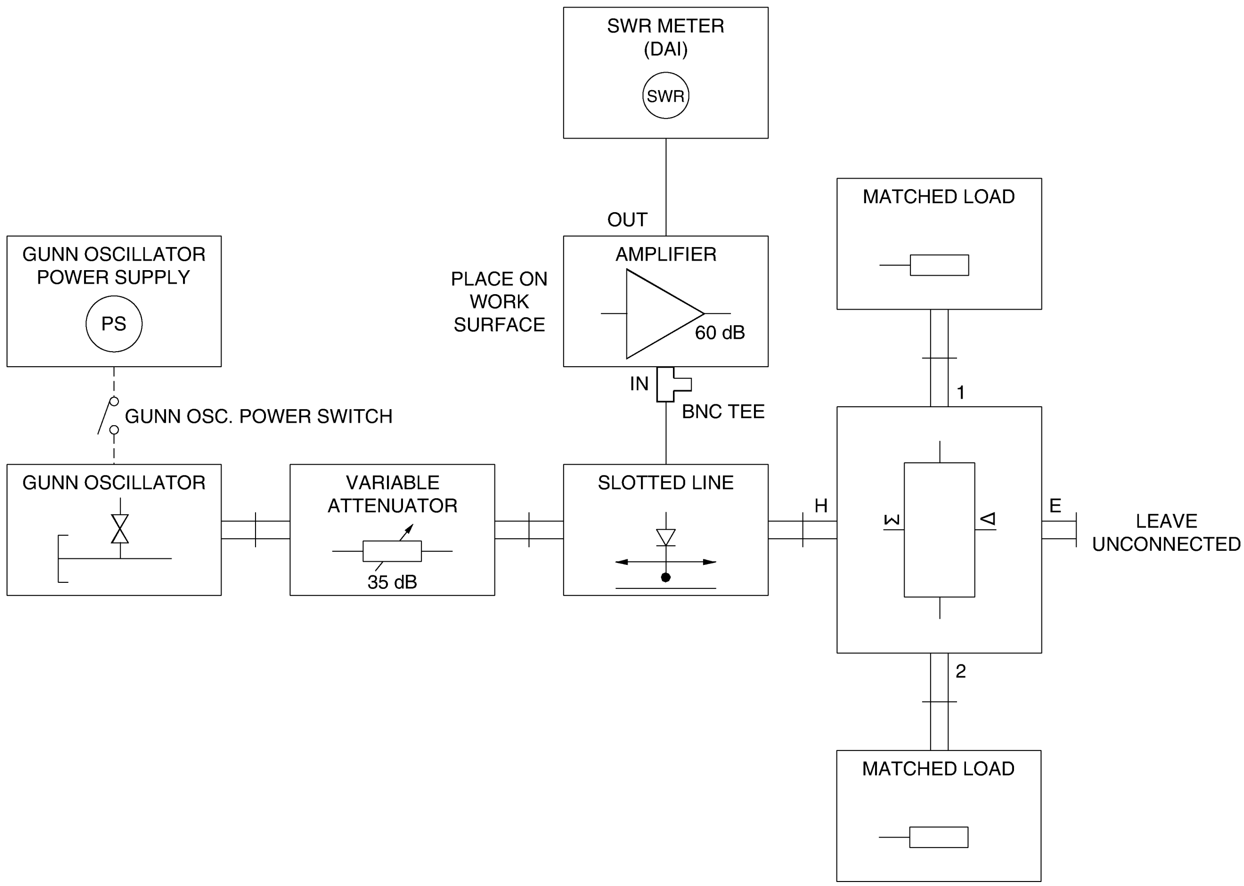


Figure 18. Setup used to measure the SWR and calculate the reflection loss.

☐ 37. With the SWR Meter to display decibels (dB), tune the frequency of this meter: using the cursor of the SWR Meter, scan through the frequency tuning range of this meter (from 900 to 1100 Hz) to find the frequency at which the signal level (indicated as a percentage below the horizontal indicator bar of the meter) is maximum (DO NOT modify the Variable Attenuator's adjustment).

a. If the maximum signal level obtained on the SWR Meter is between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 38

> **Note:** *To obtain the maximum dynamic range of measurement on the SWR Meter (once its amplifier has been tuned), a maximum level between 70 and 90% on the SWR Meter with Gain Input 3 set to 0 dB is ideal.*

b. If you are unable to tune the SWR Meter's amplifier because the maximum signal level exceeds the measurement scale (the horizontal indicator bar of the meter turns to red), loosen the thumbscrew of the Slotted Line. Readjust the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (a signal level of, for example, about 25% of full scale, once the thumbscrew of the Slotted

Line has been re-tightened since its tightening will cause the signal level to change slightly). Then, tune the frequency of the SWR Meter to obtain the maximum signal level on this meter. If this level is not between 70 and 90% of full scale, very slightly readjust the depth of the Slotted Line's probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar never turns from green to red) once the thumbscrew of the Slotted Line has been re-tightened.

c. If the maximum signal level obtained on the SWR Meter is between 10 and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

☐ **38**. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ **39**. Locate the Slotted Line's probe over the minimum nearest the load. This may require you to increase Gain Input 3.

Then, set the SWR Meter to display the SWR as a dimensionless number (linear scale). Record the SWR Meter reading below.

SWR = ______

☐ **40**. Based on the SWR, calculate the magnitude of the coefficient of reflection, ρ.

$$\rho = \frac{SWR - 1}{SWR + 1}$$

____

☐ **41**. Using the formula below and the coefficient of reflection obtained in the previous step, calculate the reflection (mismatch) loss at the load.

This loss is caused by the fact that the impedance matching at the junction of the tee is not perfect, resulting in reflection losses within the tee.

$$\text{Reflection Loss} = 10 \log (1 - |\rho^2|)$$

____

____

☐ 42. Given a theoretical attenuation of 3 dB, calculate the actual attenuation in each branch, based on the reflection loss measured in the previous step:

$$\text{Actual Attenuation}_{(dB)} = |\text{Reflection Loss}_{(dB)}| - 3\text{ dB}$$

Your result should be approximately equal to the attenuations measured for each tee branch, as recorded in Table 10-1. Is this what you observe? Explain.

____

____

____

☐ 43. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 44. Close the LVDAM-MW software.

CONCLUSION

In this exercise, you were introduced to waveguide tees. You learned that these tees come in two forms: the H-plane tee, which is in the plane of the magnetic field, and the E-plane tee, which is in the plane of the electric field.

You learned that the hybrid tee is a junction of the H-plane tee and the E-plane tee. In the dominant mode of propagation (mode TE_{10}), a microwave signal applied to the H-plane arm or E-plane arm will produce an electrical field (E-field) that is symmetrical about the midplane of the tee.

You saw that hybrid tees can be used to split a microwave signal. The incident signal can be fed into the H-(Σ) plane arm or E-(Δ) plane arm. If fed into the H-plane arm, the signal divides into two signals that exit the tee via the lateral arms, in phase with each other; no signal propagates into the E-plane arm. If fed into the E-plane arm, the signal divides into two signals that exit the tee via the lateral arms, 180° out of phase. No signal propagates into the H-plane arm.

Hybrid tees are also used to combine signals into a single signal. The two signals to couple are simultaneously fed into the H- and E-plane arms. The signal exiting a lateral arm is the vectorial sum of the two signals. The signal exiting the other lateral arm is the vectorial difference of the two signals.

You learned that the attenuation of signals propagating through a branch of the tee is greater than the theoretical figure of 3 dB, and the isolation between the H- and E-plane arm is not infinite.

Finally, you learned that hybrid tees are used in numerous microwave applications, including power splitters, power combiners, monopulse radars, and single-ended mixers for millimetric waves.

Hybrid Tees

REVIEW QUESTIONS

1. Explain what the difference is between a H-plane tee and a E-plane tee.

2. Briefly describe the construction of a hybrid tee.

3. How can a hybrid tee be used to split a microwave signal into two equal signals 180° out of phase? Explain.

4. How can a hybrid tee be used to combine two microwave signals? Briefly describe the signals exiting the two lateral arms when combining is performed.

5. State two microwave applications in which hybrid tees are used, and briefly describe each of them.

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 9 Patch Antennas

Exercise 1

Microstrip Technology: The Rectangular Patch Antenna

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the patch antenna and with the microstrip technology used to implement patch antennas.

DISCUSSION

Microstrip antenna technology

A **microstrip antenna** consists of a patch of conductive material, typically rectangular or circular, separated from a ground plane by a thin (fraction of a wavelength) layer or substrate of dielectric material. The microstrip is well suited for low-profile and conformal antennas. It also has the advantages of low cost and light weight, ease of fabrication and of installation, but its design is not always straightforward.

Figures 1 and 2 illustrate typical rectangular and circular patch microstrip antennas. They are essentially a printed circuit board with the antenna patch etched on one side and a ground plane on the other side. Figure 1 shows a rectangular patch in which the RF signal is fed through a feed line that consists of a narrow metal strip. Figure 2 illustrates a circular patch, fed by a conductor through a hole in the ground plane. It is also possible to feed the signal by "aperture coupling" through a small aperture in the ground plane.

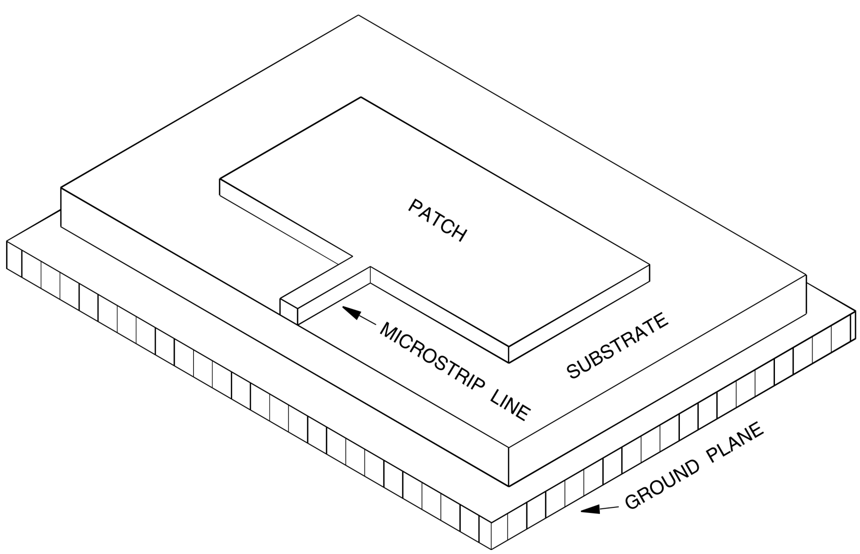


Figure 1. Microstrip patch with microstrip transmission-line feed

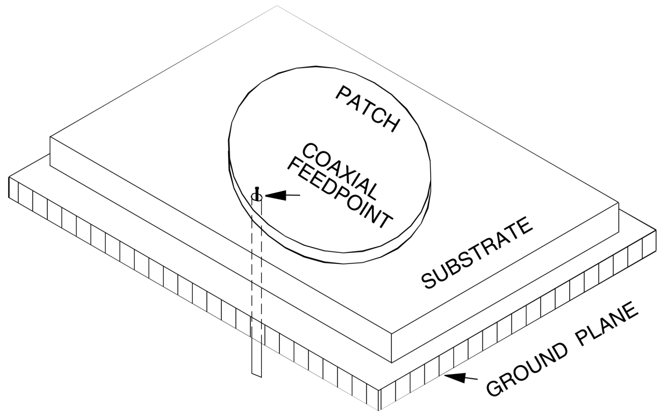


Figure 2. Circular microstrip patch with coaxial feedpoint

For microstrip antennas, the precision of the dielectric constant of the substrate is of utmost importance—it is the most important parameter affecting the propagation constant in the material, and hence the resonant frequency and the radiation characteristics of the antenna.

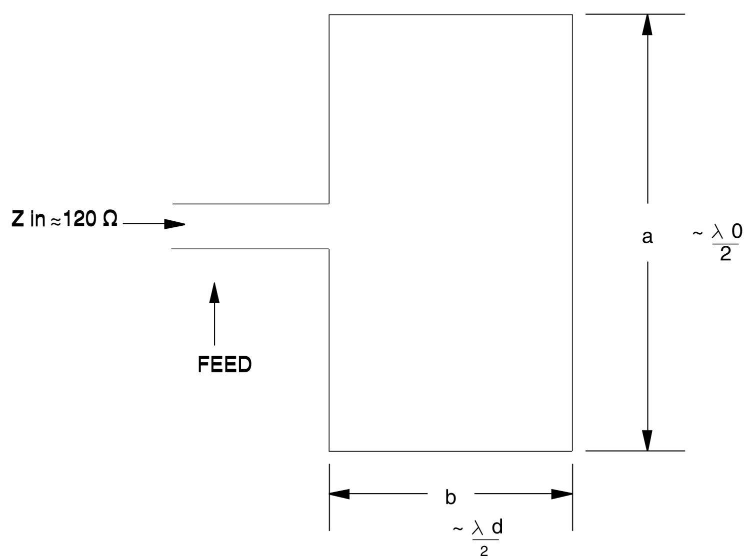


Figure 3. A basic rectangular microstrip antenna

The Rectangular Patch Antenna

Characteristics of a rectangular patch

Figure 3 gives the basic dimensions of a rectangular microstrip patch antenna. The conductance of the antenna is a function of the width *a*, whereas the resonant frequency is a function of the length *b*. The length *b* is given by

$$b \approx 0.49\lambda_d = 0.49\frac{\lambda_0}{\sqrt{\epsilon_r}} \qquad (1)$$

where λ_d is the wavelength in the dielectric
λ_0 is the free-space wavelength
ϵ_r is the relative dielectric constant of the substrate

Because of variations in the dielectric constant and the feed inductance, tests are usually required to determine the exact length of the patch.

Figure 4 shows the electric current and the predominant electric field configuration in and around the patch.

It is essentially the electric fields on the patch edge to which the feed is connected, and on the opposite edge, which contribute to the radiating characteristics of the antenna.

Theradiatedwavefromtheantennain Figure 4 has a horizontal polarization, that is, the E-plane (plane x-y) is in the horizontal direction and the H-plane (plane y-z) is vertical.

The separation b between the two edges of the patch corresponds to approximately one half wavelength in the dielectric ($0.49\lambda_d$). This causes the opposing slots to be excited out of phase. However, the two parallel radiating electric fields add in-phase in the direction normal to the elements (broadside, or y direction).

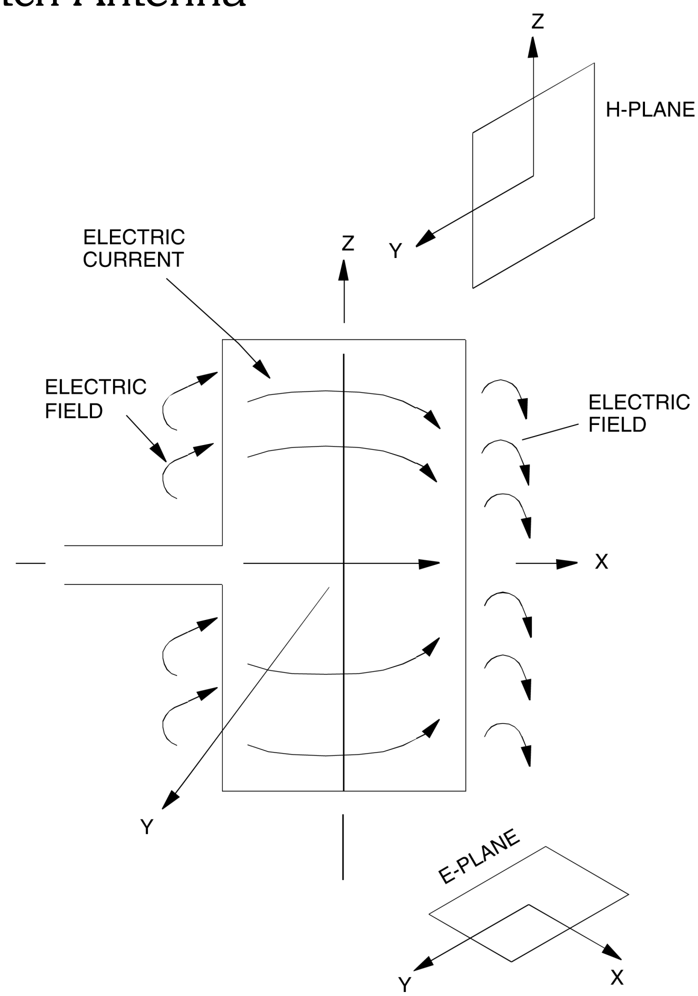


Figure 4. Electric current and predominant electric field configuration

Radiation pattern for an array of two waveguide slots

A useful analogy, which allows calculating with precision the characteristics of rectangular patch antennas, is to compare the patch antenna of Figure 3 to a two-slot waveguide slot antenna, as shown in Figure 5.

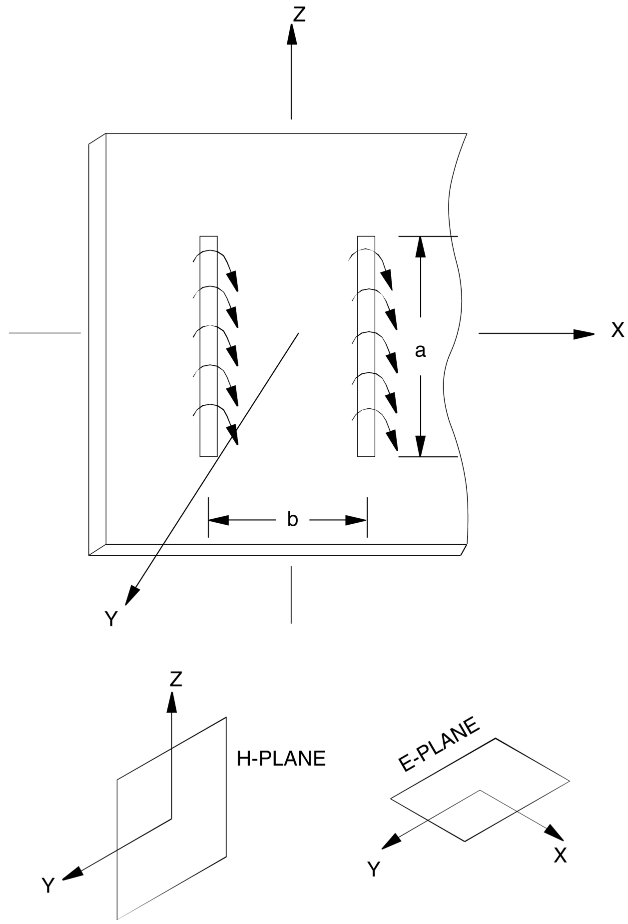


Figure 5. Two parallel slots in a waveguide

Since the two-slot waveguide antenna shown in Figure 5 is essentially equivalent to the patch antenna in Figure 3, the radiation patterns of the two antennas will be the same.

In order to understand the radiation pattern of the two-slot waveguide antenna, it is important to remember that the distance b has been chosen so that the electric fields radiated from both slots are in phase. The situation is then as illustrated in Figure 6. At any point on the y axis, the distance from each slot is identical. Therefore the fields from the two slots add up in phase in the far field, giving maximum radiation. In other directions, the distances from the two slots are unequal, so the fields do not add up perfectly in phase. For this reason, the radiation pattern will show a main lobe with a maximum in the direction of the y-axis.

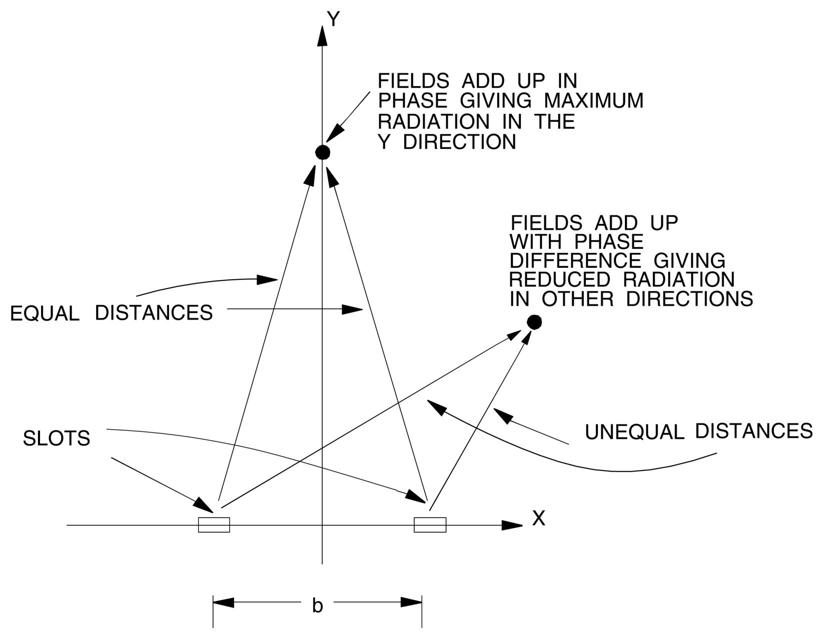


Figure 6. Explanation of the E-plane far-field radiation pattern from a rectangular patch

Figure 7 shows a three-dimensional representation of one slot. The axes and the angles ϕ and θ in this figure serve as references for the subsequent equations.

The dimension *a* and *b* in Equation (2) and (3) correspond to the width *a* and the length *b* of the patch in Figure 3. The slot width *h* in Figure 7 corresponds to the thickness of the dielectric substrate which separates the patch from the ground plane (see Figure 9 and 10).

The E-plane radiation pattern for two slots excited in phase with equal amplitudes is given by the equation

$$F_{patch}(\phi) = \frac{\sin\left(\frac{\beta h}{2}\cos\phi\right)}{\frac{\beta h}{2}\cos\phi}\cos\left(\frac{\beta b}{2}\cos\phi\right) \qquad (2)$$

where h is the slot width (equal to the thickness of the dielectric substrate of the equivalent patch antenna)

b is the separation between two slots (equal to the length of the patch antenna)

$$\beta = \frac{2\pi}{\lambda}$$

The Rectangular Patch Antenna

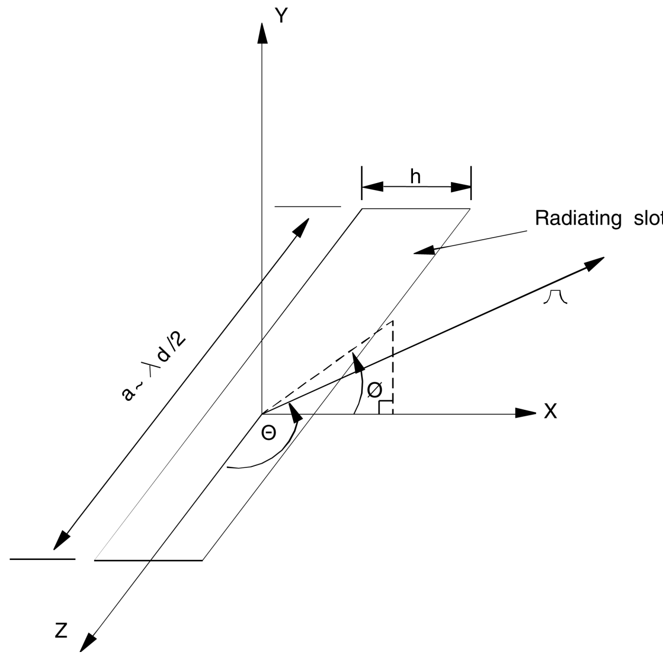


Figure 7. Geometry for calculating the E- and H-plane radiation patterns of a radiating slot

The H-plane pattern is given by

$$F_{patch}(\theta) = \frac{\sin\left(\frac{\beta a}{2}\cos\theta\right)}{\frac{\beta a}{2}\cos\theta}\sin\theta \qquad (3)$$

where a is the length of the slots.

The theoretical E- and H-plane patterns are shown in Figure 8.

Microstrip antenna impedance

The input impedance of the two-slot array, and of the λ/2 rectangular patch it represents, is resistive so it has good radiation properties. The input resistance is approximately given by

$$R_{in} \approx \frac{60\cdot\lambda_0}{a} = \frac{60\cdot\lambda_0}{\lambda_0/2} = 120\ \Omega \qquad (4)$$

where a is the slot length
λ_0 is the free-space wavelength

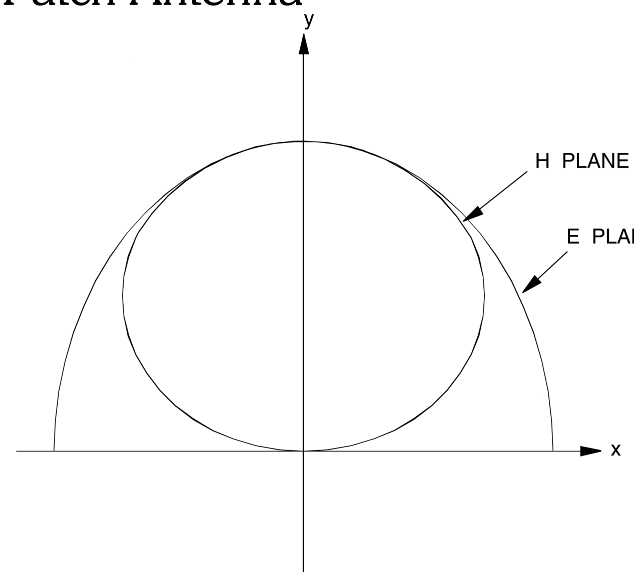


Figure 8. Theoretical E- and H-plane radiation patterns for two slots excited in phase with equal amplitudes ($b = \lambda_d/2$, where $\lambda_d < \lambda$)

Ideally, since the input impedance of the patch is around 120 Ω, the impedance of the microstrip feed line and of the coaxial cable connection should also be 120 Ω.

However, in order to connect to the 50-Ω coaxial cable used in the Antenna Training and Measuring System, a 50-Ω microstrip line is used.

To match the impedance between the 50-Ω microstrip line and the 120-Ω patch, a stub of length λ/4 is used (see Figure 9). Using a quarter-wavelength stub is a simple technique to obtain good impedance matching in a narrow frequency band. The equation relating the impedance Z_1 and Z_2 to be matched and the impedance Z_L of the quarter-wave stub is

$$Z_L = \sqrt{Z_1 Z_2} \tag{5}$$

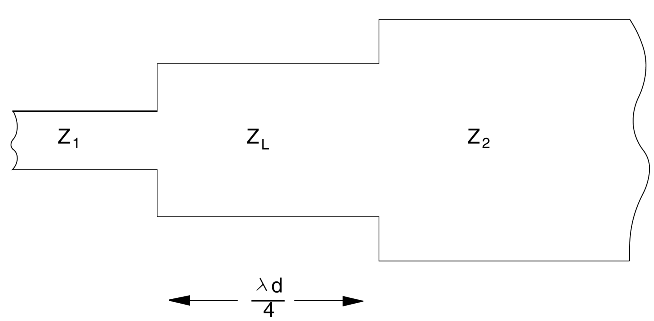


Figure 9. A quarter-wave stub of impedance Z_L for matching impedances Z_1 and Z_2

The Rectangular Patch Antenna

If Z_1 is a coaxial cable or microstrip line of 50-Ω impedance, and if Z_2 is a rectangular microstrip patch of 120-Ω impedance, the impedance of the short quarter-wave line connecting the microstrip line and the patch should be

$$Z_L = \sqrt{Z_1 Z_2} = \sqrt{(50)(120)} = 78\,\Omega \tag{6}$$

Figure 10 illustrates the layout of the single patch antenna included in the Antenna Training and Measuring System, and shows the 78-Ω quarter-wave stub.

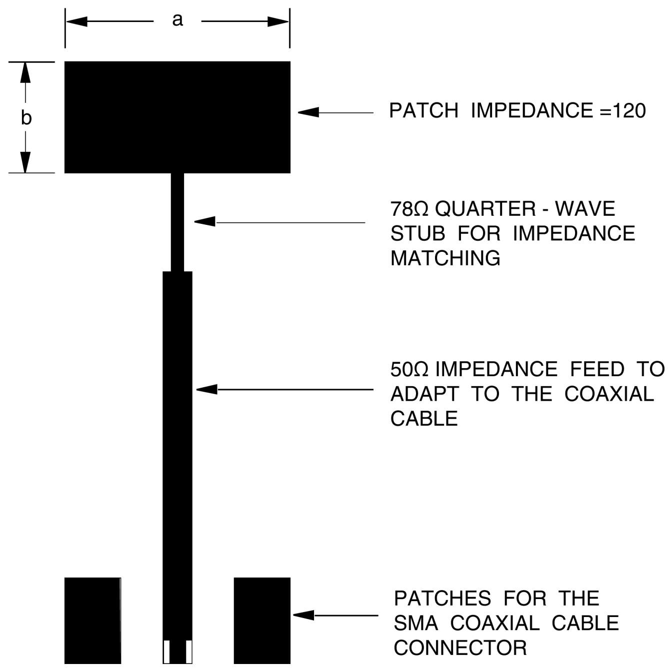


Figure 10. Single patch antenna in the Antenna Training and Measuring System.

Dielectric materials used for antenna protection and strengthening

Antennas sometimes require protection or strengthening. Depending on the type of antenna and requirements of the application, various materials can be used to accomplish this. Radomes, for example, require the use of materials which offer high strength while allowing efficient transmission of the RF signals.

In other situations, excellent transparency to electromagnetic waves is essential, but the physical solidity may be less critical. Styrofoam, for example, is well suited for strengthening the base of the 10 GHz helical antenna because of its great transparency to RF signals, despite its lack of solidity.

When selecting a material for antenna protection or strengthening, one must take into account the dielectric constant of the material and its loss tangent as a function of frequency, and its density. The choice of material is made to ensure optimal performance while providing adequate protection. A table of various materials and their dielectric constants is shown in Table 1.

MATERIAL	DIELECTRIC CONSTANT
Porcelain	4,74
E glass	6,11
Water (room temperature)	80
Styrofoam 103.7	1,03
Bakelite	3,52
Duroid 5650	2,65
Epoxy resin RN-48	2,91
Fiberglass, laminated BK-174	4,37
Lexan	2,86
Plexiglass	2,59
Teflon	2,08

Table 1. Dielectric constants of various materials (f = 10 GHz)

In certain cases, reflections may modify the behaviour of the protective material. Depending on the distance between the protective material and the antenna, reflections may occur in such a way that the received signal is either partially cancelled or amplified, depending on the relative phases of the signal and the reflections.

Procedure Summary

In this exercise you will evaluate the HPBW and the gain of a rectangular patch antenna. You will observe the influence of the patch's dimensions on antenna performance. Finally, you will see how the presence of a radome affects the radiation pattern of an antenna.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Insert the antenna mast with locking ring into the transmission support. Couple a large horn antenna to a waveguide-to-coax adapter. Using the plastic holder, install the antenna on the mast, so it is vertically polarized.

☐ 3. Place the other mast with locking ring on the sliding support of the Antenna Positioner. Install the small horn antenna on this mast, oriented to rotate in the H-plane and in line with the rotation centre of the Antenna Positioner.

☐ 4. Position the antennas a distance of r = 1.5 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 5. Make the following adjustments:

On the RF Generator

10 GHz OSCILLATOR MODE . . . . 1 kHz
10 GHz OSCILLATOR RF POWER . . . . OFF
1 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Gain and HPBW of a rectangular patch antenna

☐ 6. Set the 10 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

CAUTION!

For your own safety, never look directly into the horn antenna while the RF POWER switch is ON.

☐ 7. Using the Attenuation control, optimize the reception of the signal (you should maintain this attenuation level throughout the exercise). Start your first acquisition and store the radiation pattern in a new document (Document1).

☐ 8. Remove the receiving antenna, then replace the mast with locking ring with the mast that has vertical clips.

Join the supplied short post to the screw-on 90° adapter, as shown in Figure 11. Attach the clip-on holder to the single rectangular patch antenna, as shown in the same figure. Insert the stem of the holder into the screw-on 90° adapter. Adjust the angular orientation of the antenna so it is perpendicular to the direction of signal propagation and lock the antenna in this position. Connect the antenna to the intermediate-length SMA cable, then clip this set-up onto the mast. The antenna is now oriented to rotate in the H-plane.

The Rectangular Patch Antenna

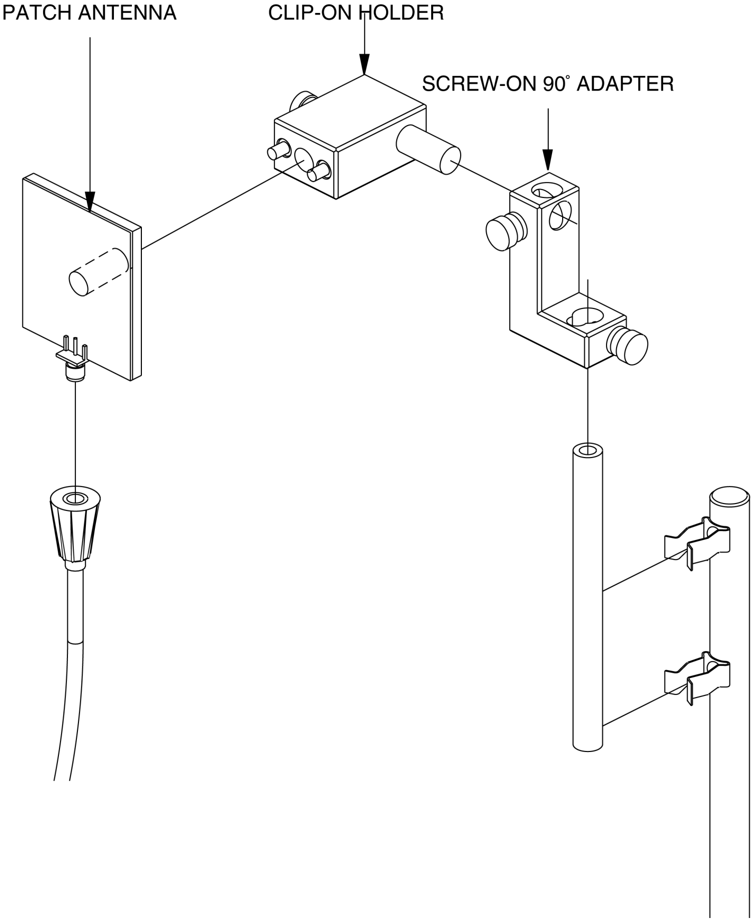


Figure 11. Set-up of the patch antenna in the H-plane

Ensure that the microstrip antenna is in line with the rotation centre of the Antenna Positioner.

☐ 9. Position the antennas a distance of r = 1.5 m apart. Start an acquisition, then store the radiation pattern in a new document (Document2).

☐ 10. Remove the patch antenna from the clip-on holder, then redo the set-up by clipping the antenna so that it is oriented in the E-plane, as shown in Figure 12. Orient the transmission antenna in the E-plane.

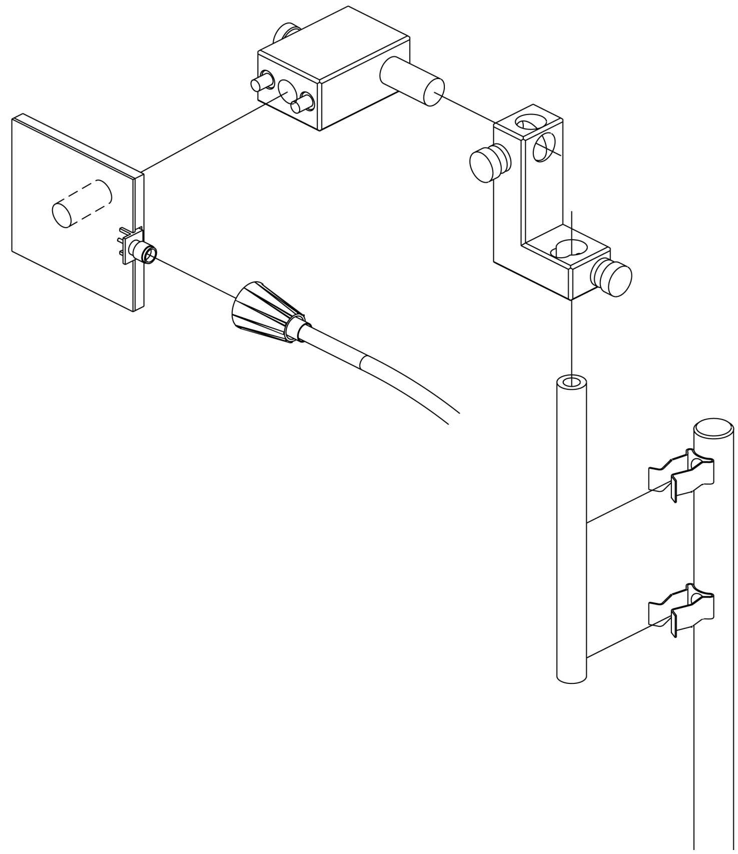


Figure 12. Patch antenna set-up in the E-plane

☐ 11. Perform an acquisition. Also store this pattern in Document2. Orient the two patterns so that their MSPs are at 0°.

☐ 12. Using the gain of the small horn antenna as a reference, calculate the gain of the rectangular patch antenna.

$$G_{patch} = MSL_{patch} - MSL_{small\ horn} + G_{small\ horn} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ dB$$

☐ 13. Evaluate the half-power beamwidth of the patch antenna H-plane.

$HPBW_H$ = ______°

☐ 14. Save the patterns stored in Document2.

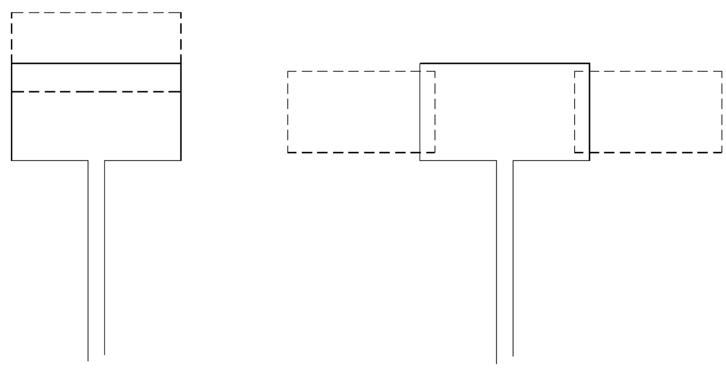
Print both planes of the rectangular patch antenna radiation pattern. Examine the 3-dimensional representation of this antenna radiation.

Matching and tuning

☐ 15. Using a small piece of adhesive copper tape, increase the height of the patch, as shown in Figure 13 (a). The tape must be the same width as the patch.

After having positioned the transmitting and receiving antennas in the H-plane, perform an acquisition, then store the pattern in a new document (Document3).

☐ 16. Remove the tape used in Step 15, then place two pieces of metallic tape on each side of the patch. The tape must be slightly shorter than the height of the patch.



(a) (b)

Figure 13. Increase (a) the height of the patch (b)the width of the patch

Acquire the radiation pattern of this antenna and store it as the H-plane of Document1.

☐ 17. Compare the last two patterns you acquired with the H-plane radiation pattern of the unmodified rectangular patch antenna. Evaluate the loss that can be observed in both cases. Can you explain these results?

The Rectangular Patch Antenna

CONCLUSION

In this exercise, you plotted the radiation pattern of a rectangular patch antenna, then you measured its gain. You observed that the resonance and the impedance match of a rectangular patch antenna are the result of the proper adjustment of the height and width of the patch.

REVIEW QUESTIONS

1. In order to correctly establish the resonant frequency and the radiation characteristics of a microstrip antenna, what parameter should be considered with the greatest accuracy?

   ____

   ____

2. Explain the radiation mode of a microstrip rectangular patch antenna.

   ____

   ____

   ____

3. How should a 120-Ω rectangular patch antenna be connected to a 72-Ω microstrip line?

   ____

   ____

   ____

Exercise 2

Microstrip Planar Array Antennas

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with planar array antennas constructed using microstrip technology. You will learn how to plot the array factor for a uniformly-spaced, uniformly-excited linear array and, from this plot, obtain the polar radiation pattern. You will also become familiar with the characteristics of both parallel-fed and series-fed microstrip arrays.

DISCUSSION

The concept of the array factor is the general effect on the radiation pattern of adopting a specific array configuration. We also saw that the overall radiation pattern of the given array can be predicted by pattern multiplication, that is, by multiplying the radiation pattern of one individual element by the array factor.

In the previous exercise, we compared a rectangular microstrip antenna to a two-slot waveguide antenna. Because the two antennas are essentially equivalent, their radiation patterns are the same.

The E-plane radiation pattern for two slots excited in phase with equal amplitudes is equal to the E-plane radiation pattern of one slot multiplied by the array factor for two elements. This is given by the equation

$$F_{patch}(\phi) = \underbrace{\frac{\sin\left(\frac{\beta h}{2}\cos\phi\right)}{\frac{\beta h}{2}\cos\phi}}_{\text{E-plane radiation pattern of one slot}} \underbrace{\cos\left(\frac{\beta h}{2}\cos\phi\right)}_{\text{Array factor}}$$

E-plane radiation Array factor
pattern of one slot

where h is the slot width (equal to the thickness of the dielectric substrate of the equivalent patch antenna)
b is the separation between the slots

$$\beta = \frac{2\pi}{\lambda}$$

The array factor

In order to better understand the calculation of the array factor of an antenna, consider the case of a linear array whose elements are uniformly spaced by a distance d, as shown in Figure 15. When receiving a signal originating in the far field and directly at broadside ($\theta = 0$), the distance between each element and the source is essentially the same. Therefore, the currents from the elements add up exactly in phase.

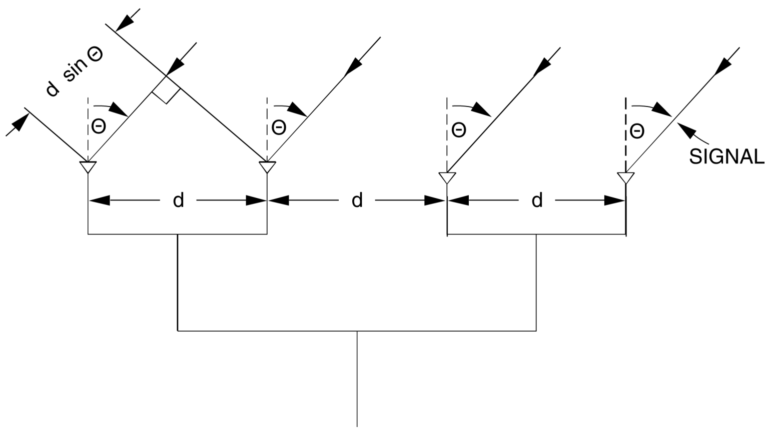


Figure 15. Four element linear array

When $\theta > 0$, the distances are not the same. Going from right to left in Figure 15, each successive element is a distance $d\sin\theta$ farther from the source than the previous element. This causes a phase difference in the currents from successive elements. This phase difference ψ is equal to

$$\psi = \beta d \sin\theta \tag{2}$$

The array factor AF for a linear array composed of N elements can be written as

$$AF = e^{j(N-1)\psi/2} \frac{\sin(N\psi/2)}{\sin(\psi/2)} \tag{3}$$

The factor $e^{j(N-1)\psi/2}$ represents the phase shift of the array phase centre relative to the origin. This phase factor can be neglected, leaving

$$AF = A_0 \frac{\sin(N\psi/2)}{\sin(\psi/2)} \tag{4}$$

For $\psi = 0$, Equation (4) has a maximum value of A_0N. By dividing Equation (4) by this maximum, we obtain the normalized array factor $f(\psi)$ for an N-element array which is uniformly spaced, uniformly excited, and centred at the origin.

$$f(\psi) = \frac{\sin(N\psi/2)}{N\sin(\psi/2)} \tag{5}$$

A plot of this normalized array factor is shown in Figure 16(a). This plot represents the response of the array antenna as a function of the phase difference ψ between successive elements of the array. The response is maximum when the phase difference is zero, that is, when the source of the signal is directly at broadside.

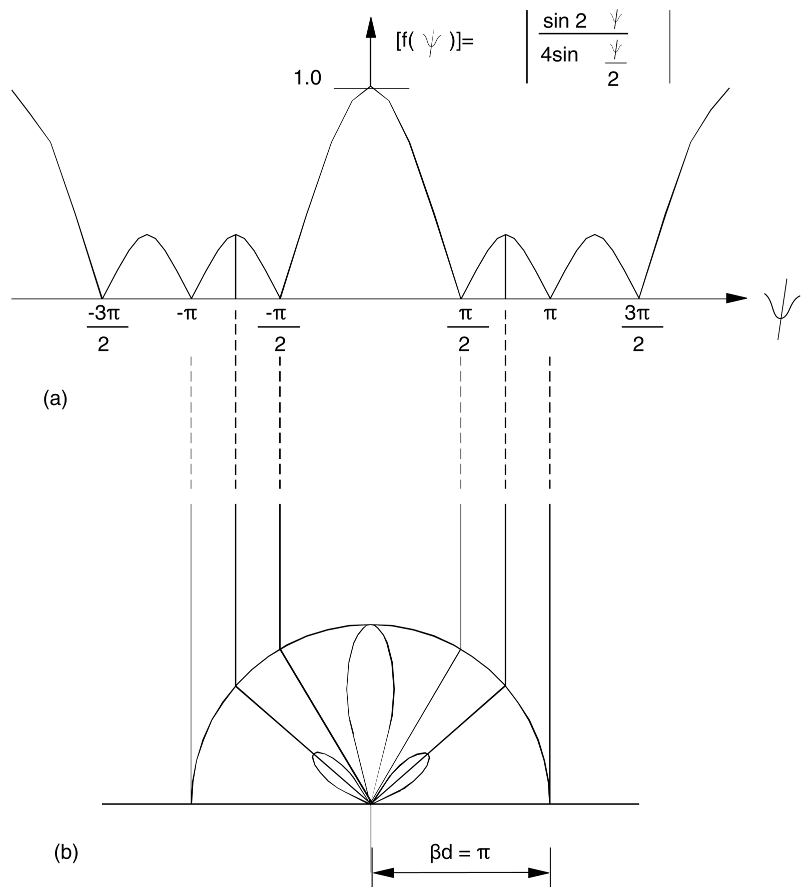


Figure 16 (a) Array factor for 4-element array, (b) Radiation pattern for d = λ/2

A graphical method can be used to obtain a polar plot of the antenna radiation pattern. This is show in Figure 16(b), and is done by drawing a semi-circle of radius βd below the array factor plot. If the element spacing is equal to one-half wavelength, for example, then the radius is $\beta d = (2\pi/\lambda)(\lambda/2) = \pi$.

Once the semi-circle is drawn, vertical lines are dropped from points on the plot of the array factor to the perimeter of the semi-circle. From the intersection of each vertical line with the perimeter, another line is drawn to the origin of the circle. A point is then plotted along this last line at a distance from the origin equal to the corresponding amplitude of the array factor.

For example, at $\psi = \pi/2$, the array factor is zero, so the corresponding point on the polar plot is at the origin. Between $\psi = \pi/2$ and $\psi = \pi$, there is a maximum in the array factor. This corresponds to a maximum in the polar plot.

Microstrip Planar Array Antennas

Parallel and series arrays

The simple patch constitutes the basic element of **microstrip array** antennas. Two types of arrays will be studied in this exercise: **parallel-fed** and **series-fed** planar microstrip arrays.

A microstrip array includes several microstrip elements and a microstrip feed network. This feed network can include passive elements such as power dividers and transmission lines, as well as active components such as phase shifters, amplifiers, oscillators, and mixers. The feed lines are connected directly to the radiating elements and do not affect the radiation pattern.

One great advantage of microstrip antennas is that all elements of the array, as well as the feed network, can be etched on one side of a printed-circuit board. This allows hundreds of components to be included in the array at little cost. The array can be very thin, and because of the high number of elements which can be included, the array can offer very high performance.

Another advantage of arrays is their reliability. Because the entire array is produced using one continuous piece of copper, problems due to faulty interconnections are minimized. As with simple patch antennas, however, microstrip arrays are very narrow-band, that is, they can only be used at precise frequencies.

In a parallel-fed microstrip array, the elements are feed in parallel, making sure that they are excited with the proper phase relationship. They are usually excited in phase in order to produce a main beam perpendicular to the plane of the array.

To avoid phase differences between the elements, there must be symmetry between the transmission lines to the elements. A tree-like structure, called a **corporate feed**, is usually used which allows the power to be evenly distributed in phase. This may result in space problems, however, when the number of elements is very large. A number of impedance-matching elements called **quarter-wavelength transformers** allow all radiating elements to be correctly adapted to the 50-Ω line which feeds the antenna (see Figure 17).

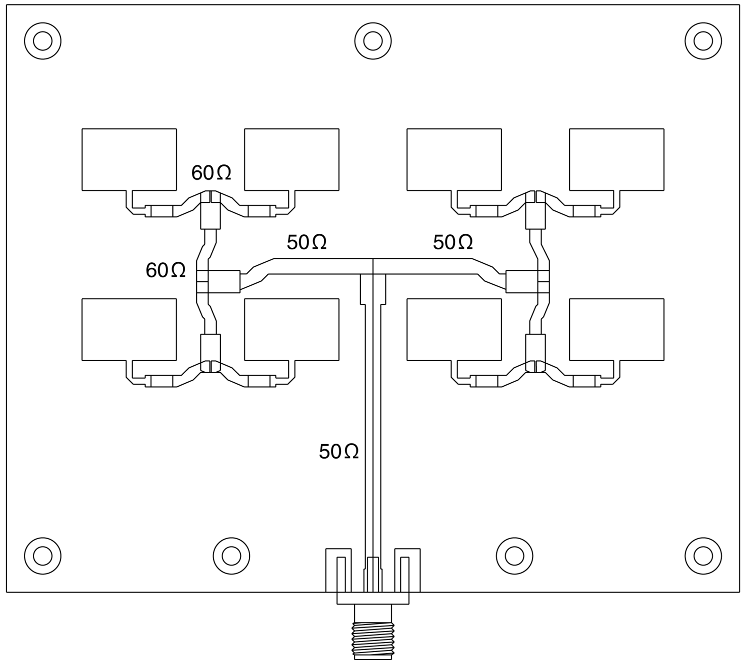


Figure 17. Microstrip patch array

It is also possible to have the array elements connected in series. Although efficient, the series-fed array is more complex to design than the parallel-fed array because of the interdependency between the elements. Each patch must be seen as the equivalent of 2 slots and coupling effects between the patches must be considered in evaluating impedance fluctuations.

With parallel-fed arrays, feed losses limit the increase in gain expected when doubling the number of elements. These losses are due to inductive and capacitive coupling between the large number of feed lines. With series patches, the connection between patches is linear and poses less of a problem.

The two types can be combined in a series-parallel array which offers advantages of both. By joining a number of small series arrays in parallel, it is possible to design large arrays while reducing the complexity of the feed network and the resulting propagation losses.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be set up properly before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place the antenna mast with locking ring on the transmission support. Couple a large horn antenna onto a waveguide-to-coax adapter. Using the plastic holder, install the antenna on the mast, oriented in the H-plane.

Install the long SMA cable on the 10 GHz OSCILLATOR OUTPUT of the RF Generator, then connect the antenna.

☐ 3. Place the mast with vertical clips on the sliding support of the Antenna Positioner. Set up the parallel-fed microstrip planar array antenna as shown on Figure 18 (see instructions in Step 8 of Exercise 9-1). Clip the antenna onto the mast, making sure that it is in line with the rotation centre of the Antenna Positioner.

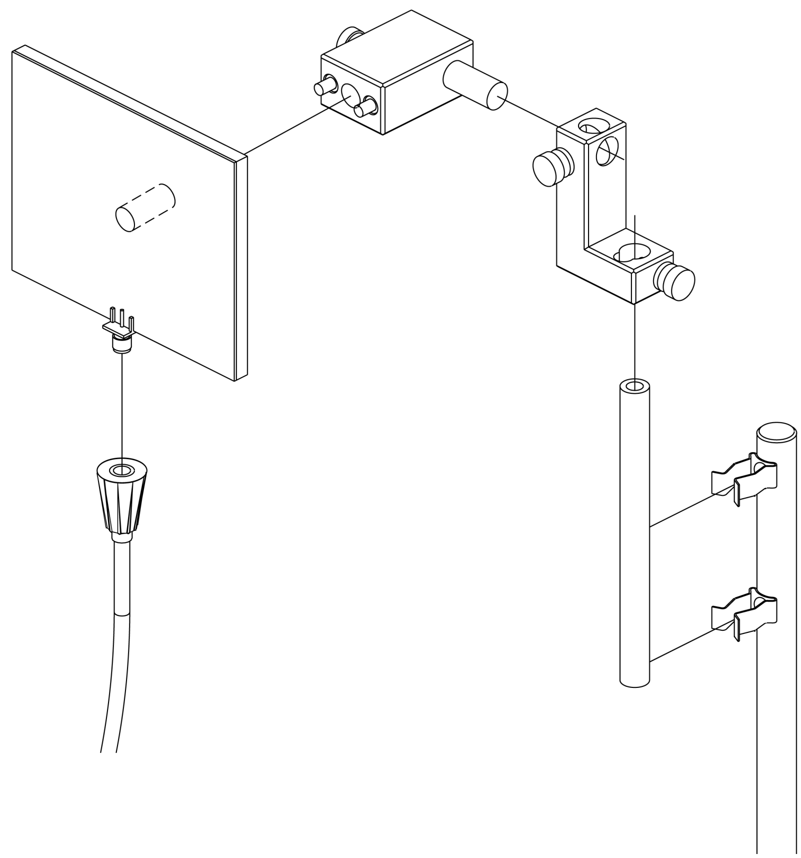


Figure 18. Set-up of the parallel-fed microstrip planar array antenna

Using the intermediate-length SMA cable, connect the antenna to the RF input on top of the Antenna Positioner.

☐ 4. Position the antennas a distance of r = 0.8 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 5. Make the following adjustments:

On the RF Generator

10 GHz OSCILLATOR MODE . . . . 1 kHz
10 GHz OSCILLATOR RF POWER . . . . OFF
1 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Polarization and propagation loss of microstrip planar array antennas.

☐ 6. Set the 10 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

CAUTION!

For your own safety, never look directly into the horn antenna while the RF POWER switch is ON.

☐ 7. Optimize reception of the signal, then perform another acquisition and store the pattern in Document1.

Observing the radiation patterns acquired, determine how the parallel-fed microstrip antenna is polarized. Did you expect this result? Explain.

☐ 8. Position the antennas a distance r = 1.6 m apart, still facing each other. Optimize reception of the signal (you should maintain this attenuation level throughout the exercise). Perform an acquisition and store the pattern as the H-plane of a new document (Document2).

In the matter of propagation loss, does the array antenna behave as a single-element antenna?

Radiation pattern

Note: *Some weak phase differences may exist between the elements of an array, resulting in a small deviation of the main beam from the normal direction. Rotating the antenna slightly will enable you to find the orientation for optimal reception (or transmission) of the signal.*

☐ 9. Orient the parallel array antenna for an acquisition in the E-plane, as shown in Figure 19.

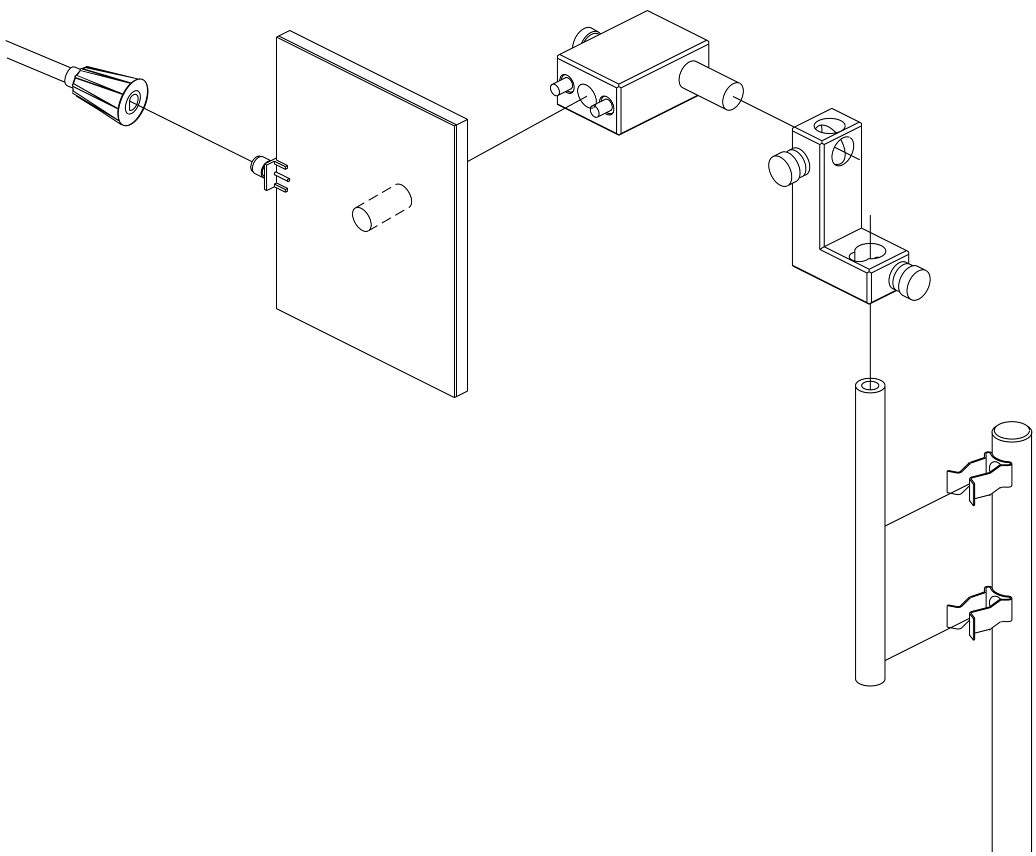


Figure 19. Set-up of the parallel-fed microstrip antenna in the E-plane.

Orient the transmitting horn in the E-plane, then start an acquisition and store the radiation pattern in Document2.

> **Note:** *You may observe that the E-plane radiation pattern of the parallel array is not symmetrical on either side of the maximum. This effect is due to coupling between the microstrip feed transmission lines and the lower row of patches.*

☐ 10. Remove the receiving parallel antenna and install the series-fed microstrip planar array antenna on the mast, oriented in the H-plane as shown in Figure 20. Orient the transmitting antenna in the H-plane. Perform an acquisition and store the radiation pattern in a new document (Document3).

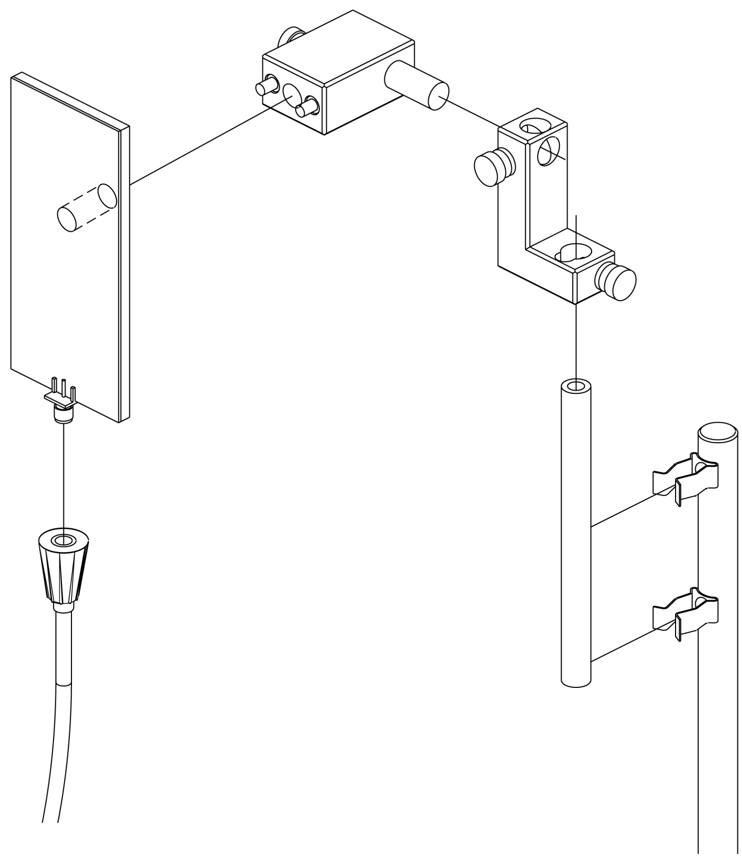


Figure 20. Set-up of the series-fed microstrip antenna in the H-plane.

☐ 11. After having correctly oriented the antennas, acquire the E-plane pattern an store it also in Document3.

☐ 12. Observe the patterns stored in Document2 and Document3. Which plane is more directive for each of these two antennas? Explain this behaviour.

____

____

____

____

☐ 13. Save the data stored in Document2 and Document3.

HPBW and gain

☐ 14. Make the appropriate changes and acquire the H-plane of the single patch antenna. Delete the Document1 patterns and store your last acquisition in this document.

☐ 15. Evaluate the H-plane half-power beamwidth of both the single patch and parallel array antennas.

$HPBW_{H\text{-single}}$ = ______°

$HPBW_{H\text{-parallel}}$ = ______°

☐ 16. Comparing the half-power beamwidth of the single patch and the parallel-fed planar array antennas, you should observe a significant increase in directivity resulting from the 8-element array design.

Narrow beam antennas must be correctly oriented to allow efficient transmission (or reception) of the signal. Evaluate by how many degrees the antenna can deviate from its optimum orientation (orientation providing maximum gain) before the losses exceed half of the power radiated (or received)

for the single patch antenna?

____

for the parallel array antenna?

____

☐ 17. Using the gain of the single patch antenna(refer to Exercise 1) as reference, evaluate the gain of the parallel-fed (refer to the H-plane) and the series-fed (refer to the E-plane) array antennas.

$G_{parallel}$ = ______dB

G_{series} = ______dB

Is the gain increase resulting from the increase in the number of elements in the arrays consistent with the theory?

____

____

____

☐ 18. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you plotted the radiation pattern of both the series-fed and parallel-fed microstrip planar array antennas. You observed that it is easier to tune the parallel patch antenna than the serial antenna. You saw that narrow-beam antennas must be oriented accurately to avoid significant power losses. Finally, you measured the gain of both the series-fed and parallel-fed array antennas and observed that the feed lines could be a source of power losses which limit the expected gain increase due to increasing the number of elements.

Microstrip Planar Array Antennas

REVIEW QUESTIONS

1. Explain the polarization of the microstrip planar array antennas you used in this exercise.

2. Explain what should be considered in the design of an array antenna to ensure that its radiating beam is pointing in the normal direction.

3. What are the main advantages of developing array antennas using microstrip technology?

4. What is a corporate feed and why is it used in the parallel-fed microstrip array antenna design?

5. Which factors should be considered to correctly adapt a series-fed microstrip array antenna?

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 10 Impedance Measurements and Impedance Matching

PART ONE: Impedance Measurements

EXERCISE OBJECTIVES

When you have completed this exercise, you will know how a Smith Chart is constructed, and how to use it to determine load impedances. You will be able to measure load impedances by using a slotted line and the Smith Chart.

DISCUSSION

Relationship Between the Reflection Coefficient at the Load and the Load Impedance

As you have already learned, when the impedance of the load does not perfectly match the characteristic impedance of the waveguide, Z_0, not all the energy incident at the load is absorbed by the load. Instead, part of this energy is reflected back toward the source by a reflection coefficient Γ_L.

The relationship between Γ_L and Z_0 is as follows:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

or

$$Z_L = Z_0 \cdot \frac{1 + \Gamma_L}{1 - \Gamma_L}$$

where Γ_L = Reflection coefficient at the load (dimensionless number, comprised between +1 and -1);
Z_L = Impedance of the load (Ω);
Z_0 = Characteristic impedance of the line (Ω).

The impedance of a load, Z_L is a complex quantity: it is composed of a real, resistive part, R, and an imaginary, reactive part ±jX. When Z_L is not purely resistive, Γ_L is a vectorial quantity carrying both magnitude and phase information:

$$\Gamma_L = \rho \angle \varphi$$

where Γ_L = Reflection coefficient at the load, expressed as a vector quantity;
ρ = Magnitude of the reflection coefficient;
φ = Phase angle of the reflection coefficient.

The Smith Chart

The Smith Chart is a graphical computation tool developed by Dr. P. H. Smith in 1939. This chart simplifies evaluation of transmission line parameters, such as

- the SWR produced by a given load;
- the reflection coefficient, when the characteristic impedance and the load impedance are known, and vice versa;
- the impedance of the load, when the SWR is known.

Figure 11-8 shows a Smith Chart. It consists of a set of impedance coordinates used to represent impedance at any point along a line in rectangular form: R ± jX:

- **R** is the **purely resistive** component of the impedance;

- **± jX** is the **reactive** component (reactance) of the impedance

All resistance and reactance values on the chart are normalized to the characteristic impedance of the line, Z_0. Resistance values correspond to R/Z_0. Reactance values correspond to $\pm jX/Z_0$.

Circles of Constant Resistance (R) *Value*

The "**R**" coordinates of a Smith Chart are a set of circles tangent at the right end of the horizontal centerline of the chart, as Figure 11-9 (a) shows. The point of tangency is called the common point, or infinity (∞) point.

Each circle represents a **constant resistance** (or conductance, G, = 1/R) value, as Figure 11-9 (b) shows:

- The largest circle, which outlines the chart, corresponds to a constant R value of 0 Ω.

- The smaller circles correspond to higher, constant R values.

The horizontal (center) line of the chart represents pure resistance, or zero reactance. The normalized values for R/Z_0 are marked all along the horizontal center line. These values range from **0** to **50**. The shown circles for constant R/Z_0 values of 0, 0.3, 1.0, 2.0, and 5.0 are emphasized.

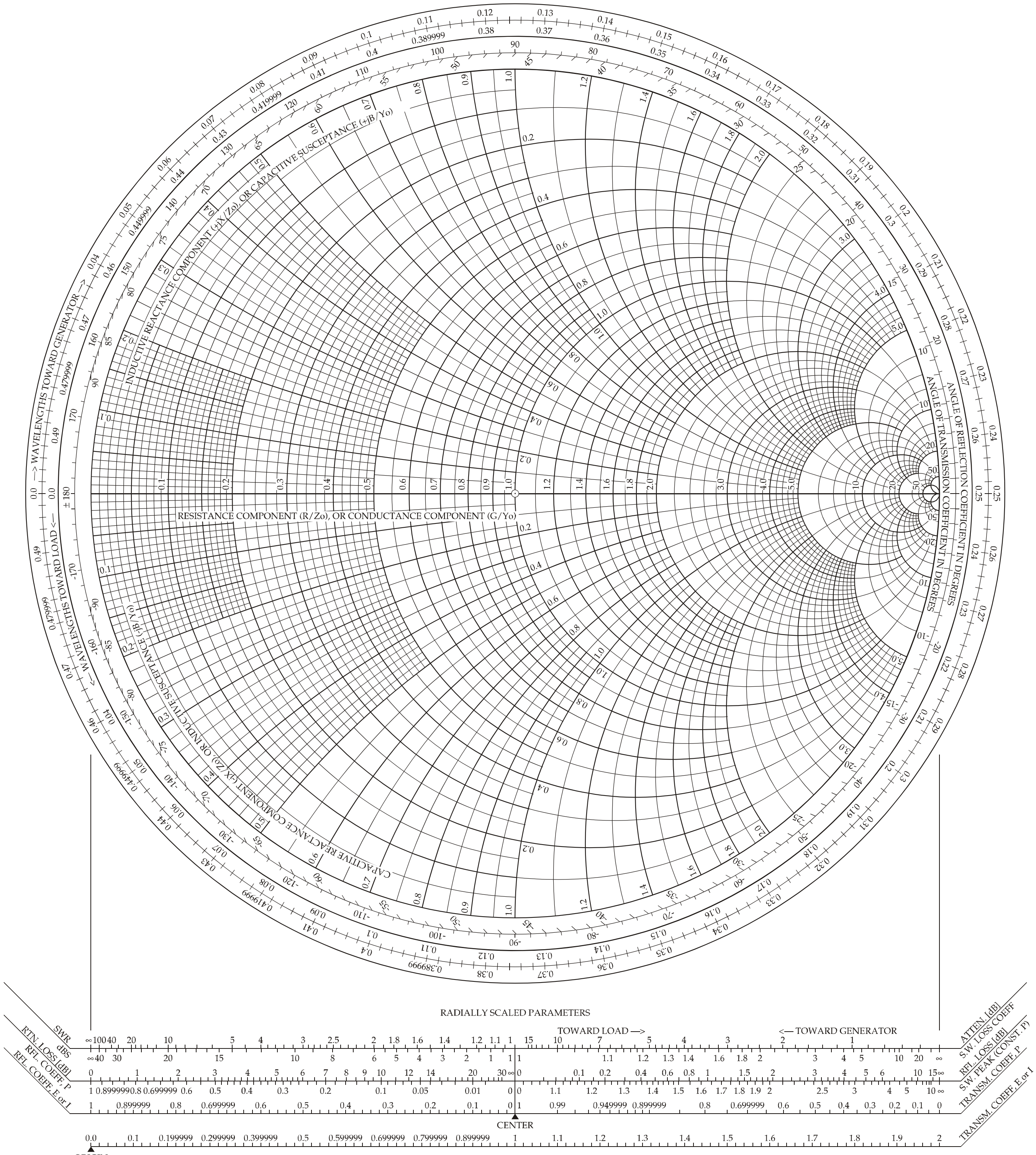


Figure 11-8. The Smith Chart.

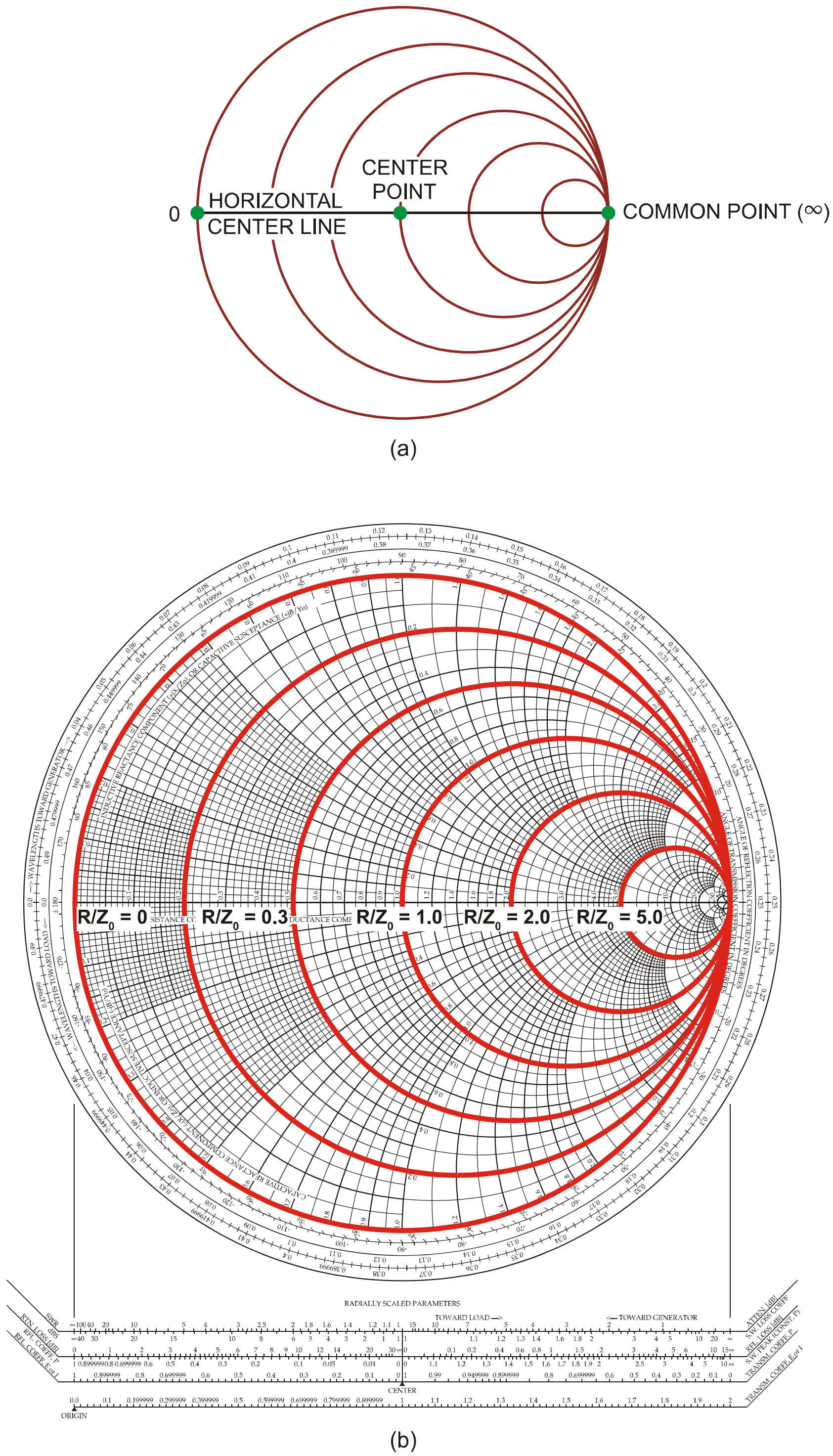


Figure 11-9. Circles of constant resistance (R/Z_0) values.

Arcs of Constant Reactance (±jX/Z_0) Values

The "± jX" coordinates of a Smith Chart are a **set of arcs** starting from the common, or infinity point, as Figure 11-10 (a) shows. Each arc represents a **constant reactance** value.

- The upper half of the chart contains coordinates for inductive reactance (+ jX). Thus, each arc curving upward represents a constant inductive reactance.
- The lower half of the chart contains coordinates for capacitive reactance (- jX). Thus, each arc curving backward represents a constant capacitive reactance.

As Figure 11-10 (b) shows, the normalized values for ± jX/Z_0 are marked on the inner scale just beneath the 0-Ω R circle of the chart. These values range from **0** to **50**. The shown arcs for constant jX/Z_0 values of +0.4, +1.2, +3.0, -0.6, -1.0, and -2.0 are emphasized.

In the next sections, you will learn how to use the Smith Chart to perform various measurements.

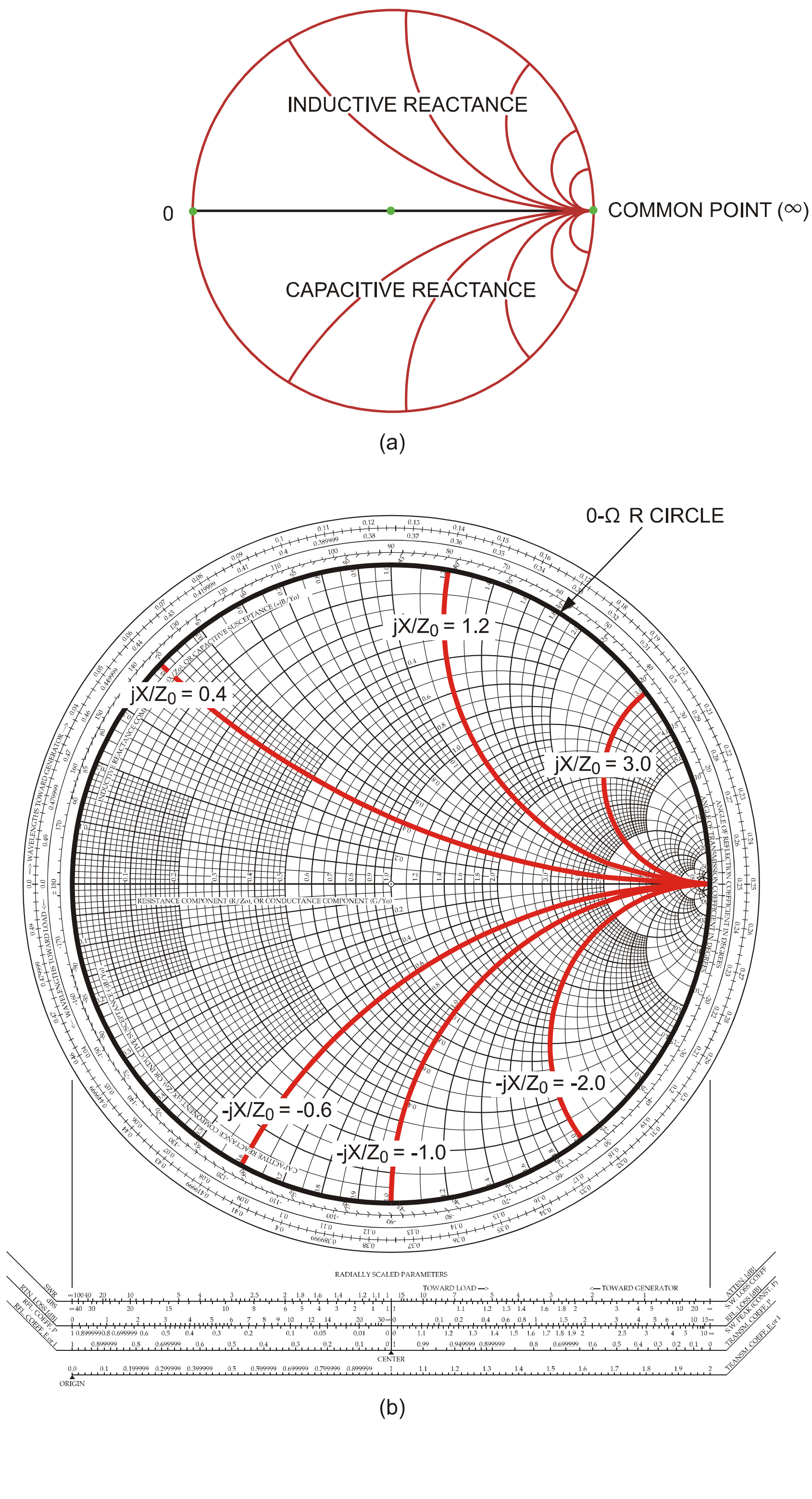


Figure 11-10. Arcs of constant reactance ($\pm jX/Z_0$) values.

Plotting a Normalized Impedance on the Smith Chart

The following impedance is measured at a point along a transmission line having a characteristic impedance, Z_0, of 50 Ω:

$Z_{ACTUAL} = 5 + j25\ \Omega$.

Plot this impedance on the Smith Chart of Figure 11-11.

1. First, normalize the impedance as follows:

$$Z_{NORM.} = \frac{Z_{ACTUAL}}{Z_0} = \frac{5 + j25\ \Omega}{50\ \Omega} = 0.1 + j0.5$$

2. From the center point of the Smith Chart (the mark "1.0", that is, 1 + j0), move to the left along the horizontal line to find the 0.1 resistance circle, as Figure 11-11 shows.

3. Move around the 0.1 resistance circle to the point intersecting the 0.5 inductive reactance arc. This point, marked "A" on the chart, represents the normalized impedance 0.1 + j0.5.

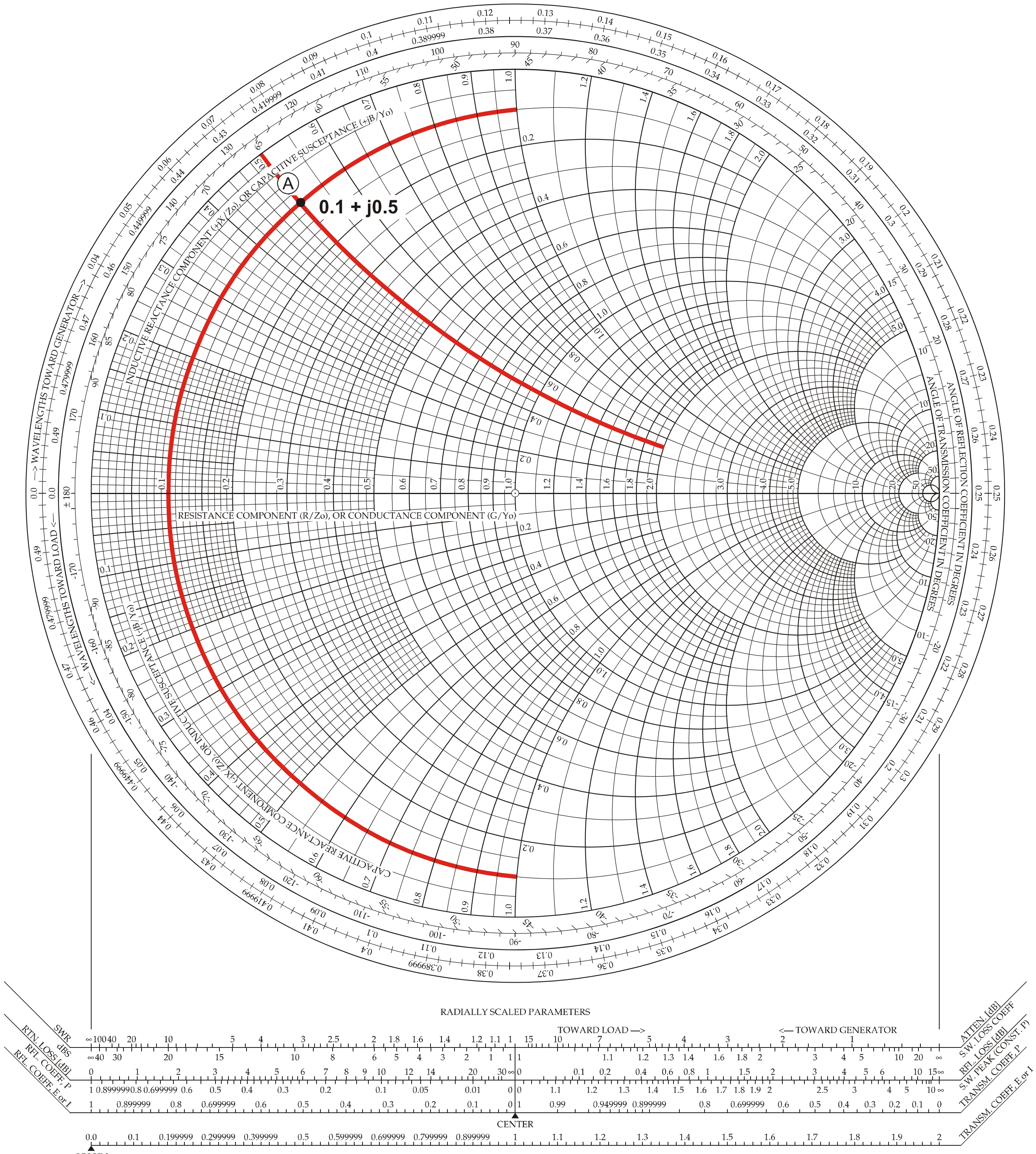


Figure 11-11. Plotting a normalized impedance.

Determining the SWR Produced by a Given Load

A 50-Ω line is terminated by a load impedance Z_L = 50 + j35 Ω. Determine the SWR produced by this load by drawing the corresponding SWR circle on the Smith Chart of Figure 11-12.

1. Normalize the load impedance and then plot this impedance on the Smith Chart (point marked "A" on the chart).

$$Z_{NORM.} = \frac{Z_L}{Z_0} = \frac{50 + j35\ \Omega}{50\ \Omega} = 1.0 + j0.7$$

2. Using a compass, draw a circle having its origin at the center point of the chart, and with a radius such that the circle crosses the load impedance (point A).

   (This circle is a constant SWR circle: all load impedances located on this circle will produce the same SWR.)

3. Read the SWR from this circle at the point where it cuts the centerline on the right (SWR = 2).

Another way of determining the SWR and its corresponding value in decibels (dB) is by using the RADIALLY SCALED PARAMETERS (scales at the bottom of the Smith Chart). To do this, first set the compass for the distance from the center point of the Smith Chart to point A. Then, place one leg of the compass on the line "CENTER" (SWR = 1) of the RADIALLY SCALED PARAMETERS and determine where the other leg cuts the scale "SWR". This scale gives the SWR as a dimensionless number in dB (SWR = 2.0 or 6.0 dB).

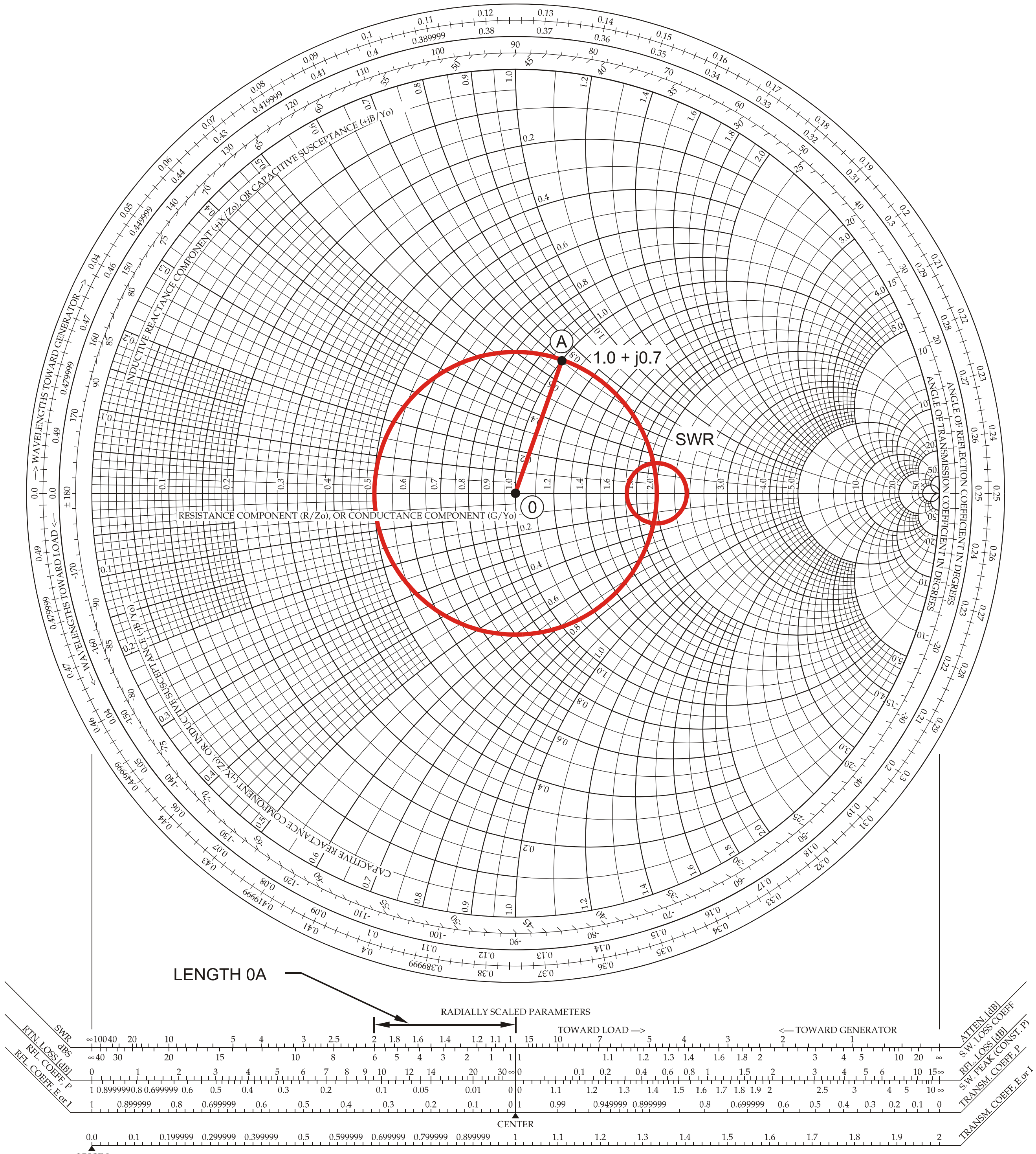


Figure 11-12. Determining the SWR produced by a given load.

Determining the Magnitude (ρ) and Phase Angle (φ) of the Reflection Coefficient Produced by a Given Load

A 50-Ω line is terminated by a load impedance Z_L = 150 + j100 Ω. Determine the magnitude of the reflection coefficient, ρ.

(Refer to the Smith Chart of Figure 11-13.)

1. Normalize the load impedance.

$$Z_{NORM.} = \frac{Z_L}{Z_0} = \frac{150 + j100\,\Omega}{50\,\Omega} = 3.0 + j2.0$$

2. Plot the normalized impedance on the Smith Chart (point A).

3. Draw the corresponding SWR circle on the Smith Chart.

4. Set the compass for the radius of the SWR circle. Transfer this distance to the scale "REFLECTION COEFFICIENT, E or I" at the bottom of the chart, starting at the "CENTER" line. Read off the magnitude of the reflection coefficient (ρ = 0.63).

5. Draw a vector from the center point of the chart through point A to the scale "ANGLE OF REFLECTION COEFFICIENT IN DEGREES", just beneath the outer rim of the chart (point B). Read off the phase angle of the reflection coefficient ($\varphi \cong 18°$).

> **Note:** *The complete reflection coefficient Γ may be written in its polar form as* $\rho\angle\varphi$*, where ρ and φ are the magnitude and the phase angle of the reflection coefficient, respectively.*

The reverse procedure can be used to determine an unknown impedance when the magnitude and the phase of the reflection coefficient are known.

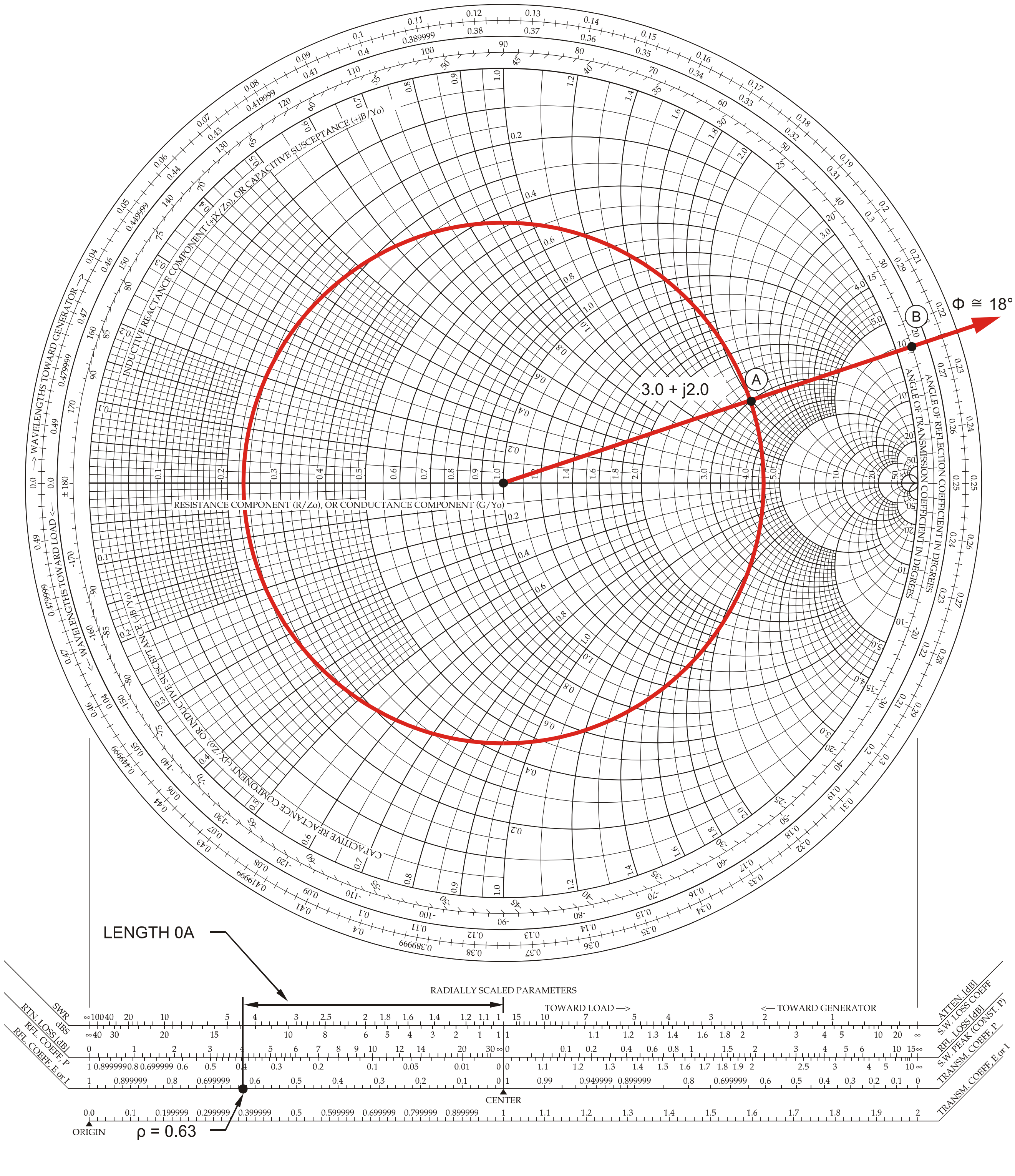


Figure 11-13. Determining the magnitude (ρ) and phase (φ) of the reflection coefficient produced by a given load.

Determining the Impedance of a Load with a Slotted Line (Short-Circuit Minima-Shift Method)

The SWR produced by a load is 3. This SWR has been measured by using a slotted line and a SWR meter. Determine the impedance of the load.

1. Draw the SWR circle on a Smith Chart (Figure 11-15).

2. Determine the phase angle (φ) of the reflection coefficient, using the steps below.

   a. Temporarily replace the load of unknown impedance by a short circuit, which will produce a standing wave like the one shown in Figure 11-14. By using the slotted line, locate a minimum of the standing wave, preferably the minimum closest to the short circuit.

      In Figure 11-7, the closest measurable minimum to the short circuit is MIN_1.

      Location of MIN_1 = 31.9 mm

   b. Then, locate the next minimum towards the source. In Figure 11-14, this minimum is MIN_2.

      Location of MIN_2 = 50.2 mm

   c. Replace the short circuit with the load of unknown impedance. Locate the minimum between the two minima previously measured with the short circuit. In Figure 11-14, this minimum is MIN_3.

      Location of MIN_3 = 37.9 mm

   d. Determine the distance, d, that the minimum shifted:

      $d = MIN_2 - MIN_3 = 50.2\text{ mm} - 37.9\text{ mm} = 12.3\text{ mm}$

   e. Determine the guided wavelength, λ_g, based on the location of MIN_1 and MIN_2.

      $\lambda_g = 2 \cdot (MIN_2 - MIN_1) = 2 \cdot (50.2\text{ mm} - 31.9\text{ mm}) = 36.6\text{ mm}$

   f. Based on the guided wavelength, λ_g, calculate the phase angle (φ) of the reflection coefficient:

$$\varphi = 180° \left(1 - \frac{4d}{\lambda_g}\right)$$

$$= 180° \left(1 - \frac{4 \cdot 12.3\text{ mm}}{36.6\text{ mm}}\right) = 180° \cdot -0.344 \cong -62°$$

3. On the Smith Chart of Figure 11-15, draw a vector from the center point of the chart to the mark on the scale "ANGLE OF REFLECTION COEFFICIENT IN DEGREES" that corresponds to the angle -62° (point B).

The point where this vector crosses the SWR circle (point C) corresponds to the normalized load impedance ($Z_{L\ NORM.}$ = 0.95 - j1.13).

> **Note:** *This method can also be used to determine the impedance seen by the source at any point along the guide. Once you have determined the impedance at that point, you can use the scale WAVELENGTHS TOWARD GENERATOR on the outer rim of the Smith Chart to determine the impedance at any other point along the waveguide.*

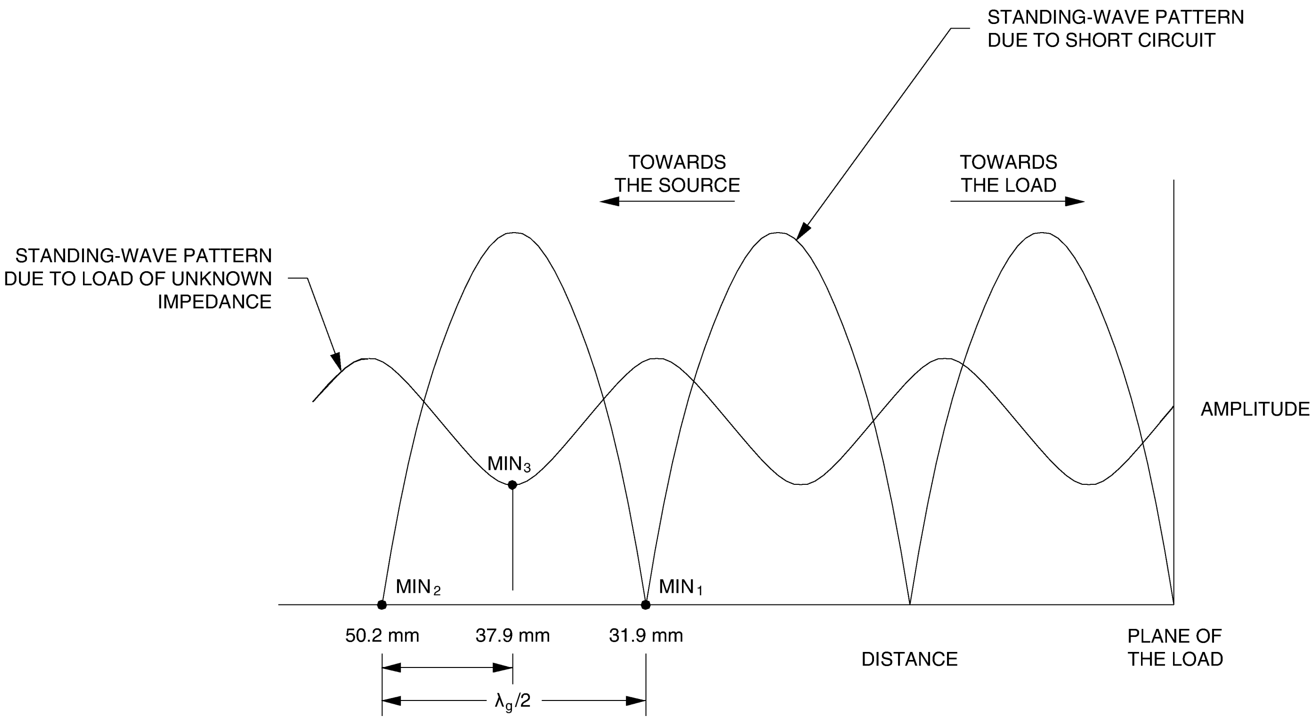


Figure 11-14. Determining the phase angle (φ) of the reflection coefficient from the standing-wave pattern.

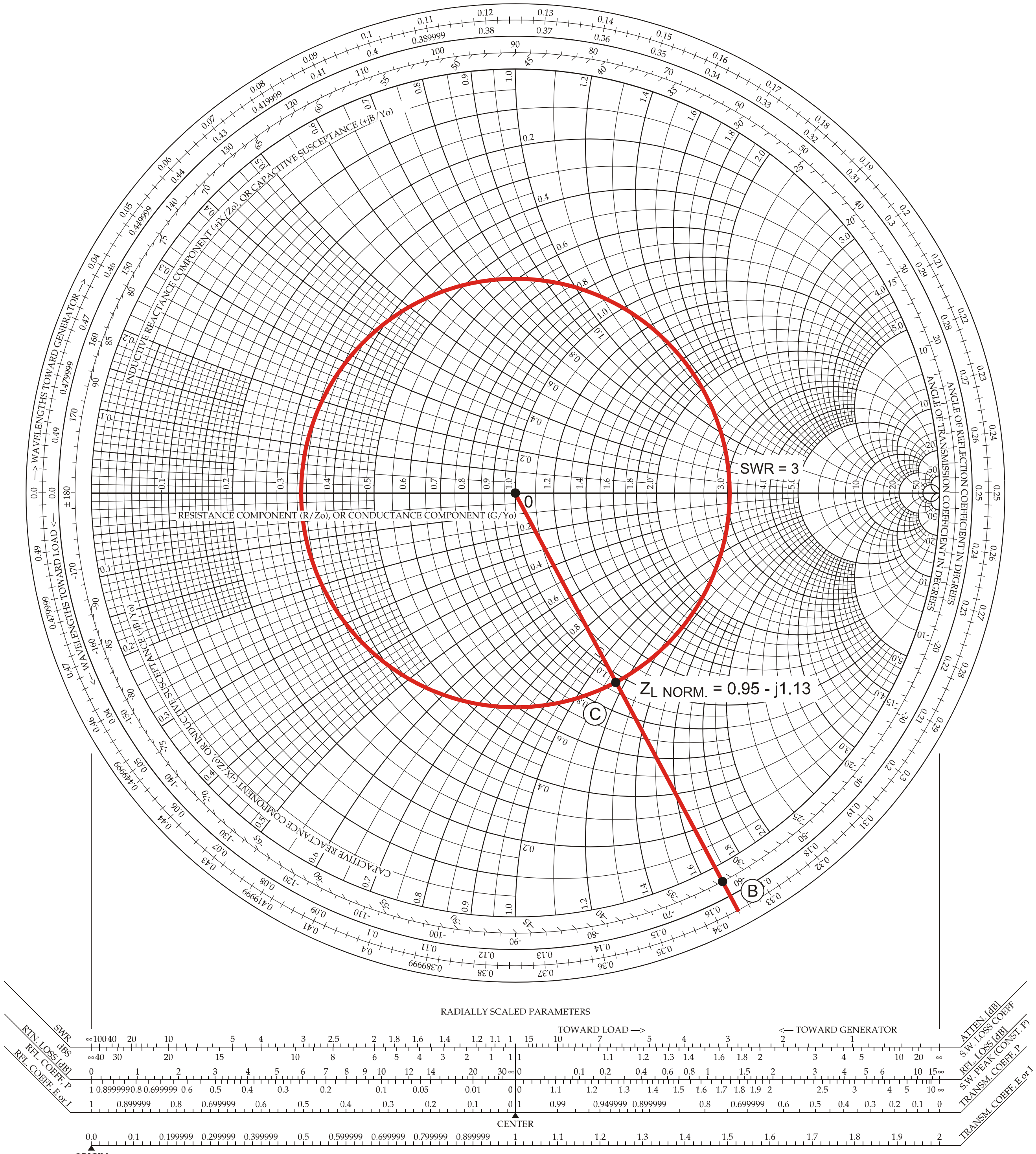


Figure 11-15. Determining the load impedance with a slotted line (short-circuit minima-shift method).

Procedure Summary

In the first part of this exercise, you will measure the guided wavelength by locating two successive minima in the standing wave produced by a short-circuited load.

In the second part of the exercise, you will measure the impedance of two loads by using the short-circuit minima-shift method. The loads will consist of a short-circuited Variable Attenuator set to produce two different attenuations.

> **Note:** *For detailed information on how to use the Smith Chart of LVDAM-MW, please refer to Section 4 of the Lab-Volt User Guide "Microwave Data Acquisition and Management", part number 85756-E.*

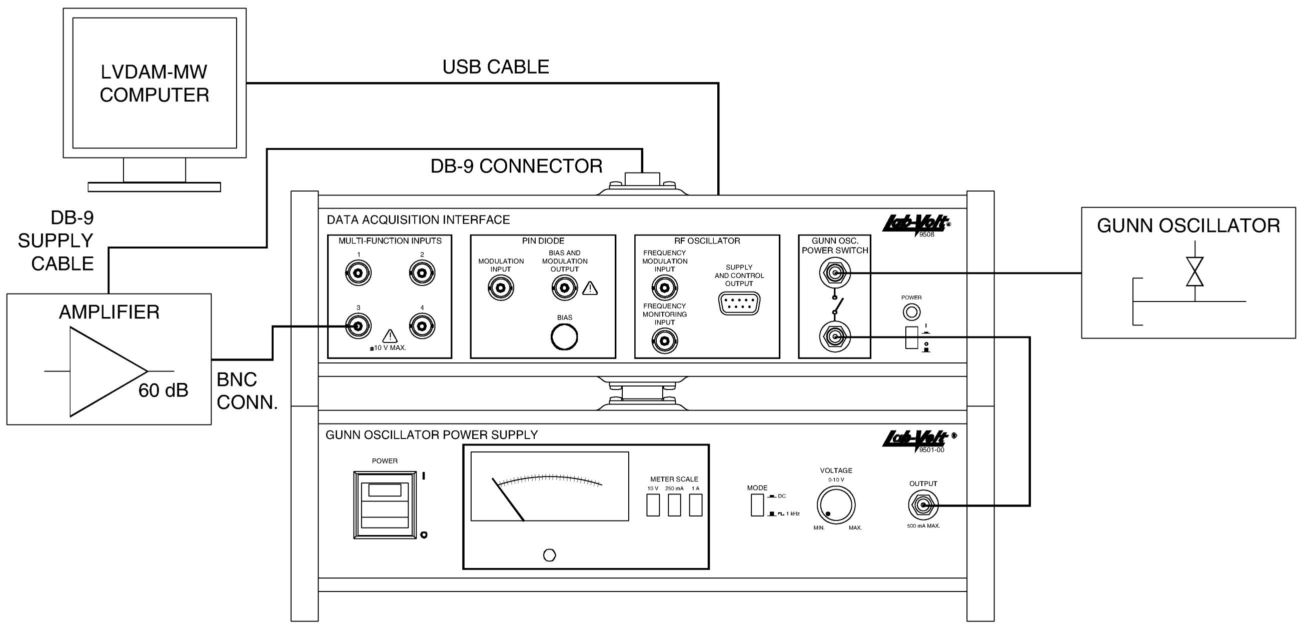
EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix F of this manual, to obtain the list of equipment required to perform this exercise.

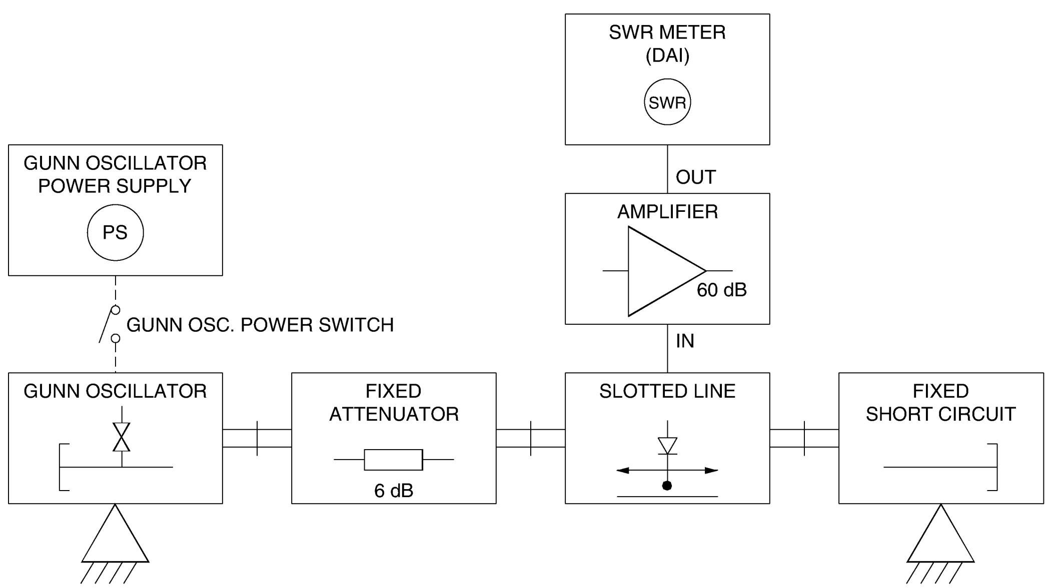
PROCEDURE

Determining the Guided Wavelength with the Slotted Line

☐ 1. Make sure that all power switches are in the O (off) position. Set up the modules and assemble the microwave components as shown in Figure 11-16.



(a)



(b)

Figure 11-16. Computer and module arrangement (showing electrical connections to microwave components), and microwave setup.

☐ 2. Make the following settings on the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . 1 kHz
METER SCALE . . . . 10 V

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Set the Gunn Oscillator supply voltage to 8.5 V. Wait for about 5 minutes to allow the modules to warm up.

☐ 4. Move the probe of the Slotted Line along the waveguide and locate it over the 45-mm position. (The 45-mm mark on the waveguide scale intersects the 0-mm (rightmost) mark on the carriage scale).

☐ 5. On the Slotted Line, loosen the thumbscrew of the sliding carriage adjust the depth of the Slotted Line's probe to approximately 1/3 of maximum (the Slotted Line's pointer must be aligned with the second lowermost mark approximately), then tighten the thumbscrew.

Note: *Particular attention must be paid to the adjustment of the probe depth inside the Slotted Line. If the probe penetrates too deep into the Slotted Line, the field distribution can be distorted, especially when the SWR is high. Moreover, the probe's crystal detector is then more likely to operate outside of its square-law region, causing the measurements to be erroneous.*

☐ 6. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

☐ 7. In LVDAM-MW, start the SWR Meter and set it to display decibels (dB).

☐ 8. Tune the frequency of the SWR Meter's amplifier: using the cursor of the SWR Meter, scan through the frequency tuning range of this meter (from 900 to 1100 Hz) to find the frequency at which the signal level (indicated as a percentage below the horizontal indicator bar of the meter) is maximum.

a. If the maximum signal level obtained on the SWR Meter is between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 9.

Note: *To obtain the maximum dynamic range of measurement on the SWR Meter (once its amplifier has been tuned), a maximum level between 70 and 90% on the SWR Meter with Gain Input 3 set to 0 dB is ideal.*

b. If you are unable to tune the SWR Meter's amplifier because the maximum signal level exceeds the measurement scale (the horizontal indicator bar of the meter turns to red), loosen the thumbscrew of the Slotted Line. Readjust the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (a signal level of, for example, about 25% of full scale, once the thumbscrew of the Slotted Line has been re-tightened since its tightening will cause the signal level to change slightly). Then, tune the frequency of the SWR Meter to obtain the maximum signal level on this meter. If this level is not between 70 and 90% of full scale, very slightly readjust the depth of the Slotted Line's probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar never turns from green to red) once the thumbscrew of the Slotted Line has been re-tightened.

c. If the maximum signal level obtained on the SWR Meter is between 10 and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

☐ 9. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 10. While observing the SWR Meter reading, locate the Slotted Line's probe over the minimum nearest the load. This will require you to increase Gain Input 3 to 20 dB and then 40 dB. The minimum should be around 36 mm.

Record the location of this minimum, MIN_1.

Location of MIN_1 = ______ mm

☐ 11. While observing the SWR Meter reading, slowly move the Slotted Line's probe towards the source until you encounter the second minimum. This minimum should be around 54 mm.

Record the location of this minimum, MIN_2.

Location of MIN_2 = ______ mm

☐ 12. Calculate the guided wavelength, λ_g.

$\lambda_g = 2 \cdot (MIN_2 - MIN_1) =$ ______ mm

Measuring the Load Impedance by Using the Short-Circuit Minima-Shift Method

Measuring the Load Impedance with the Variable Attenuator Set for an Attenuation of 5.0 dB

☐ 13. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.

☐ 14. Modify your microwave circuit in order to obtain the circuit shown in Figure 11-17 (the 35-dB Variable Attenuator is added).

Leave the rest of the equipment connected and set as before.

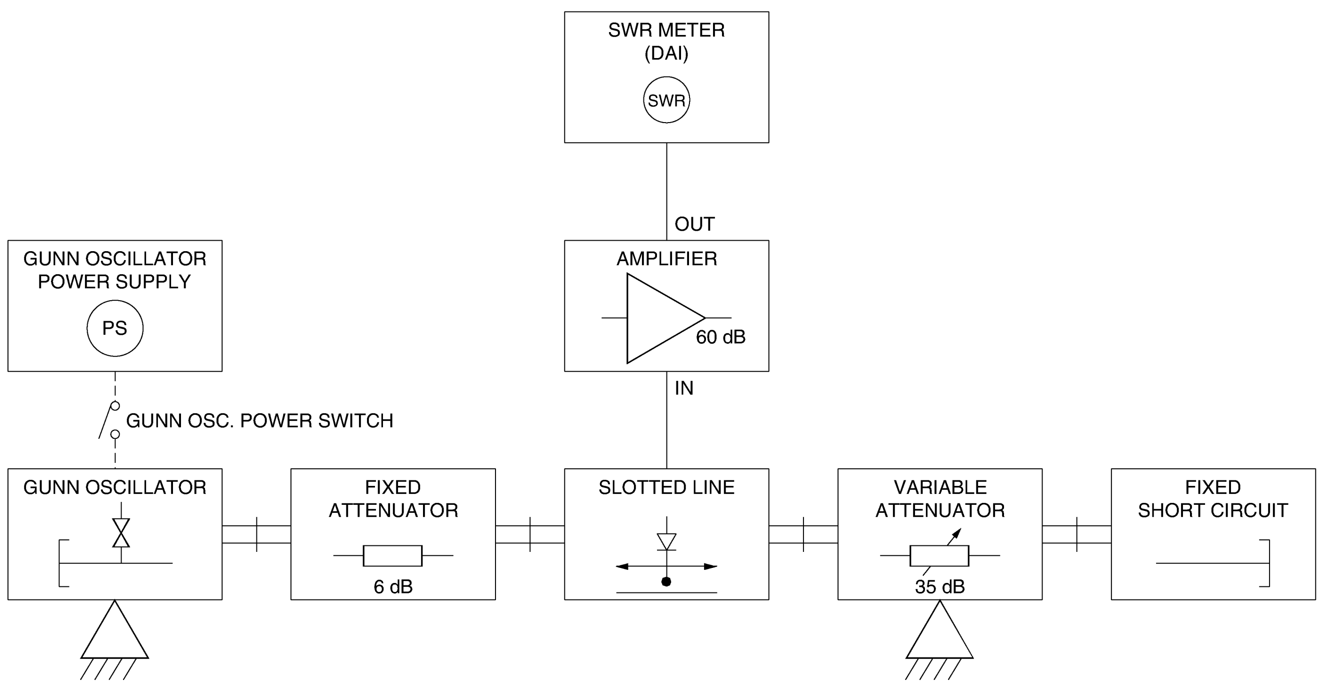


Figure 11-17. Modified microwave circuit used to determine the load impedance by measuring the phase angle of the reflection coefficient and then using the short-circuit minima-shift method.

☐ 15. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to ON.

Wait for about 5 minutes to allow the modules to warm up.

☐ 16. Referring to the attenuation-versus-blade position curve (or the corresponding Data Table) of the Lab-Volt Variable Attenuator , determine the attenuator blade's position required for this attenuator to provide an attenuation of 5.0 dB.

Set the Variable Attenuator's blade to this position.

☐ 17. Set Gain Input 3 to 0 dB. While observing the SWR Meter reading, locate the Slotted Line's probe over the maximum nearest the load to obtain the maximum signal level on this meter.

Then, adjust the frequency of the SWR Meter's amplifier for the signal level to be maximum on this meter. DO NOT modify the adjustment of the Variable Attenuator's blade.

If the maximum signal level obtained on the SWR Meter is

a. between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 18.

b. between 10 and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

Note: *If you cannot find the location of the maximum because the signal level displayed by the SWR Meter exceeds the measurement scale (the horizontal indicator bar of the meter turns to red), DO NOT modify the adjustment of the Variable Attenuator's blade. Instead readjust (decrease) the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (for example, about 25% of full scale once the thumbscrew of the Slotted Line has been re-tightened). Then, locate the Slotted Line's probe over the maximum nearest the load and perform step 17.*

☐ 18. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 19. Locate the Slotted Line's probe over the minimum between the two minima previously observed with the short-circuited load (that is, MIN_1 and MIN_2, as recorded in steps 10 and 11). Record the location of this MIN below.

Then, set the SWR Meter to display the SWR as a dimensionless number (linear scale). Record the SWR Meter reading below.

Location of MIN = ______ mm

SWR = ______

Calculate the distance, d, that the minimum shifted due to the change in load impedance, using the equation below:

$d = MIN_2 - MIN =$ ______ mm

where MIN_2 = Location of the second minimum with the short-circuited load, as recorded in step 11;
MIN = Current location of the Slotted Line's probe.

☐ 20. Based on the distance, d, obtained in the previous step, and on the guided wavelength, λ_g, recorded in step 12, calculate the phase angle (φ) of the reflection coefficient:

$$\varphi = 180° \left(1 - \frac{4d}{\lambda_g} \right)$$

$\varphi =$ ______

☐ 21. In LVDAM-MW, select the Smith Chart function, which will bring up this chart.

In the Smith Chart Settings panel, enter the measured SWR (as recorded in step 19) to plot the corresponding SWR circle.

Rotate the vector of the Smith Chart along the scale of the reflection coefficient angle—on the outer rim of the chart—until it intersects the angle (φ) recorded in step 20. (The field Reflection Coefficient Angle in the Settings panel of the Smith Chart indicates this angle when the vector is properly positioned.)

The point where the vector crosses the SWR circle corresponds to the normalized load impedance. The real and imaginary part of this impedance (reactance and inductance) are indicated in the Settings panel of the Smith Chart. Record this impedance below.

$Z_{L\ NORM.} =$ ______ + j ______

Figure 11-18 shows an example in which the normalized impedance is 1.35 + j0.62, when the SWR is 1.83 and the phase angle φ is 45.5°. This impedance is indicated in the field Impedance of the Settings panel.

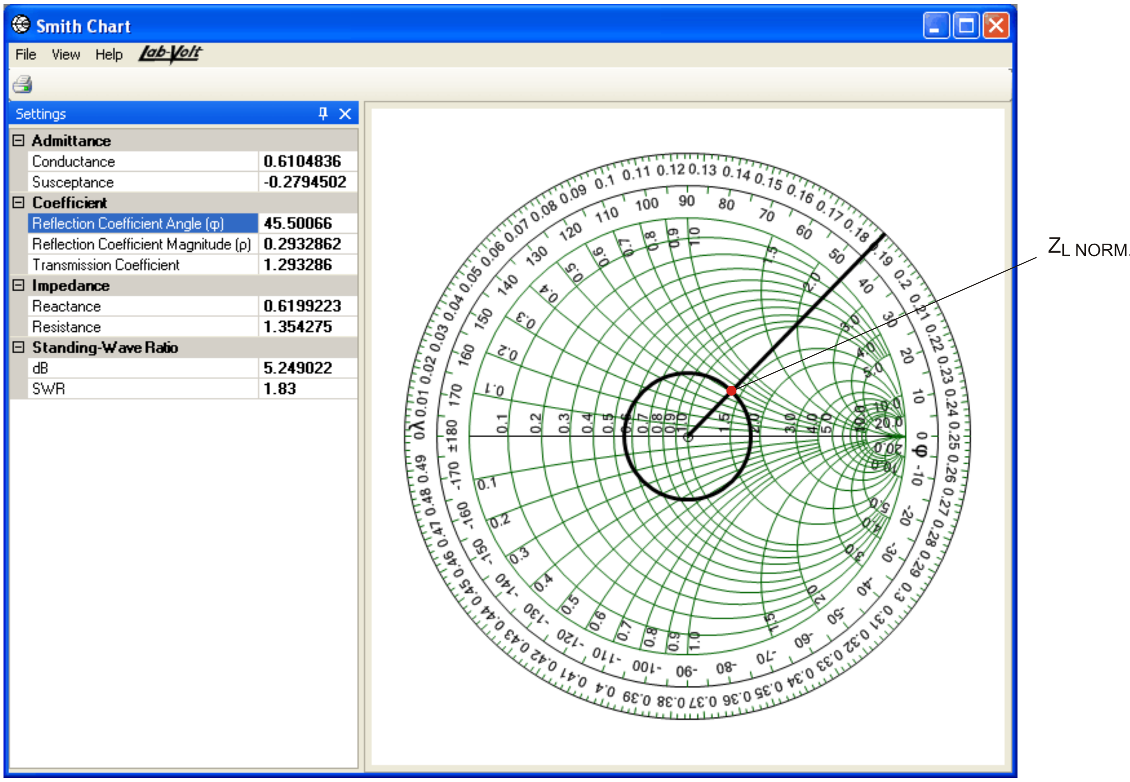


Figure 11-18. The normalized impedance corresponds to the point where the vector crosses the SWR circle.

Measuring the Load Impedance with the Variable Attenuator Set for an Attenuation of 1.5 dB

☐ 22. Referring to the attenuation-versus-blade position curve (or the corresponding Data Table) of the Lab-Volt Variable Attenuator , determine the attenuator blade's position required for this attenuator to provide an attenuation of 1.5 dB.

Set the Variable Attenuator's blade to this position.

☐ 23. Repeat steps 17 through 21 in order to determine the load impedance. Record your results below.

Location of MIN = ______ mm

SWR = ______

d = MIN_2 - MIN = ______ mm

φ = ______

$Z_{L\ NORM.}$ = ______ + j ______

Figure 11-19 shows an example in which the normalized impedance is 0.37 + j1.10 when the SWR is 6.1 and the phase angle φ is 81°.

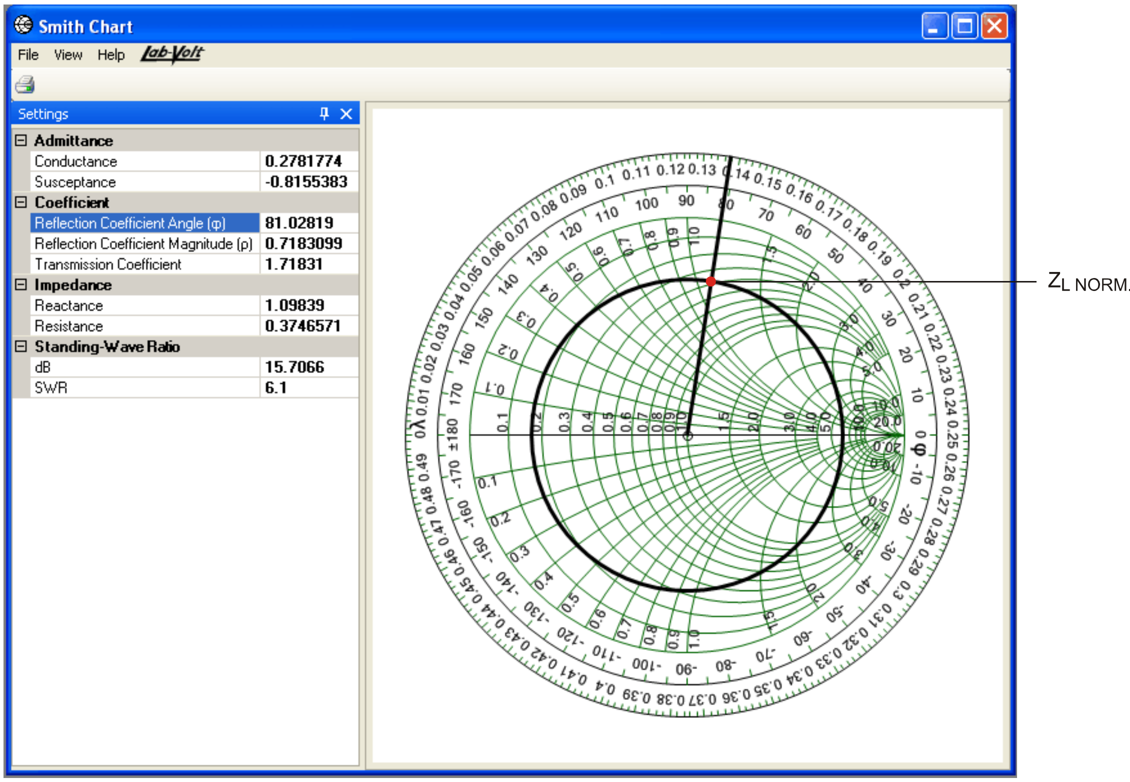


Figure 11-19. The normalized impedance corresponds to the point where the vector crosses the SWR circle.

☐ 24. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 25. Close the LVDAM-MW software.

CONCLUSION

In this exercise, you learned how to use a Smith Chart to obtain both the magnitude and the phase of the reflection coefficient from a normalized impedance, and vice versa.

You learned how to measure the normalized impedance of a load by using the short-circuit minima-shift method. With this method, a slotted line and a SWR meter are used to measure the SWR and the distance the minima in the standing wave shifted due to the change in the load impedance. The SWR and the measured distance are then used to calculate the angle of the reflection coefficient and find the normalized load impedance with the Smith Chart.

REVIEW QUESTIONS

1. What are the two parts of a complex impedance?

2. What is the purpose of the Smith Chart as it was used in this exercise?

3. Explain how to plot the locus of all impedances which produce the same SWR on a Smith Chart.

4. Explain how to plot a complex impedance on a Smith Chart.

5. On the Smith Chart in Figure 11-20, plot the axis of purely resistive loads.

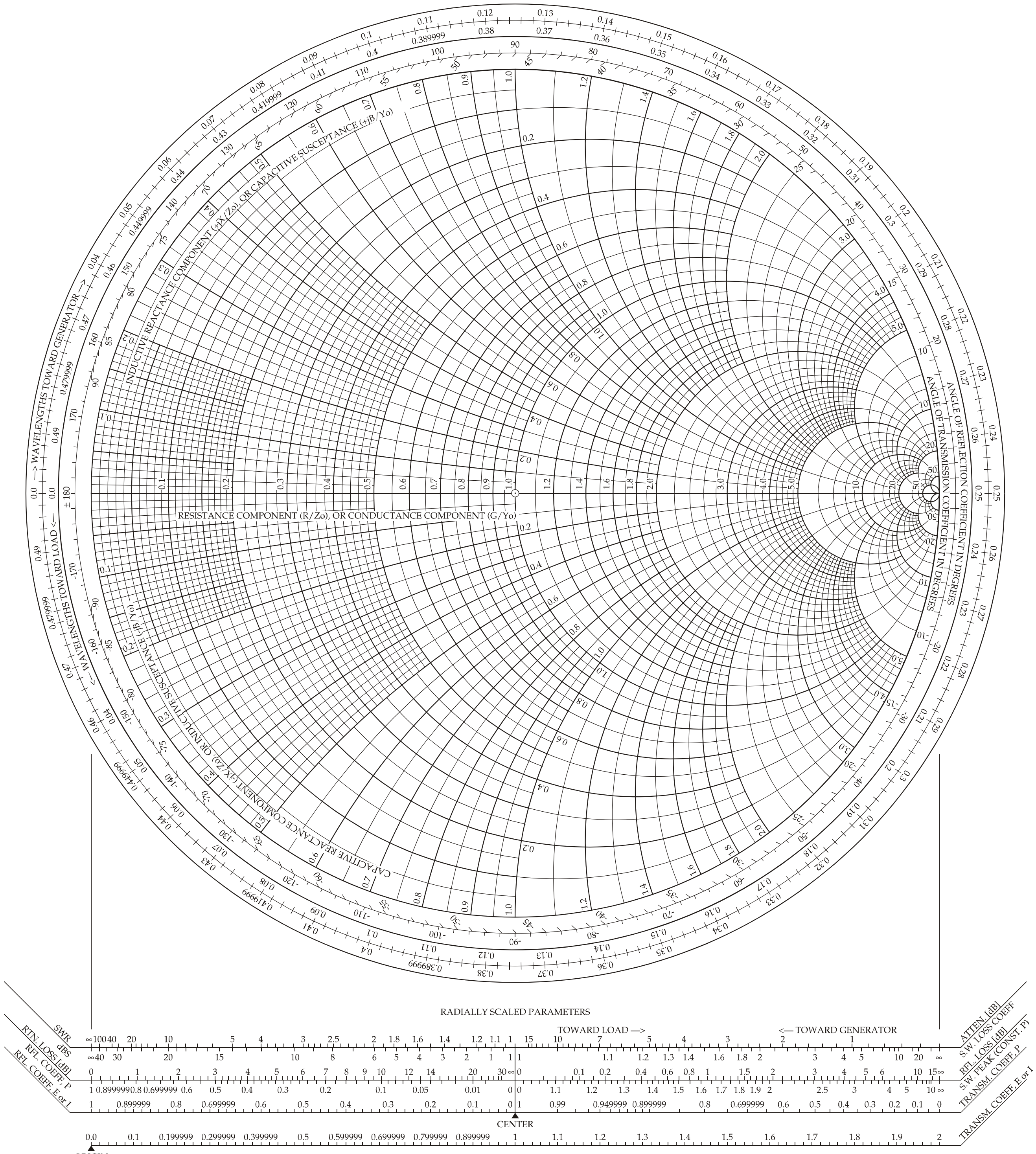


Figure 11-20. Plotting the locus of purely resistive loads.

PART TWO : Impedance Matching

EXERCISE OBJECTIVES

When you have completed this exercise, you will be familiar with the concept of impedance matching. You will be able to match a load using a slide-screw tuner.

DISCUSSION

Reflection Coefficient Along a Waveguide

The relative phase angle between the incident voltage and the reflected voltage varies periodically along the waveguide. Since the reflection coefficient is the ratio of the reflected voltage to the incident voltage, its phase angle will also vary periodically along the waveguide.

The reflection coefficient at a given point along a waveguide is the reflection coefficient at the load plus an additional phase term. This phase term depends on the distance between the given point of observation and the load.

When the waveguide is lossless, the magnitude of the reflection coefficient stays constant along the guide. The phase of the reflection coefficient is the sum of the initial phase angle at the load plus the additional phase angle due to the displacement along the guide.

Determining an Impedance Along a Waveguide

The impedance at any point along a waveguide from a reference reflection coefficient can be easily determined with a Smith Chart. All that is required is the location of the reference point and the reflection coefficient at that point. This reference point can be at the load or at any other point along the guide.

The reflection coefficient defines a point on the Smith Chart which is the intersection of the SWR circle and a straight line.

On the Smith Chart, the reflection coefficient circle is the same thing as the SWR circle. It represents the impedance locus for a given mismatched load, that is, all the impedances that can be encountered along the line for that given SWR or mismatched condition.

To find the impedance at a certain distance from a reference point, the impedance at the reference point is located on the SWR circle. The impedance vector is then rotated through an angle corresponding to the phase difference between the reference point and the point of unknown impedance.

To help rotate the vector through the required angle, the Smith Chart has two wavelength scales on its outer rim, as Figure 11-21 shows. Both scales start at the same point: the zero (0) point of the horizontal centerline. They are graduated in hundredths of a wavelength, going from 0 to 0.50λ. They are used to add the required phase angle to the reference point.

- The outer scale is marked "WAVELENGTHS TOWARD GENERATOR". It is used when the displacement is from the reference point towards the generator. The scale values increase in the clockwise (CW) direction.

- The inner scale is marked "WAVELENGTHS TOWARD LOAD". It is used when the displacement is from the reference point towards the load. The scale values increase in the counterclockwise (CCW) direction.

The impedance variation along a line invariably follows a precise pattern that repeats cyclically at every half-wavelength. This is the reason why the maximum value of each wavelength scale of the Smith Chart is 0.5λ.

Distances greater than 0.5λ are measured by turning around the circle as many times as necessary.

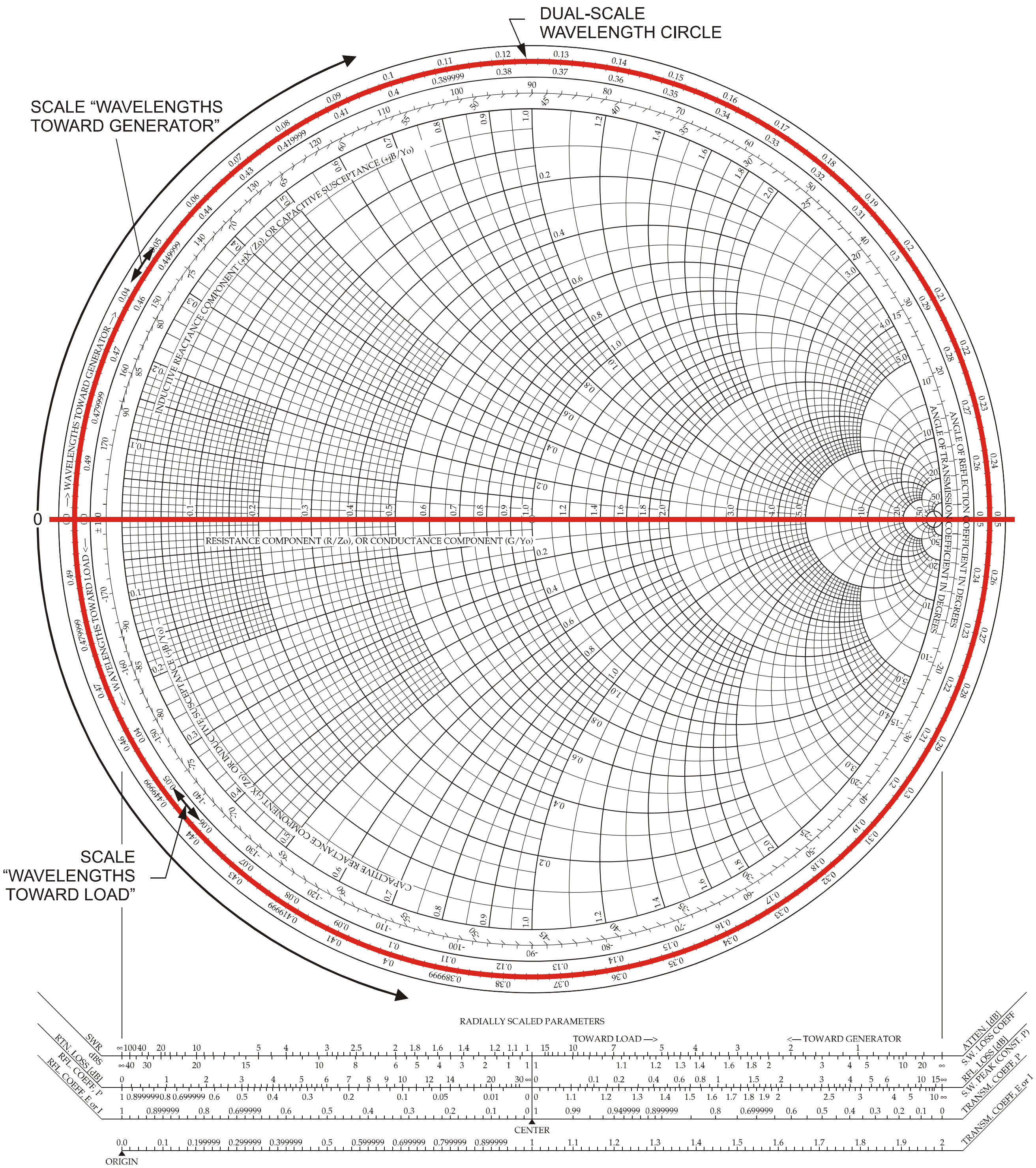


Figure 11-21. The wavelength scales.

Determining the Impedance at a Given Point Along a Waveguide (Example)

Refer to Figure 11-22. The normalized impedance at a reference point, point A, is 0.5 + j0.5. The guided wavelength, λ_g, is 36 mm. Determine the normalized impedance at point B, which is 46.8 mm closer to the generator.

1. On the Smith Chart of Figure 11-23, plot the impedance at reference point A: $Z_{A\ NORM.}$ = 0.5 + j0.5.
2. Plot the SWR circle corresponding to this impedance.
3. Draw a vector from the center point of the chart, through the impedance point $Z_{A\ NORM.}$, to the scale "WAVELENGTHS TOWARD GENERATOR". The vector intersects this scale at 0.088λ (point A).
4. A complete rotation around the Smith Chart corresponds to a displacement of $0.5\lambda_g$. Since 46.8 mm/36 mm = 1.3, the impedance is 0.3λ clockwise from point A on the scale "WAVELENGTHS TOWARD GENERATOR". Therefore, rotate the vector clockwise by 0.3λ (point B).
5. The point where the vector crosses the SWR circle corresponds to the normalized impedance at point B, $Z_{B\ NORM.}$ = 0.59 - j0.7.

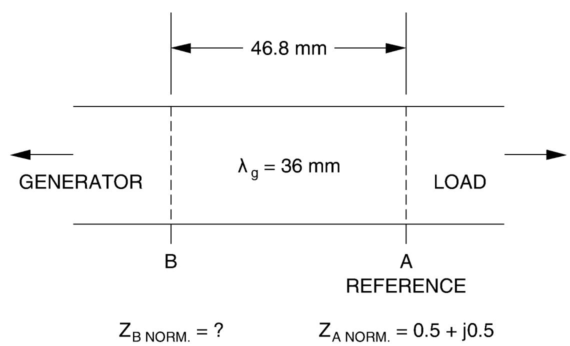


Figure 11-22. Example of circuit in which the impedance at a given point must be determined.

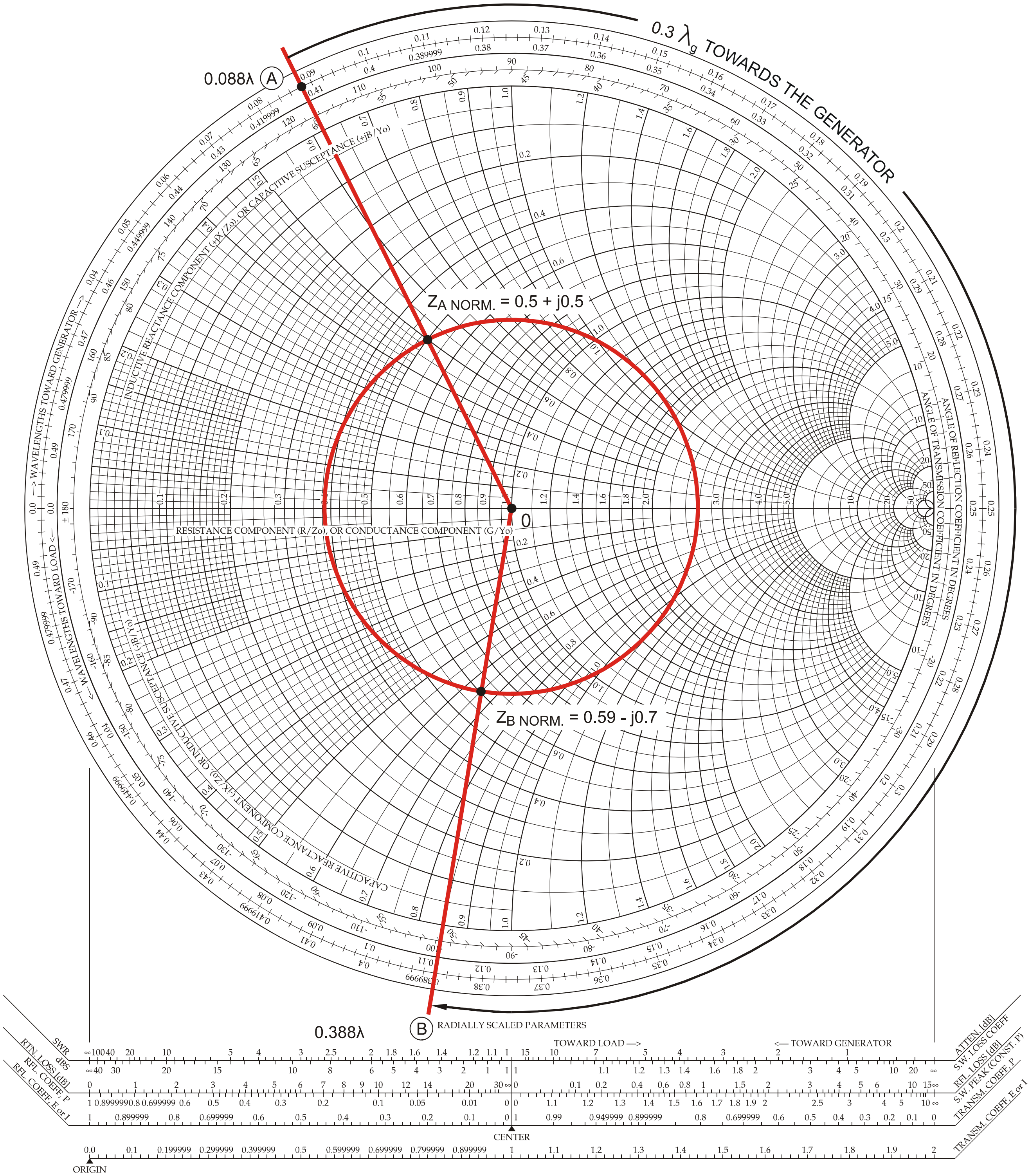


Figure 11-23. Using the Smith Chart to determine the impedance at a given point when the impedance at another point (reference point) is known.

Impedance Matching

At microwave frequencies, matching a load means cancelling the reflected wave so that all the energy that reaches the load is absorbed by the load. This can be done by adding an impedance of proper value to the microwave circuit.

The simplest way of adding an impedance to a microwave circuit is in parallel. For this reason, calculations are often carried out in terms of admittances. As already mentioned, admittance is the inverse of impedance, and is denoted by the letter Y:

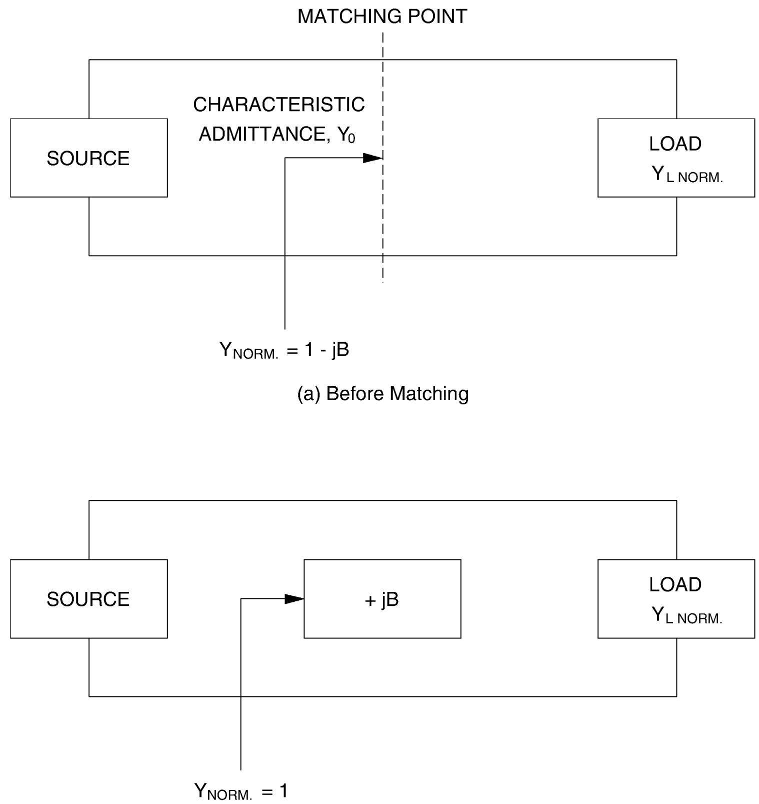
$$Y = \frac{1}{Z} = G + jB$$

where
- Y = Admittance;
- Z = Impedance;
- G = Conductance, or real part of the admittance;
- jB = Susceptance, or imaginary part of the admittance.

One method of obtaining an impedance match consists in adding a pure susceptance, jB, of proper value at a specific location along the waveguide. The specific location is determined by the point along the line where the normalized conductance is equal to 1.

The susceptance to add must be equal in magnitude, but opposite in sign, to the susceptance at the point where the conductance is equal to 1. For example, if the normalized admittance at the point of matching is 1 - jB, the normalized susceptance to add is +jB, as Figure 11-24 shows.

Once the matching has been performed, there is no reflected energy between the source and point of matching because the admittance is equal to the characteristic admittance, Y_0, on that part of the waveguide.



(a) Before Matching

(b) After Matching

Figure 11-24. Matching a load.

Impedance Matching of a Load (Example)

The normalized impedance of a load is $Z_{L\ NORM.}$ = 3 + j0. The guided wavelength, λ_g, is 36 mm.

Determine the value of the susceptance to add in order to match the load, and the location where this susceptance must be placed.

1. On the Smith Chart of Figure 11-25, plot the impedance of the load: $Z_{L\ NORM.}$ = 3 + j0 (point A). Then plot the SWR circle corresponding to this impedance.

2. Draw a vector from the center point of the chart through point A to the wavelength circle.

3. Rotate the vector by 180°: the point where the vector crosses the SWR circle corresponds to the normalized load admittance: $Y_{L\ NORM.}$ = 0.333 + j0 (point B) .

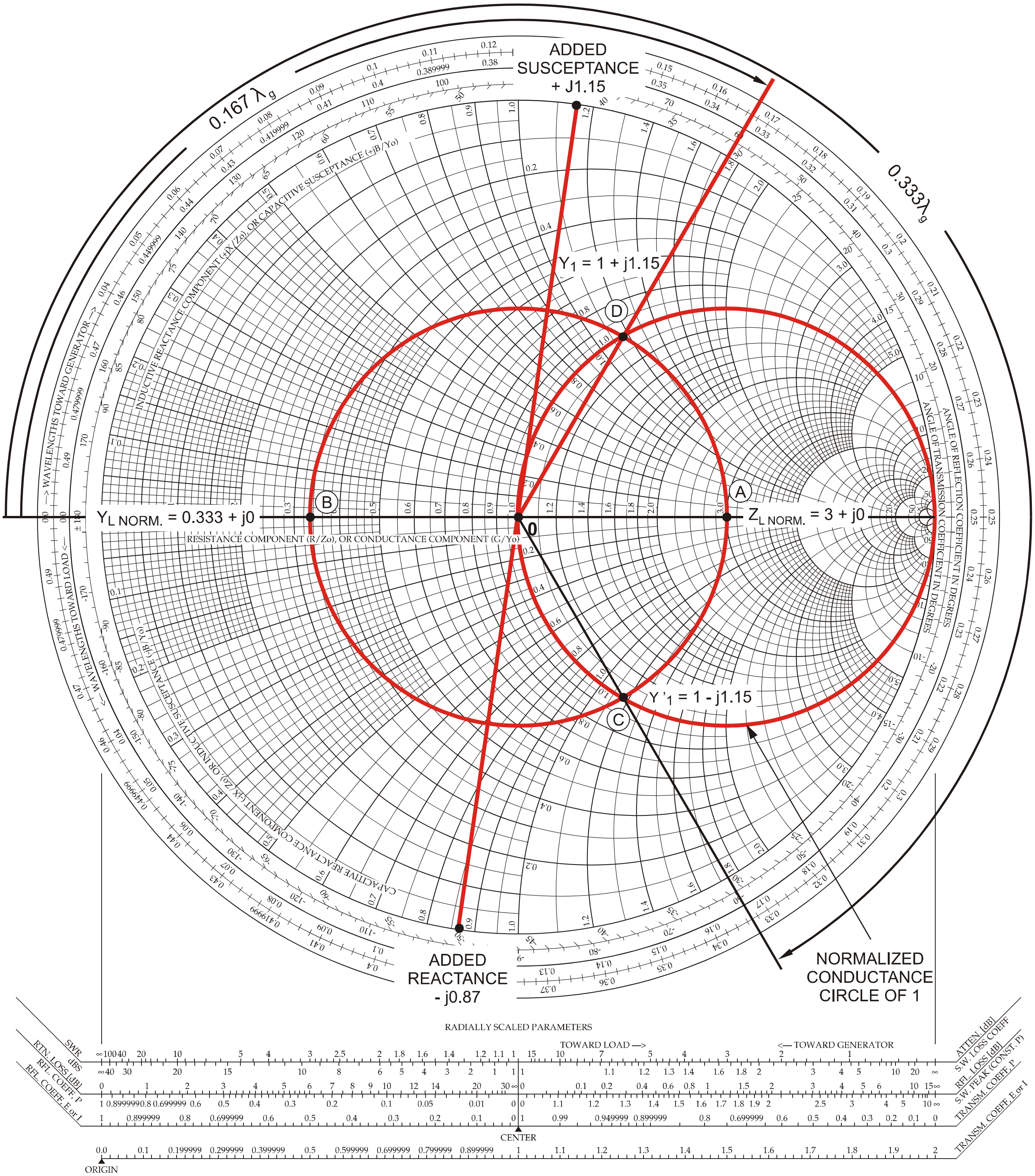


Figure 11-25. Example of impedance matching.

4. Rotate the vector clockwise until the admittance point (point B) is located on the normalized conductance circle of 1.0 in the inductive susceptance (lower) part of the chart (point C): $Y'_1 = 1 - j1.15$.

   On the scale "WAVELENGTHS TOWARD GENERATOR", it can be seen that the vector has been rotated by $0.333\lambda_g$. This rotation corresponds to a distance, d, of $0.333\lambda_g \cdot 36\ mm/\lambda_g = 12.0$ mm.

   Therefore, to match the load, a susceptance of +j1.15 must be added at 12 mm from the load.

   When the susceptance +j1.15 is plotted on the chart, and this point is moved by exactly 180° (λ/4), the chart indicates that the conjugate impedance is a reactance of -j0.87. Therefore, the load could also be matched by adding a reactance of -j0.87 at 12 mm from the load.

   Note: *Note that the admittance point (point B) could also have been moved in the capacitive susceptance (upper) part of the chart on the normalized conductance circle of 1 (point D): $Y_1 = 1 + j1.15$. In that case a susceptance of −j1.15 or a reactance of +j0.87 would be required at 6.00 mm from the load to match it.*

Slide-Screw Tuner

In many applications, the technique just described must be used to match a load.

However, in applications where a variable susceptance of adjustable position such as a slide-screw tuner is available, matching may be carried out without calculations.

Figure 11-26 shows the Lab-Volt Slide-Screw Tuner, Model 9530, and its symbolic representation.

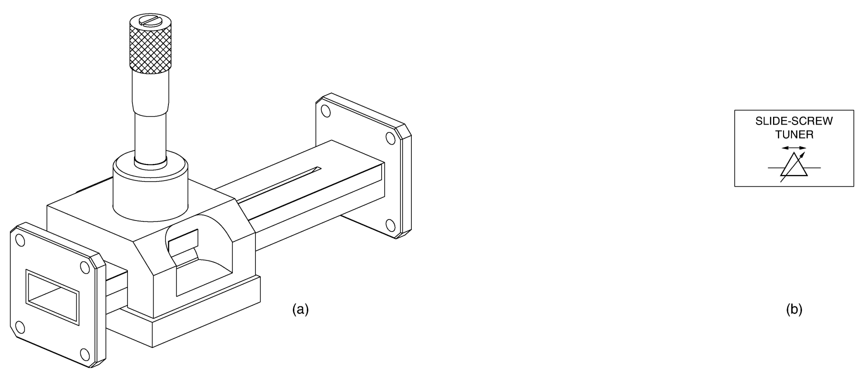


Figure 11-26. The Slide-Screw Tuner and its symbolic representation.

The value of the reactance is varied and its position is adjusted to minimize the reflection coefficient in the waveguide.

The probe is usually placed at a distance such that the susceptance presented by the load is inductive. There are two reasons for this: first of all, it is generally easier to adjust the susceptance of the slide-screw tuner in its capacitive region rather than in its inductive region. And also, the screw penetration is shallower in the capacitive region so that less microwave power is lost because of the screw.

Procedure Summary

In the first part of the exercise, you will measure the impedance of an unmatched load consisting of a capacitive iris mounted in front of a matched load, using the short-circuit minima-shift method learned in part 1 of this EXP.

In the second part of the exercise, you will match the load by using the Slide-Screw Tuner.

In the third part of the exercise, you will measure the SWR of the load to verify that it has been properly matched.

In the last part of the exercise, you will use the Smith Chart to determine the theoretical impedance and the location of the matching device (the Slide-Screw Tuner) required to match the load. You will compare your results with the practical results obtained in the exercise.

PROCEDURE

Measuring the Impedance of an Unmatched Load

☐ 1. Make the following settings

On the Gunn Oscillator Power Supply:

VOLTAGE . . . . MIN.
MODE . . . . 1 kHz
METER SCALE . . . . 10 V

☐ 2. Referring to the attenuation-versus-blade position curve (or the corresponding Data Table) of the Lab-Volt Variable Attenuator determine the attenuator's blade position required for this attenuator to provide an attenuation of 12 dB approximately.

Set the attenuator's blade to this position.

Attenuator blade's position: ______ mm

☐ 3. Turn on the Gunn Oscillator Power Supply and the Data Acquisition Interface (DAI) by setting their POWER switch to the "I" (ON) position.

Set the Gunn Oscillator supply voltage to 8.5 V. Wait for about 5 minutes to allow the modules to warm up.

☐ 4. On the host computer, start the LVDAM-MW software. In the Application Selection window, make sure the Work in stand-alone box is unchecked, and click OK.

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

☐ 5. **Taking care not to modify the Variable Attenuator's blade adjustment**, modify your microwave circuit in order to obtain the circuit shown in Figure 11-28. The capacitive iris is the iris that has a rectangular orifice (it is included in your accessories kit). When installing this iris, make sure to align its four holes with the holes of the waveguide flanges, since the orientation will affect the impedance of the iris.
Leave the rest of the equipment connected and set as before.

☐ 6. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to ON.
Wait for about 5 minutes to allow the modules to warm up.

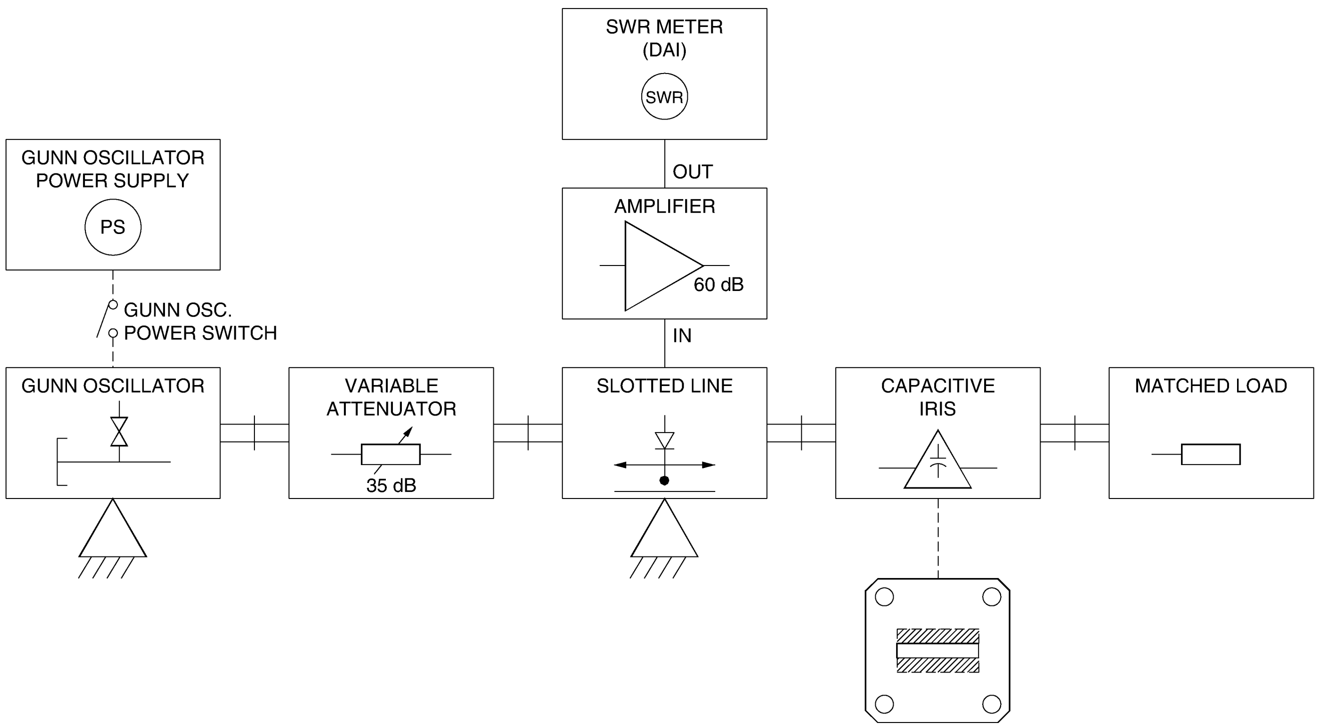


Figure 11-28. Modified microwave circuit to measure the impedance of the unmatched load.

☐ 7. Set Gain Input 3 to 0 dB. While observing the SWR Meter reading, locate the Slotted Line's probe over the maximum nearest the load to obtain the maximum signal level on this meter.

Then, adjust the frequency of the SWR Meter's amplifier for the signal level to be maximum on this meter.

If the maximum signal level obtained on the SWR Meter is

a. between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 18.

b. between 10 and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

Note: *If you cannot find the location of the maximum because the signal level displayed by the SWR Meter exceeds the measurement scale (the horizontal indicator bar of the meter turns to red). Readjust (decrease) the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (for example, about 25% of full scale once the thumbscrew of the Slotted Line has been re-tightened). Then, locate the Slotted Line's probe over the maximum nearest the load and perform step 7.*

☐ 8. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 9. Locate the Slotted Line's probe over the minimum that is nearest the unmatched load. Record the location of this MIN below.

Then, set the SWR Meter to display the SWR as a dimensionless number (linear scale). Record the SWR Meter reading below.

Location of MIN = ______ mm

$SWR_{\text{(UNMATCHED LOAD)}}$ = ______

Calculate the distance, d, that the minimum shifted due to the change in load impedance, using the equation below:

d = MIN_2 - MIN = ______ mm

where MIN_2 = Location of the second minimum with the short-circuited load.
MIN = Current location of the Slotted Line's probe.

____

Does the measured SWR suggest a matched load? Explain.

____

____

☐ 10. Based on the distance, d, obtained in the previous step, and on the guided wavelength, λ_g calculate the phase angle (φ) of the reflection coefficient:

$$\varphi = 180° \left(1 - \frac{4d}{\lambda_g}\right)$$

φ = ______ °

☐ 11. In LVDAM-MW, select the Smith Chart function, which will bring up this chart.

In the Settings panel of the Smith Chart, enter the measured SWR to plot the corresponding SWR circle.

Determine the normalized impedance, $Z_{L\ NORM.}$ of the unmatched load: rotate the vector of the Smith Chart along the scale of the reflection coefficient angle—on the outer rim of the chart—until it intersects the angle (φ). (The field Reflection Coefficient Angle in the Settings panel of the Smith Chart indicates this angle when the vector is properly positioned.)

The point where the vector crosses the SWR circle corresponds to $Z_{L\ NORM}$. The real and imaginary parts of this impedance are indicated in the Impedance section of the Settings panel. Record this impedance below.

$Z_{L\ NORM.}$ = ____________

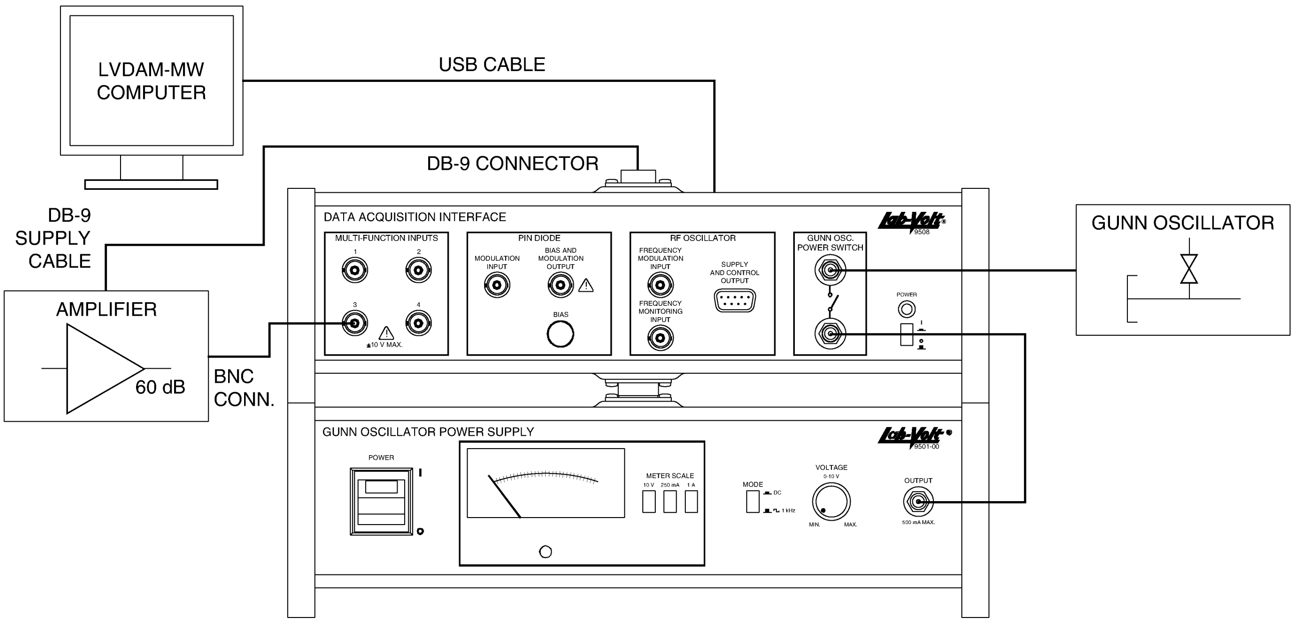
Close the Smith Chart.

Adjusting the Slide-Screw Tuner to Match the Load

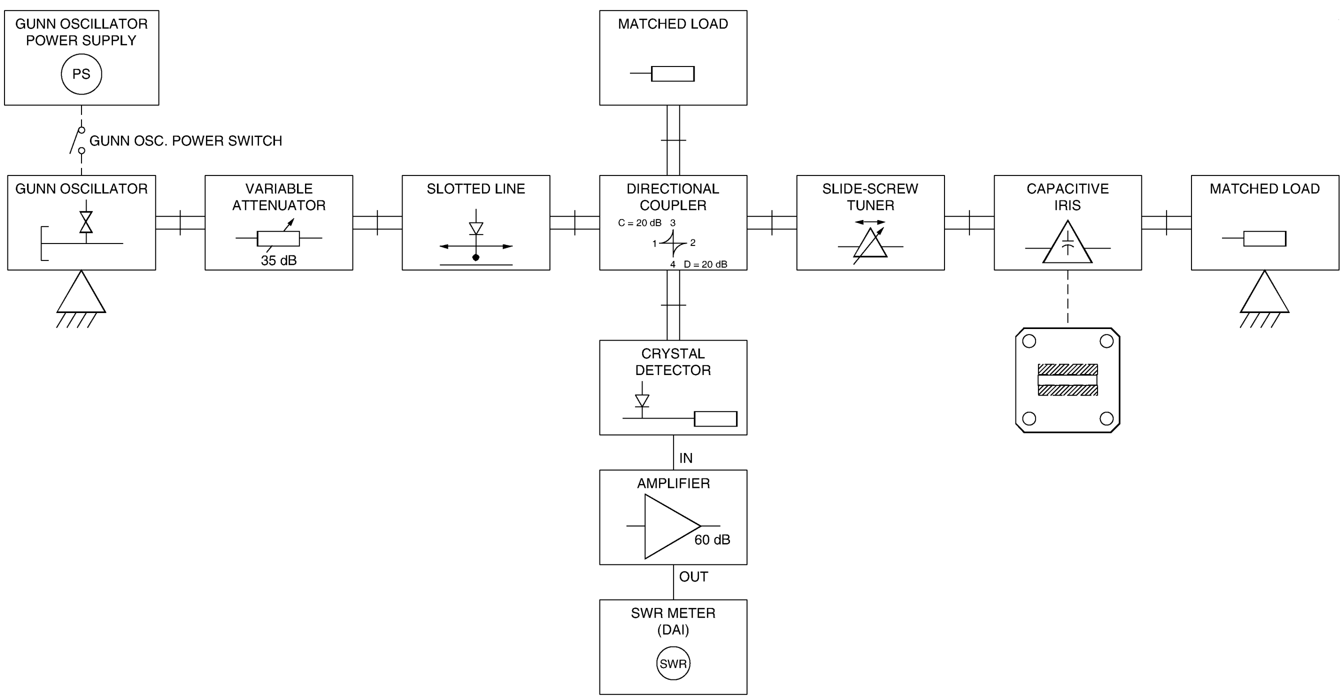
☐ 12. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.

☐ 13. **Taking care not to modify the Variable Attenuator's blade adjustment**, modify your microwave circuit in order to obtain the circuit shown in Figure 11-29.

Move the probe of the Slide-Screw Tuner along the waveguide and set it over the 45-mm position. (The 45-mm mark on the waveguide scale intersects the 0-mm (rightmost) mark on the carriage scale). Adjust the probe penetration on the Slide-Screw Tuner to 0.00 mm.



(a)



(b)

Figure 11-29. Modified microwave circuit used to match the load impedance with the Slide-Screw Tuner.

☐ 14. Set the SWR Meter to display decibels (dB).

In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

Wait for about 5 minutes to allow the modules to warm up.

☐ 15. Using the cursor of the SWR Meter, scan through the frequency range of this meter to find the frequency at which the signal level is maximum. Set the cursor to this frequency. (Increase the Gain on Input 3, if necessary).
Once the SWR Meter has been tuned to obtain the maximum signal level, click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 16. Increase the depth of penetration of the probe of the Slide-Screw Tuner until the SWR Meter reading (and, therefore, the magnitude of the reflected signal) increases or decreases by about 1 dB.

☐ 17. If the amplitude of the reflected signal has increased, move the carriage of the Slide-Screw Tuner to minimize the reading. Otherwise go immediately to the next step.

☐ 18. By using the Slide-Screw Tuner, minimize the magnitude of the reflected wave in order to match the load:

Adjust both the penetration and the location of the Slide-Screw Tuner's probe along the waveguide carriage scale until you obtain the minimum signal level on the SWR Meter. (Increase the Gain on Input 3 as necessary).

For the location of the Slide-Screw Tuner's probe, find the location nearest the load that provides the minimum signal level. (There are other locations where the signal level is minimum. Using the location nearest the load will simplify the calculations made with the Smith Chart in the steps to follow).

Record below the location of the Slide-Screw Tuner's probe nearest the load where the signal level is minimum. (Normally, the reflected signal can be reduced down to the minimum measurable level of the SWR Meter when Gain Input 3 is set to 40 dB.)

Location of the Slide-Screw Tuner's probe: ______ mm

Measuring the SWR of the Matched Load

☐ 19. In the Settings panel of LVDAM-MW, set the field Gunn Oscillator/VCO Power to OFF.

☐ 20. Disconnect the 60-dB Amplifier from the Crystal Detector and connect it to the Slotted Line in order to obtain the circuit shown in Figure 11-30. **DO NOT modify the adjustments of the Slide-Screw Tuner and the Variable Attenuator's blade**.

☐ 21. In the Settings panel of LVDAM-MW, make the following settings:

Gunn Oscillator/VCO Power . . . . ON
Function Input 3 . . . . SWR Meter
Gain Input 3 . . . . 0 dB
60 dB Ampli on Input 3 . . . . ON

Wait for about 5 minutes to allow the modules to warm up.

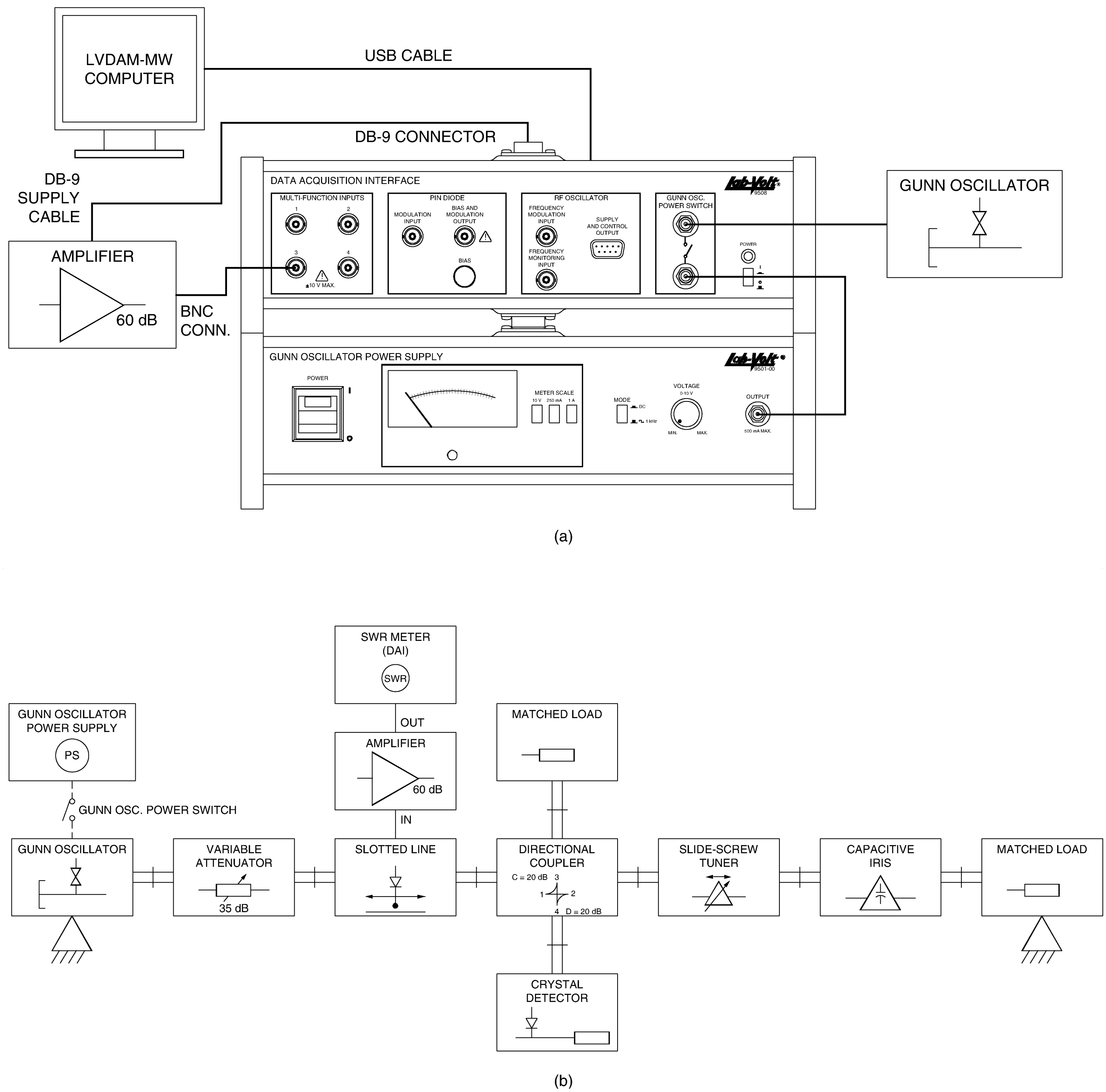


Figure 11-30. Modified microwave circuit used to determine the SWR of the matched load.

☐ 22. While observing the SWR Meter reading, locate the Slotted Line's probe over the maximum nearest the load to obtain the maximum signal level on this meter.

Then, adjust the frequency of the SWR Meter's amplifier for the signal level to be maximum on this meter.

If the maximum signal level obtained on the SWR Meter is

a. between 70 and 90% of full scale and the horizontal indicator bar stays green, the equipment is properly adjusted. Go immediately to step 23.

b. between 10 and 70% of full scale, loosen the thumbscrew of the Slotted Line and very slightly readjust the depth of its probe so that the maximum signal level indicated by the SWR Meter is between 70 and 90% of full scale (and the green bar stays green) once the thumbscrew of the Slotted Line has been re-tightened (the tightening of the thumbscrew will cause the signal level to vary slightly).

Note: *If you cannot find the location of the maximum because the signal level displayed by the SWR Meter exceeds the measurement scale (the horizontal indicator bar of the meter turns to red), DO NOT modify the adjustment of the Variable Attenuator's blade. Instead readjust (decrease) the depth of the Slotted Line's probe in order to obtain a significant reading on the SWR Meter (for example, about 25% of full scale once the thumbscrew of the Slotted Line has been re-tightened). Then, locate the Slotted Line's probe over the maximum nearest the load and perform step 22.*

☐ 23. Click on the REFERENCE button of the SWR Meter to set the reference level to 0.0 dB.

☐ 24. Locate the Slotted Line's probe over the minimum nearest the load. Then, set the SWR Meter to display the SWR as a dimensionless number. Record below the SWR indicated by the SWR Meter at that location.

$SWR_{(MATCHED\ LOAD)}$ = ______

Is the measured SWR very close to 1, suggesting a matched load? Explain.

____

____

Determining the Impedance and the Location of the Matching Device (Slide-Screw Tuner) Required to Match the Load

☐ 25. Using the Smith Chart, determine the location where the matching device (the Slide-Screw Tuner's probe) must be located and the impedance that this matching device must have to match the load.

a. In LVDAM-MW, select the Smith Chart function, which will bring up this chart.

b. In the Smith Chart Settings panel, enter the SWR measured for the unmatched load: the corresponding SWR circle apppears on the Smith Chart .

$SWR_{(unmatched\ load)}$ = ______

c. Determine the normalized impedance of the unmatched load $Z_{L\ NORM.\ (UNMATCHED\ LOAD)}$: rotate the vector of the Smith Chart along the scale of the reflection coefficient angle—on the outer rim of the chart—until it intersects the angle (φ) . (The field Reflection Coefficient Angle in the Settings panel of the Smith Chart indicates this angle when the vector is properly positioned.)

   The real and imaginary part of $Z_{L\ NORM.\ (UNMATCHED\ LOAD)}$ are now indicated in the Impedance section of the Settings panel. Record this impedance below.

   $Z_{L\ NORM.\ (UNMATCHED\ LOAD)}$ = ____________

d. Record the corresponding normalized admittance of the unmatched load below, as recorded in the field Admittance of the Settings panel.

   $Y_{L\ NORM.\ (UNMATCHED\ LOAD)}$ = ____________

e. Move the vector by 180°: the field Impedance of the Settings panel now indicates the real and imaginary values recorded for $Y_{L\ NORM.\ (UNMATCHED\ LOAD)}$ in step d.

f. Read off the wavelength currently indicated by the vector, λ_1, that is, the point where the vector crosses the wavelength (λ) scale on the outer rim of the chart. Record this wavelength below.

   λ_1 = ______

g. Rotate the vector clockwise to the point where the SWR circle cuts the normalized conductance circle of 1.0 in the inductive susceptance (lower) part of the chart (admittance $Y'_1 = 1 - jB$).

   The susceptance to be added to match the load must be equal in magnitude, but opposite in sign, to the susceptance at point Y'_1.

   This susceptance corresponds to the reactance value currently indicated in the Impedance section of the Settings panel, but with the opposite sign. Record below the susceptance required to match the load.

   Susceptance required to match the load = ______

   Read off the wavelength currently indicated by the vector, λ_2, on the wavelength scale. Record this wavelength below.

   λ_2 = ______

h. Based on λ_1 and λ_2 recorded in steps f. and g., calculate the rotational displacement of the vector in wavelength units, λ_g:

   Rotational displacement = $\lambda_2 - \lambda_1$ = ______ λ_g

i. Convert the rotational displacement into a real distance, in millimeters units, based on the guided wavelength .

$$\text{Rotational Displacement } (\lambda_g) \cdot \text{ Guided Wavelength } (\text{mm} / \lambda_g) = \_\_\_\_\_\_ \text{ mm}$$

j. Add one guided wavelength to the distance obtained in step i to obtain the distance from the load.

$$\text{Guided Wavelength } (\text{mm} / \lambda_g) + \text{ Distance } (\text{mm}) = \_\_\_\_\_\_ \text{ mm}$$

Compare your result to the current distance of the Slide-Screw Tuner's probe from the load .

How do your results compare?

____

____

☐ 26. Turn off the Gunn Oscillator Power Supply and the Data Acquisition Interface by setting their POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

☐ 27. Close the LVDAM-MW software.

CONCLUSION

In this exercise, you learned how to use the Smith Chart to evaluate the impedance at any point along a waveguide from a reference point. You also learned how to match a complex impedance, using a matching device called a slide-screw tuner. You saw that the location where the slide-screw tuner must be placed, and the impedance required to match the load can be determined by using the Smith Chart.

REVIEW QUESTIONS

1. What is impedance matching?

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2. Briefly describe the procedure used to match a load with a slide-screw tuner.

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   ____

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3. Why are admittances used instead of impedances when doing calculations to match loads?

   ____

   ____

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4. Why is it easier to match an impedance with a slide-screw tuner than with an iris?

   ____

   ____

5. Figure 11-31 shows a waveguide with a load that has been matched by using a slide-screw tuner located at point 1. What impedance will be presented by the waveguide to the generator if the screw is moved from point 1 to point 2? Explain.

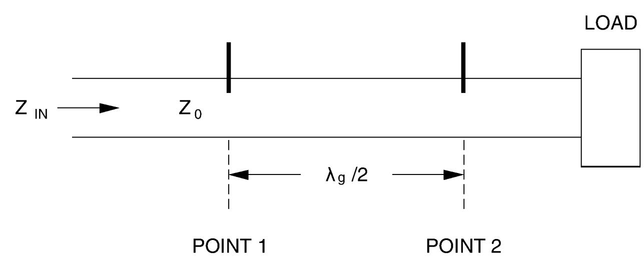


Figure 11-31. Line terminated by a load that has been matched with a slide-screw tuner.

PART ONE :Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

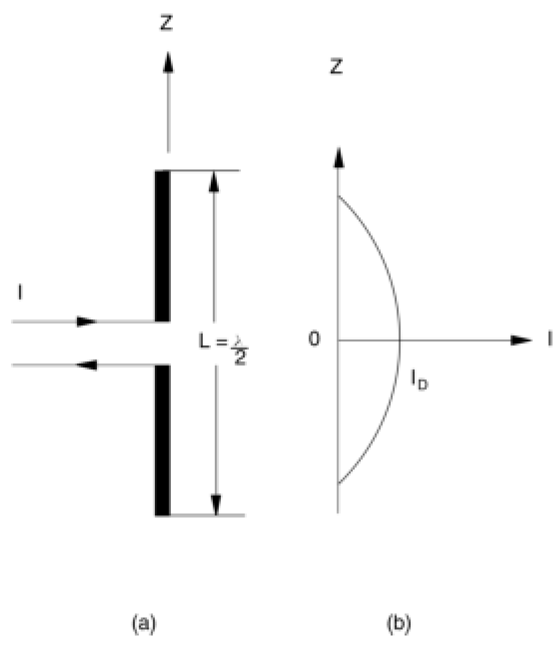
EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the characteristics of the half-wave folded dipole antenna and with the use of baluns for impedance transformation.

DISCUSSION

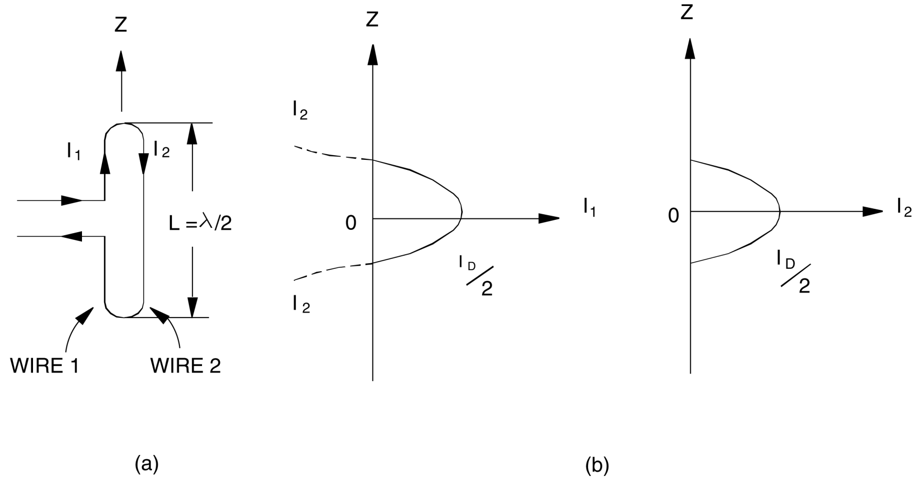
Description of the half-wave folded dipole

The **folded dipole** antenna consists of two parallel dipoles connected into a narrow wire loop. Figures 12-1 and 12-2 illustrate the differences between a half-wave dipole and a half-wave folded dipole.



(a) physical configuration, (b) current distribution

Figure 12-1. The half-wave dipole



(a) physical configuration, (b) current distributions

Figure 12-2. The half-wave folded dipole

In the half-wave dipole of Figure 12-1, the current is forced to zero at both ends of the dipole. The current distribution is sinusoidal with a maximum of I_D at the centre.

The current distribution on a dipole can be expressed as

$$I(z) = I_D \sin\left[\frac{2\pi}{\lambda}\left(\frac{L}{2} - |z|\right)\right], \quad |z| < \frac{L}{2} \tag{1}$$

where z and L are as shown in Figure 12-11.

The half-wave folded dipole of Figure 12-12 has the same sinusoidal current distribution on wire 1, except that the maximum value at the centre is $I_D/2$ instead of I_D. The sinusoidal current falls to zero at both ends of wire 1, then increases again as wire 1 turns into wire 2. The current goes through another maximum at the centre of wire 2.

The two current distributions on wire 1 and wire 2 of the folded dipole, added together, are the same as the current distribution on the half-wave dipole. The radiating power is also the same.

$$P_D = \frac{1}{2}Z_D I_D^2 = P_F = \frac{1}{2}Z_F I_F^2 = \frac{1}{2}Z_F\left(\frac{I_D}{2}\right)^2 \tag{2}$$

where P_D, Z_D, I_D are the power, impedance and current of the dipole, respectively
P_F, Z_F, I_F are the power, impedance and current of the folded dipole, respectively.

Consequently, the input impedance of the folded dipole is four times larger than that of the half-wave dipole, which is 73 Ω.

$$Z_F = (4)Z_D = (4)(73) = 292\ \Omega \tag{3}$$

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

Note: *Different authors quote slightly different values for the input impedance of the half-wave dipole, for instance, 70, 72, or 73 Ω. Consequently, the input impedance of the folded dipole is also quoted at different values from 280 Ω to 300 Ω.*

When there is an impedance mismatch, Equation (4) relates the power transmitted through the impedance junction to the power reflected.

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - \left|\frac{Z_{ant} - Z_L}{Z_{ant} + Z_L}\right|^2$$

where P_T is the power transmitted through the impedance junction
P_{Rfl} is the power reflected at the impedance junction
SWR is the voltage standing wave ratio ($SWR = Z_{ant}/Z_L$)

For instance, if there is a perfect match, $Z_{ant} = Z_L$ and there is no standing wave since $SWR = Z_{ant}/Z_L = 1$. In this case, there is no reflected power.

$$P_{Rfl} = \left|\frac{SWR - 1}{SWR + 1}\right|^2 = \left|\frac{0}{1}\right|^2 = 0$$

and all the power is transmitted.

In the case of a 73 Ω transmission line feeding into a half-wave folded dipole with four times the line impedance (4 × 73 = 292 Ω), a standing wave is produced and the SWR is

$$SWR = \frac{Z_{ant}}{Z_L} = \frac{4}{1} = 4$$

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - \left|\frac{3}{5}\right|^2 = 0.64$$

In this case, 64% of the power would be transmitted and 36% would be reflected.

This effect is not necessarily catastrophic (although it might be at high power levels), but it is undesirable. It would be preferable to obtain good impedance matching between the line and the antenna, as shown in Figure 12-3.

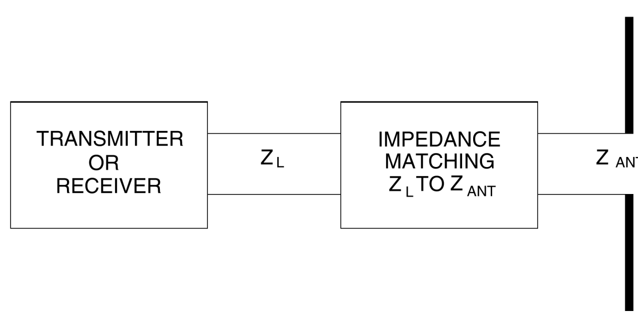


Figure 12-3. Impedance matching between transmission line and antenna

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

Connecting balanced to unbalanced transmission lines through a balun

A problem which is related to the problem of impedance matching is to connect a balanced antenna (such as a centre-fed dipole) to an unbalanced transmission line (such as a coaxial cable).

If the centre-fed dipole is connected to a balanced transmission line, such as a parallel-wire pair, the question of balanced to unbalanced connection does not arise.

If the centre-fed dipole is connected to a coaxial cable, however, the balance is upset. One side of the dipole is connected to the inner conductor while the other side is connected to the shield, and a current will flow on the outside of the shield. This current creates a field which cannot be cancelled by the fields from the current on the inner conductor, because of the shielding. Therefore there will be radiation from the current on the outside shield of the coaxial cable.

This problem can be resolved by using an extra length (λ/4) of coaxial cable as illustrated in Figure 12-4, connecting the outside shields together at a point λ/4 below the antenna terminals. A second current is then induced on the outside shield and the two currents cancel each other. This arrangement is called a **balun**, which is a contraction of "balanced to unbalanced."

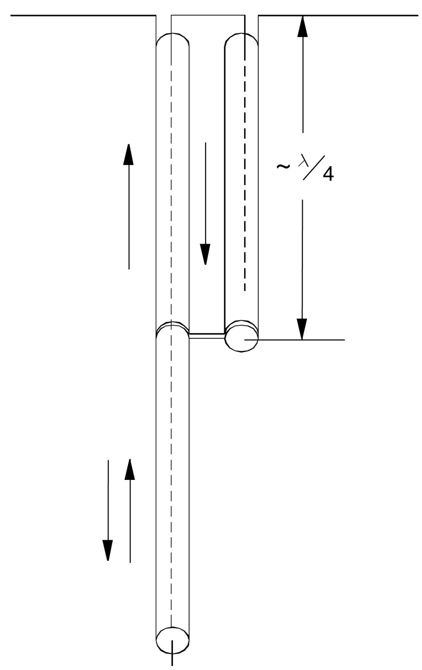


Figure 12-4. Balun for connecting a centre-fed dipole to a coaxial cable

The principle is that the λ/4 transmission line appears as an infinite impedance to the dipole and does not affect its operation. However, the current which flows on it balances the current which flows on the outside of the coaxial cable.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

There are a number of types of baluns. The dipole connectors in the Antenna Training and Measuring System are equipped with baluns similar to that shown in Figure 12-4. There are also baluns which, in addition to a balanced-to-unbalanced connection, offer impedance transformation.

In the next section, you will study a half-wave folded dipole connected to a coaxial cable, in one case without a balun, and in the second case, through a balun which offers a 4-to-1 impedance transformation.

The Lab-Volt half-wave folded dipole

The Antenna Training and Measuring System includes a 1-GHz half-wave folded dipole. As shown previously, this type of dipole has an input impedance of 292 Ω.

The transmission lines used for connecting to the 1 GHz antennas in the Lab-Volt system are 50-Ω coaxial cables.

The Lab-Volt system offers two types of transitions from the 50-Ω coaxial cable to the 292-Ω folded dipole antenna, one without a balun and one with a "four-to-one" impedance transformation balun.

Transition without a balun

Figure 12-5 illustrates a transition without a balun from a 50-Ω coaxial cable to a 300-Ω parallel wire pair balanced transmission line and then to the approximately 300-Ω half-wave folded dipole.

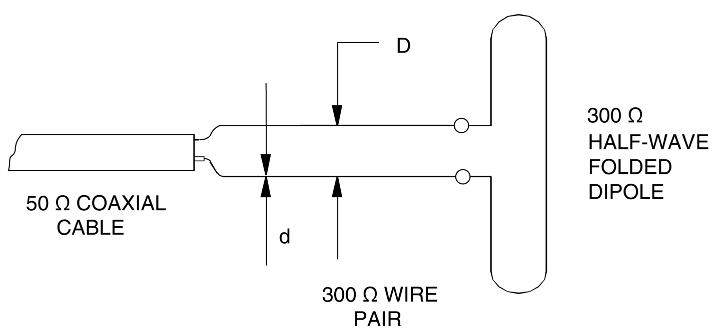


Figure 12-5. Transition without a balun from a 50-Ω unbalanced coaxial cable to a 300-Ω balanced wire pair and to a 300-Ω half-wave folded dipole

> **Note:** *The impedance of a parallel wire pair is a function of the ratio D/d, where D is the distance between the two wires and d is the diameter of each wire. For 300 Ω, D/d ≈ 6, for 75 Ω, D/d ≈ 1.25.*

In the case of Figure 12-5, due to the impedance mismatch between 50 Ω and 300 Ω, the SWR will be 300/50 = 6.

The relationship between the transmitted power P_T and the reflected power P_{Rfl} will be

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - 0.51 = 0.49 \qquad (8)$$

With perfect impedance matching, 100% of the power would be transmitted. In this case, however, only about 50% of the power will be transmitted. The other half will be reflected—a loss of 3 dB relative to the perfect impedance matching case.

Transition by a four-to-one impedance transformation balun

Figure 12-6 illustrates the transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole using a four-to-one impedance transformation balun. Folded dipole-balun assemblies may occasionally be connected to a 72 Ω coaxial cable such as RG-59U.

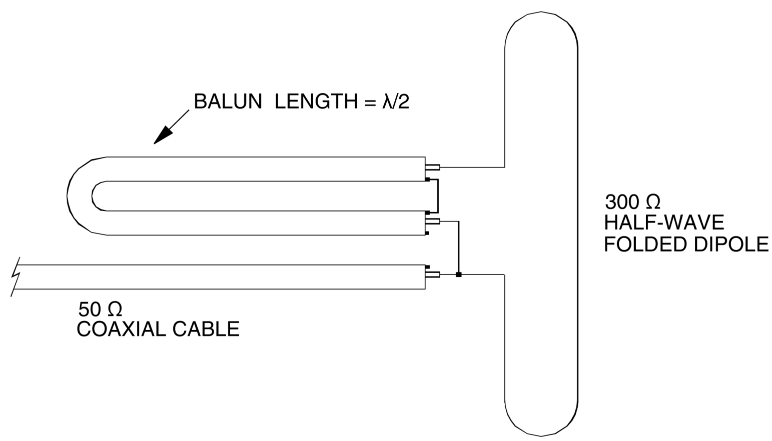


Figure 12-6. Transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole through a four-to-one impedance transformation balun.

Note that the four-to-one transformation is not quite ideal in this case. Ideally, a 6-to-1 impedance transformation would be required to go from 50 to 300 Ω.

Although imperfect, this four-to-one impedance transformation offers substantial improvement. The impedance transformer transforms the 300-Ω impedance into a 75-Ω impedance so that the impedance transition from the 50-Ω coaxial cable causes a SWR of 75/50 = 1.5

The relation between the transmitted and the reflected power is now

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - 0.04 = 0.96 \qquad (9)$$

Therefore, 96% of the power is transmitted and only 4% is reflected, which is not far from the ideal 100% transmission.

The half-wave folded dipole with balun is almost twice as efficient as the one without a balun. This will result in a difference of approximately 3 dB in measurements.

Operation of the four-to-one impedance transformation balun

The operation of the balun can be explained as follows.

Suppose that there is a voltage $V_1 = V_o \cos(\omega t)$ between the centre connector of the coaxial cable and the grounded outside shield. This is in particular the case at the unbalanced end at point c of Figure 12-7.

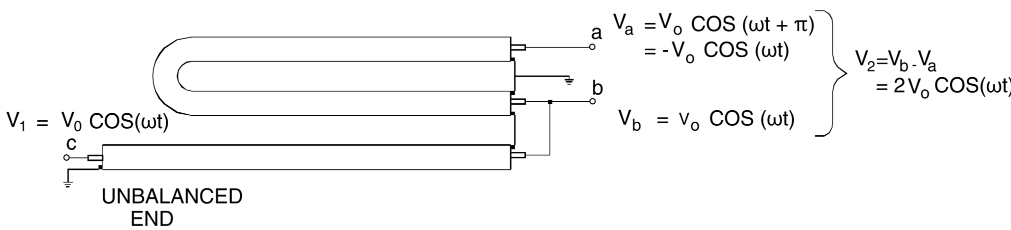


Figure 12-7. Operation of the four-to-one impedance transformation balun

Since there is no significant loss in the cable, the voltage between the centre conductor and the grounded shield will again be $V_b = V_o \cos(\omega t)$ at point b some distance away.

Between point b and point a, however, there is exactly a distance of $\lambda/2$. Between these two points a phase shift of π or 180° will occur and the voltage between the centre conductor and the grounded shield at point a will be

$$V_a = V_o \cos(\omega t + \pi) = -V_o \cos(\omega t) \qquad (10)$$

Then

$$V_2 = V_b - V_a = 2V_o \cos(\omega t) \qquad (11)$$

Since there is no significant loss in the coaxial cable, the radiated power P_2 measured at the balanced end (antenna end, i.e., points a and b) will be the same as the power P_1 measured at the unbalanced end (cable end, i.e., point c).

Using the relationship $P = \frac{V_{rms}^2}{Z}$, one can then write

$$P_1 = \frac{(v_{1\,rms})^2}{Z_1} = P_2 = \frac{(V_{2\,rms})^2}{Z_2} \qquad (12)$$

or

$$\frac{Z_2}{Z_1} = \frac{(v_{2\,rms})^2}{(v_{1\,rms})^2} = 2^2 = 4 \qquad (13)$$

Thus, $Z_2 = 4\,Z_1$.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

Procedure Summary

In this exercise you will plot the radiation patterns of a folded dipole with and without a balun. You will then better understand the increase in gain resulting from the use of a 4:1 balun on an antenna having an input impedance of 300 Ω. You will learn the meaning of gain expressed in dBd and use this concept to evaluate the gain of the folded dipole. Finally, you will observe how a metal boom placed behind a dipole affects its directivity.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission mast support. Clip the Yagi antenna on the mast, oriented for an acquisition in the E-plane, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator, using the long SMA cable.

☐ 3. Select the folded dipole connector **with** balun and the folded wire, then set up a folded dipole antenna, as shown in Figure 12-8.

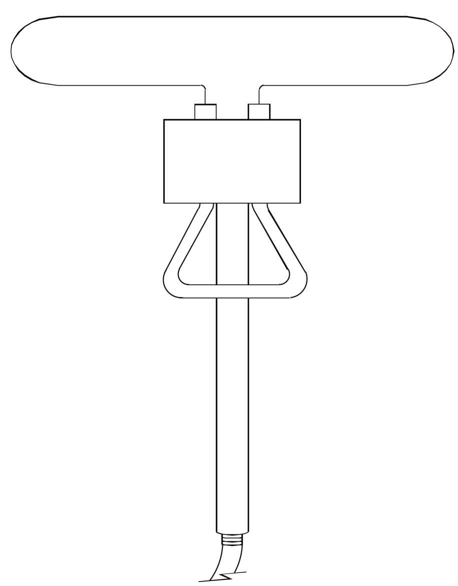


Figure 12-8. Set-up of a folded dipole antenna with balun

☐ 4. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner. Attach the folded dipole to the mast.

Using the sliding support, ensure that the antenna is in line with the rotation centre of the Antenna Positioner and oriented to rotate in the E-plane (the folded dipole has the same polarization as that of the basic dipoles in Exercise 1-4).

Screw the 10 dB attenuator onto the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

☐ 5. Position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Use the Attenuation control to optimize reception of the signal.

Start your acquisition and store the radiation pattern in a new document (Document1), making sure you have selected the correct plane.

☐ 8. Rotate the Yagi antenna so that it is vertically polarized.

Remove the antenna mast with vertical clips from the sliding support and replace it with the other mast that uses horizontal clips. Making sure that it rotates in the H-plane, install the folded dipole on this new mast and replace the short SMA cable with the intermediate one, as in Figure 12-9.

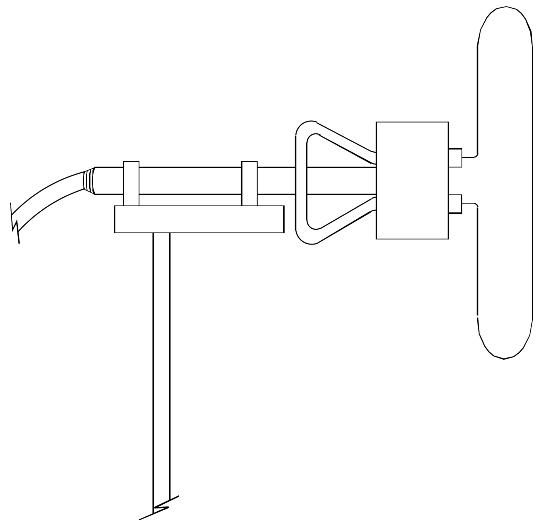


Figure 12-9. Set-up for a rotation in the H-plane

Perform a new acquisition and store it as the H-plane of Document1.

☐ 9. Remove the complete folded dipole assembly from the receiving mast. Use the folded wire of this antenna, and set up another antenna using the folded dipole connector **without** the balun. Clip this new antenna onto the mast.

> **Note:** *Make sure that the set-up here is the same as that in the preceding step - otherwise you won't be able to compare the two. This remark also applies to acquisitions made in the E-plane.*

☐ 10. Do not modify the attenuation level; start an acquisition of the H-plane pattern.

Make the appropriate modifications (including the replacement of the receiving cable), then perform an acquisition of the E-plane. Store these two patterns in a new document (Document2).

☐ 11. Observe the patterns carefully. Which antenna gives the better gain and what is the difference (in dB) between them? To obtain a convenient graph for your comparison, print the H-plane patterns of both antennas on the same sheet (remember to save the patterns stored in the Document1 and Document2 before printing).

____

Gain of a folded dipole

☐ 12. Set-up a λ/2 dipole to replace the folded dipole antenna. Without changing the attenuation level, perform an acquisition of the E-plane. Store this pattern in a new document (Document3).

☐ 13. In Exercise 1-2, you saw that the antenna gain, which equals directivity multiplied by antenna efficiency, is a value expressed in dB relative to a hypothetical isotropic antenna. In antenna literature, you will often encounter antenna gain expressed in dBi, which is the gain relative to an isotropic radiator. Antenna gain can also be expressed relative to a half-wave dipole, thus gain in dBd, as shown in Figure 12-10. This figure shows the E-plane radiation patterns of a half-wave dipole (the 0-dB reference) and an example antenna, AntX. As can be seen from these patterns, the MSL of AntX is about 8.4 dB greater than the MSL of the dipole. Therefore, the gain of AntX is 8.4 dBd with respect to the 0-dB reference plot of the half-wave dipole.

If the gain in dBi of a half-wave dipole is known, then it is easy to convert from a gain in dBd to a gain in dBi. The typical, measured gain in dBi of the half-wave dipole in the Lab-Volt system is 1.9 dBi (the theoretical value for a half-wave dipole is 2.14 dBi). Therefore the gain of AntX expressed in dBi equals 8.4 + 1.9 = 10.3 dBi.

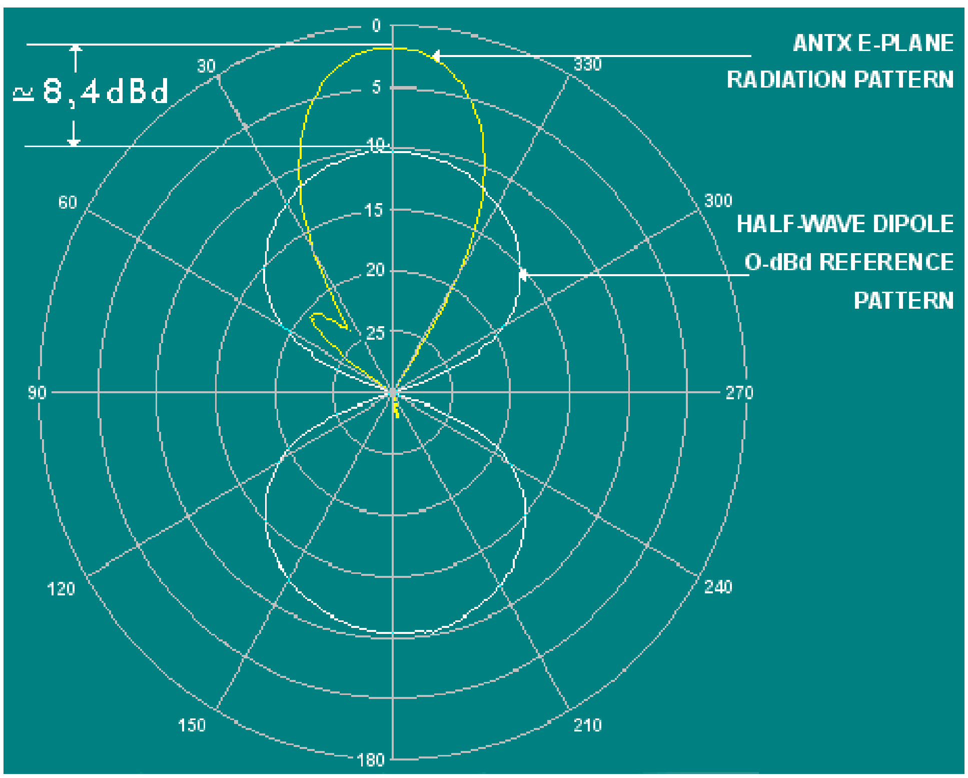


Figure 12-10. Gain expressed as a value over a dipole reference

In theory, the gain of the half-wave dipole and the folded dipole are supposed to be the same; in practice, however, differences sometimes occur. Using the typical dBi gain of the Lab-Volt half-wave dipole, express the gain of the folded dipole with balun in both dBd and dBi.

G = ______ dBd = ______ dBi

☐ 14. Print the 3-D representation of the radiation pattern of the folded dipole with balun and observe its similarity to that of the λ/2 dipole printed in Exercise 1-4.

CONCLUSION

In this exercise, you saw the radiation pattern of a folded dipole and observed the efficiency of a 4:1 balun used on an unmatched antenna. Using the gain of a λ/2 dipole antenna as a reference, you evaluated the gain of a folded dipole; you saw that these two gains are very similar. Finally, you improved the directivity of the folded dipole antenna by placing a metal boom behind it.

REVIEW QUESTIONS

1. Why is the impedance of the folded dipole four times greater than that of a λ/2 dipole?

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2. What does the expression "perfect impedance match" mean? Why is it important for the antenna and the transmission line impedances to match, and what happens when a transmitting antenna is not correctly matched with the transmission line?

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3. An antenna has a $HPBW_E$ = 28° and a $HPBW_H$ = 32°. Calculate the gain of this antenna referenced to a theoretical half-wave dipole.

___

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4. The use of a 4:1 balun improves the gain of a folded dipole fed by a 75 Ω transmission line. Explain why.

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PART TWO :Loop Antennas

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with loop antennas of length λ, and with the characteristics of small loop antennas.

DISCUSSION

Full-wave loop antennas

Loop antennas with a loop length of λ (full-wave loop antennas) are useful because they offer reasonable gain and a convenient input impedance. They come in many shapes: circular, square, rectangular, and lozenge (diamond) shape. All shapes give more or less equivalent radiation patterns and gains.

Current distribution along a full-wave antenna

The key to understanding the radiation pattern of the full-wave loop antenna is to understand the current distribution along the loop and how the resulting fields add up or cancel.

Consider a circular loop of length λ in the x-y plane. The feed point can be anywhere around the loop but the position of the feed point will affect the radiation pattern.

Suppose that the feed point is in the lower half of the y axis, and that the loop is broken into two equal parts and unfolded along the x axis, as shown in Figure 12-11. This figure shows that the current distribution looks like a cosine wave with a maximum at the feed point.

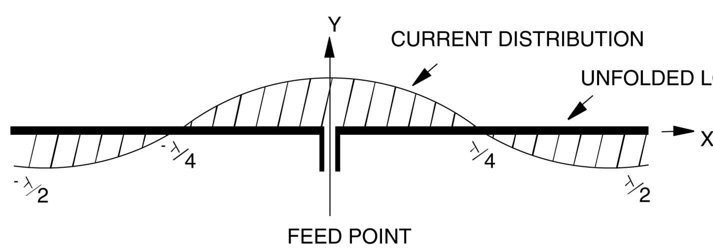


Figure 12-11. Current distribution along an unfolded loop antenna of length λ

Figure 12-12 shows the current distribution in the circular antenna, and how the resulting fields add up or cancel. In this case, the fields add up in the +y, -y and +z, −z directions, but cancel in the +x, −x direction.

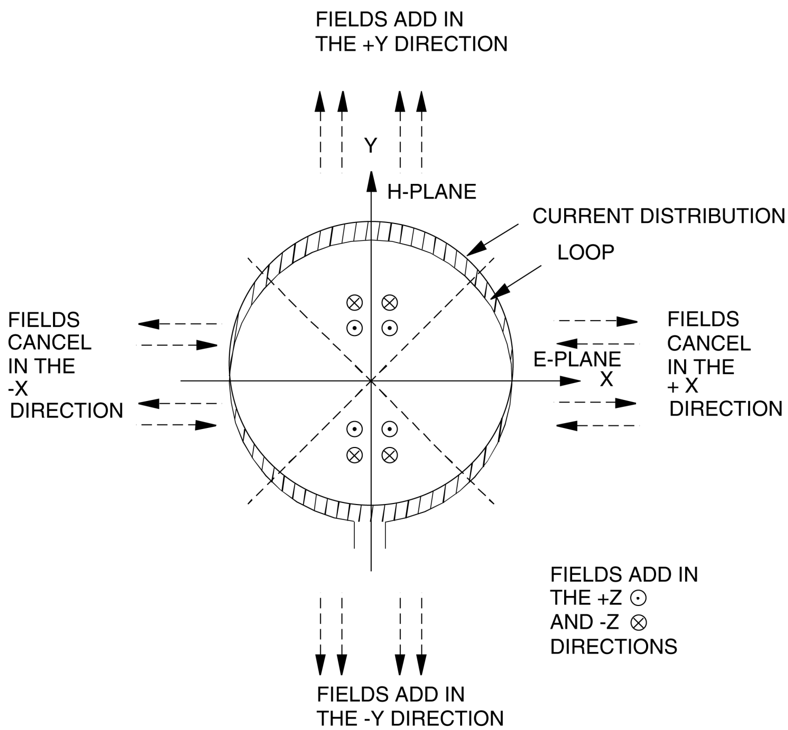


Figure 12-12. Current distributions in circular loop antenna of length λ

Radiation pattern of the full-wave loop antenna

There are three planes of interest with the loop antenna: the E- and H-planes and the loop plane, which is the plane containing the antenna. To illustrate these planes, consider a square loop antenna.

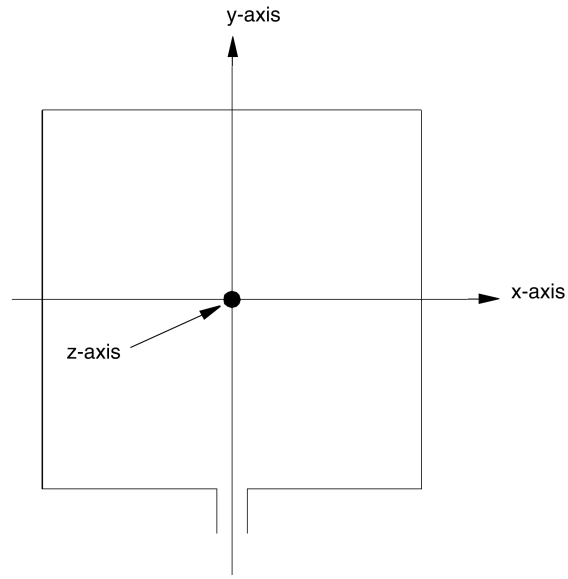


Figure 12-13. Square loop antenna

Suppose that the loop antenna is held vertically in front of you in the x-y plane, and that the z axis is pointing towards you, as shown in Figure 12-13. Comparing the loop to a center-fed dipole, you can see that the x-z plane is the E-plane, the y-z plane is the H-plane, and the loop plane is the x-y plane.

The theoretical radiation pattern in the E-plane (x-z plane) is shown in Figure 12-14(a). In order to measure it, the loop must be rotated around the y axis, as shown in Figure 12-14(b).

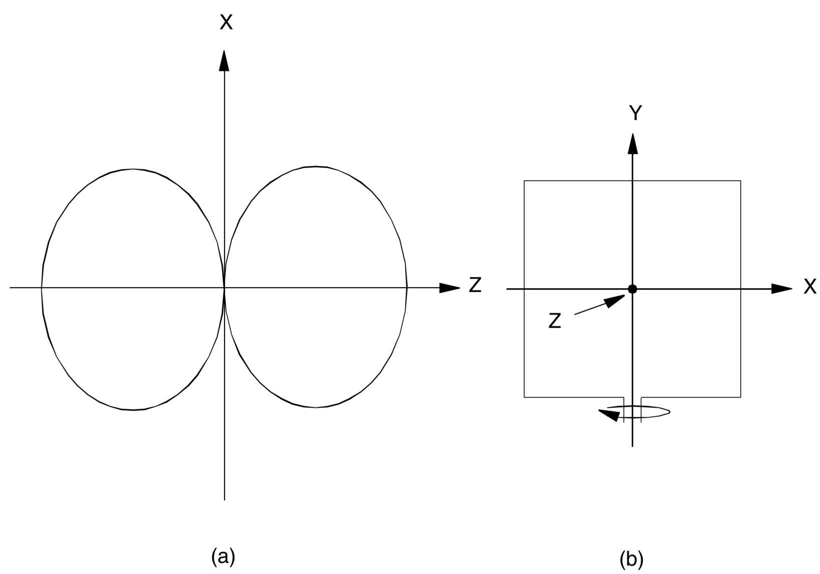
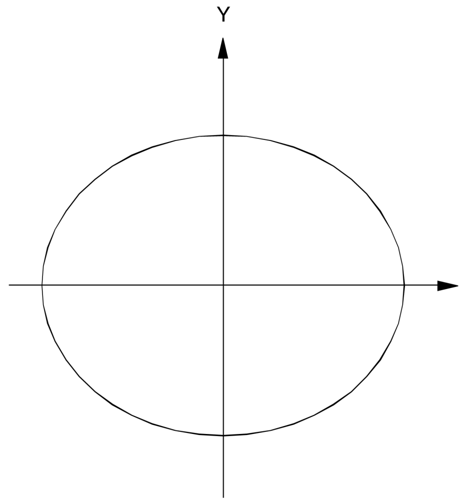
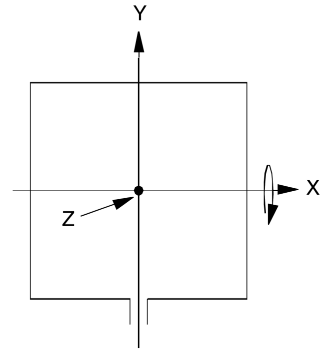


Figure 12-14. a) E-plane radiation pattern of a full-wave loop antenna; b) Rotation required to measure the E-plane radiation pattern



(a)



(b)

Figure 12-14.a) H-plane radiation pattern of a full-wave loop antenna; b) Rotation required to measure the H-plane radiation pattern

To measure the H-plane (y-z plane) radiation pattern shown in Figure 12-14(a), the loop must be rotated around the x axis, as shown in Figure 12-14(b).

Finally, to measure the radiation pattern in the loop plane (x-y plane), shown in Figure 12-15(a), the loop must be rotated around the z axis, as shown in Figure 12-15(b).

We will now consider more closely the theoretical radiation patterns in the E-plane, the H-plane, and the loop plane, represented in Figures 12-13(a), 12-14(a), and 12-15(a), respectively. Although the E-plane and the loop-plane patterns are similar, the amplitude of the patterns are different. As can be seen in Figure 12-11, the resultant in the centre of the loop comes from the addition of fields produced by currents in phase. On the y axis outside of the loop, the fields also add, but with a small phase difference. This causes the field in the loop plane to be 3 dB weaker than that in the E-plane.

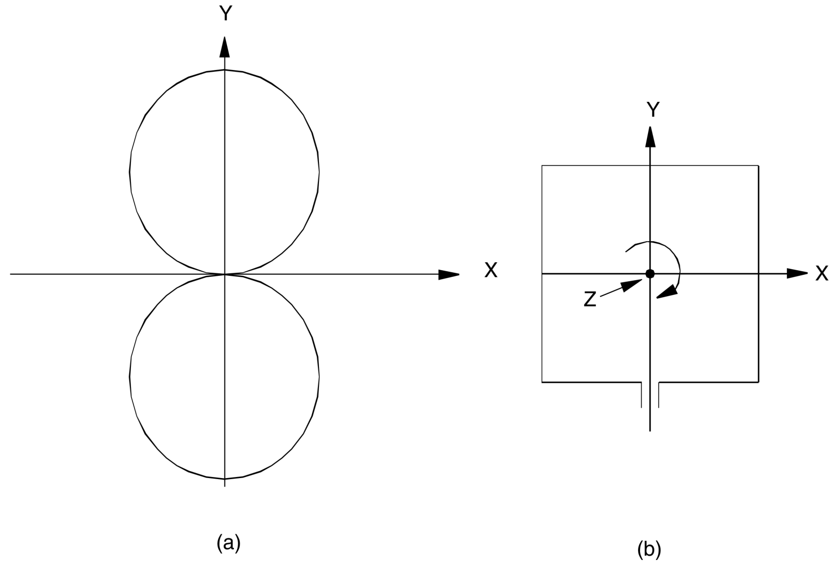


Figure 12-15. a) Loop-plane radiation pattern of a full-wave loop antenna; b) Rotation required to measure the loop-plane radiation pattern

Polarization

Figure 12-16 (a) and (b) show the current flow in the loop antenna at two different instants. The figure shows that, in the x direction, the currents in both halves of the loop add up, whereas in the y direction, the currents cancel. For this reason, the E-plane wave is polarized in the x direction.

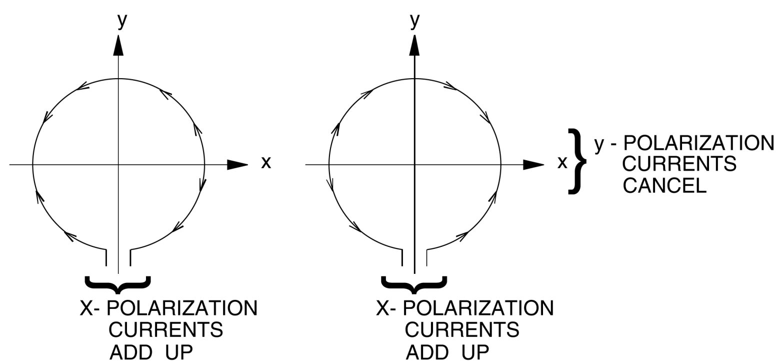


Figure 12-16. Polarization of the E-plane in the x direction

In practice, this means that if the loop is vertical with the feed point at the bottom or at the top, the E-wave is horizontally polarized. If the loop is vertical with the feed point at the right or the left, the E-wave is vertically polarized.

Impedance, gain, and beamwidth

The input resistance of a loop antenna drops to a value of around 100 Ω when the loop length is near λ. At this length, the input reactance falls to a very small value. Under these conditions the loop antenna is useful and has a reasonable bandwidth. It has a gain of about 3.09 dB, which is less than the 3.82 dB gain of the full-wave dipole, but more than the 2.15 dB gain of the half-wave dipole. Consequently, its beamwidth, in theory, is between the 47° of the full-wave dipole and the 78° of the half-wave dipole.

Small loop antennas

Small loop antennas are loop antennas having a length of approximately λ/8 or less. They have a radiation pattern which is strikingly different from that of full-wave loop antennas and are useful in special applications such as direction finding.

Since the length of the loop is much less than the wavelength, the current in all parts of the loop can be considered to be in phase, as shown in Figure 12-17. Because of this, the electric field on the z axis is zero. This is different from the full-wave loop, where the electric field is strongest on the z axis.

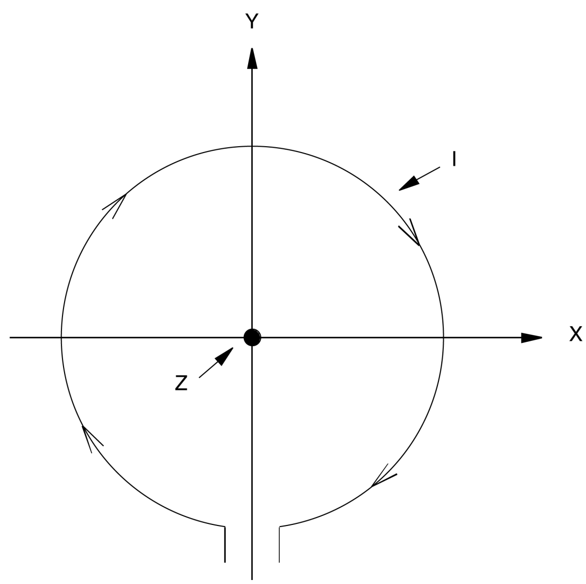


Figure 12-17. Current in a small loop antenna

In all directions other than the z axis, the radiation pattern has a non-zero value, as for a short dipole. In fact, the small loop is the **dual** of the short dipole: it could be replaced by a short dipole located at the origin and along the z axis without changing the radiation pattern.

The input resistance of the small loop antenna is extremely low, in the range of a fraction of an ohm.

Procedure Summary

In this exercise you will observe the relation between the feed point on the antenna loop and its polarization. You will plot the radiation pattern of the antenna and, using the λ/2 dipole as a reference, you will evaluate its gain. Finally, you will study the relationship between the shape of a loop antenna and its directivity.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission support. Clip the Yagi antenna onto the mast, oriented for an acquisition in the E-plane, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator using the long SMA cable.

☐ 3. Using the loop connector without balun (the same one you used with the folded dipole) and the square loop of length λ, set up a loop antenna.

☐ 4. Place the other antenna mast with horizontal clips on the sliding support of the Antenna Positioner. Attach the loop antenna to the mast.

Using the sliding support, ensure that your antenna is in line with the rotation centre of the Antenna Positioner and oriented as shown in Figure 12-18.

Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the intermediate SMA cable.

☐ 5. Position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

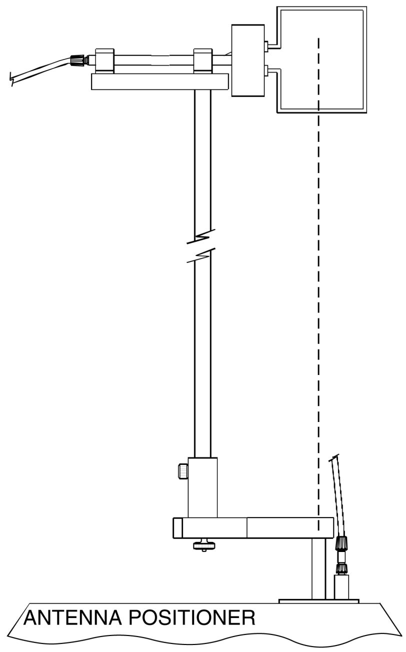


Figure1 2-18. Set-up of the loop antenna

☐ 6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Adjust the attenuation level to 6 dB; you should maintain this level throughout the exercise.

Start your acquisition and store the radiation pattern as the E-plane of a new document (Document1).

☐ 8. Rotate the receiving antenna so the loop is perpendicular to the previous set-up, as shown in Figure 12-19. Perform an acquisition and store it as the E-plane of a new document (Document2).

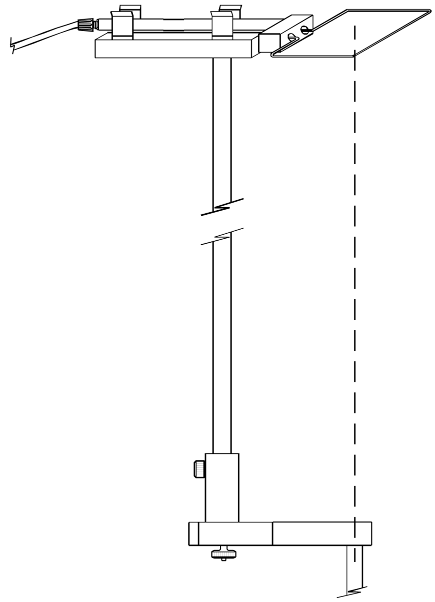


Figure 12-19. Second set-up with the loop antenna

☐ 9. Remove the mast with horizontal clips from the sliding support and replace it with the one that has vertical clips. Clip the loop antenna onto this new mast and replace the intermediate cable with the short one. Do not modify the orientation of the Yagi antenna. Refer to Figure 12-20.

Start an acquisition and store the pattern as the E-plane of a new document (Document3).

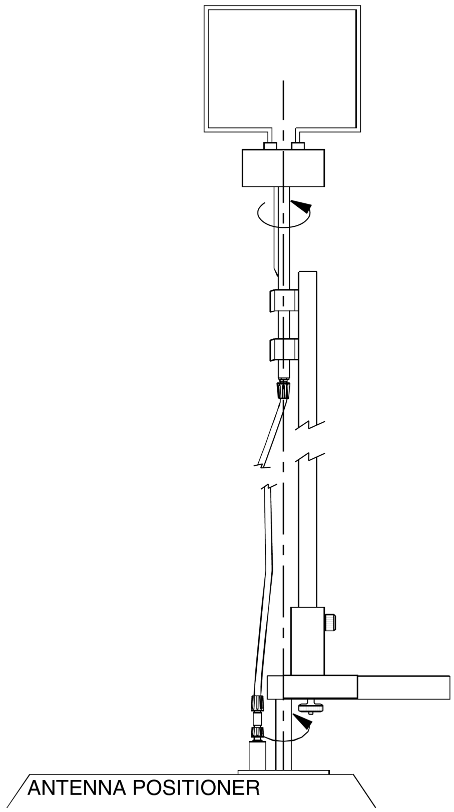


Figure 12-20. Third set-up with the loop antenna

☐ 10. Compare your three acquisitions. Taking into consideration the orientation of the loop antenna in each case and the orientation of the Yagi antenna, do the results acquired confirm the theory? What set-up allows the acquisition of the E-plane? Explain.

____

____

____

____

☐ 11. Remove the mast with vertical clips and replace it with the mast that has horizontal clips. Install your antenna on the mast, as seen in Figure 12-18, and rotate the Yagi antenna so that it is vertically polarized.

Perform an acquisition of the H-plane radiation pattern and store it in Document3.

☐ 12. After having oriented their MSPs to 0°, observe the spatial representations of Document3 patterns using the E-H and 3-D tabs.

After having saved the data stored in Document3, print the radiation patterns of the loop antenna in the 2-D and 3-D configurations.

Half-power beamwidth and gain

☐ 13. Evaluate the half-power beamwidth of the loop antenna E-plane.

$HPBW_E$ = ______ °

☐ 14. Remove the antenna mast with horizontal clips from the sliding support and replace it with the mast that has vertical clips. Also replace the loop antenna with a λ/2 dipole, and connect it to the Antenna Positioner using the short cable. Rotate the Yagi antenna so that it is horizontally polarized.

Perform an acquisition and replace the E-plane pattern of Document1 with this new radiation pattern.

☐ 15. Compare the E-planes of the dipole and loop antennas. Give the gain (in dBi) of the loop antenna.

____

Shape and directivity

☐ 16. Remove the square loop from the connector. Set up a new antenna with the circular loop and attach it to the mast, orienting it for an E-plane acquisition (refer to Figure 12-20).

Acquire the radiation pattern, then replace the E-plane pattern of Document1 with this last acquisition.

☐ 17. Remove the circular loop and replace it with the diamond shaped one. Perform an acquisition of the antenna pattern and store it as the E-plane of Document2.

☐ 18. Observe the similarity between the E-plane radiation patterns of these three different shapes of loop antenna. Does the similarity confirm the theory? Explain.

____

____

☐ 19. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you observed the relation between the feeding point of a loop antenna and its polarization. You plotted the radiation patterns of an antenna having a length of λ and evaluated its half-power beamwidth. Comparing this antenna with the λ/2 dipole, you evaluated its gain. Finally, you observed that the form of the loop antenna does not significantly influence its directivity.

REVIEW QUESTIONS

1. Describe the current distribution along the wire of the loop antenna of length λ.

 ____

 ____

2. You want to set up a loop antenna of length λ to receive a vertically polarized, 28 MHZ signal. Describe this antenna.

 ____

 ____

3. You set up a loop antenna of length λ using a cable having an impedance of 50 Ω. Calculate the SWR, then evaluate what percentage of the power is transmitted (refer to PART TWO FOLDED DIPOLE for the equations).

 ____

 ____

 ____

4. You want to use a small loop antenna to receive the same signal as in Question 2. What is the maximum length of the loop of your antenna? Explain.

 ____

 ____

5. Explain why we say that the small loop antenna is the dual of the short dipole.

 ____

 ____

PART THREE : Monopole Antennas

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the characteristics of both standard monopole antennas and drooping monopole antennas.

DISCUSSION

Image theory

A perfectly conducting **ground plane** acts as a mirror. For example, if there is a dipole transmitting above a perfectly conducting ground plane, the received signal will be the sum of a direct ray and a ray reflected by the ground plane, as shown in Figure 12-21(a). This is equivalent to replacing the ground plane by a mirror as in Figure 12-21(b). This is **image theory** in its simplest form.

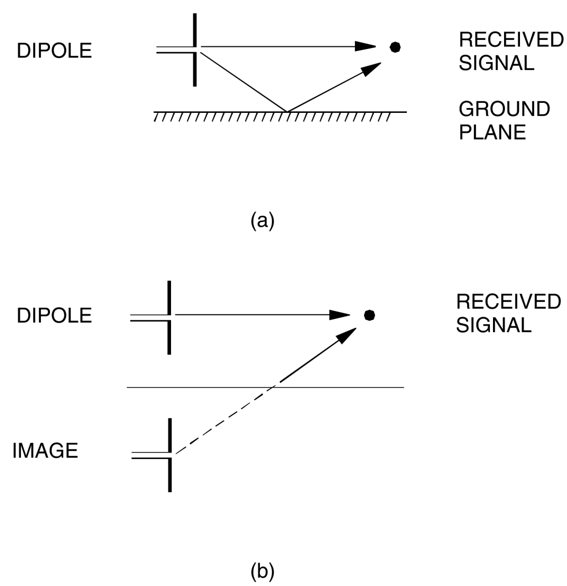
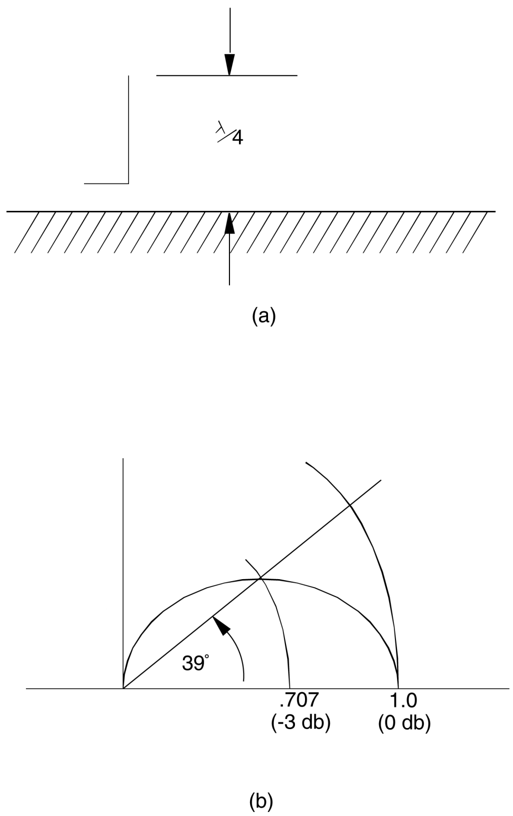


Figure 12-21. a) Dipole over a perfectly conducting plane, b) equivalent model with image theory

Monopole

Figure 12-22 shows a quarter-wave or λ/4 **monopole** over a perfectly conducting plane. It is essentially one-half of a half-wave or λ/2 dipole.



a) physical description, b) radiation pattern

Figure 12-22. λ/4 monopole over perfectly conducting ground plane

The current in the monopole is the same as in one half of a dipole. However, the input voltage is only half that of the dipole. Consequently, the input impedance of the monopole is half that of the dipole.

$$Z_{in\ (\lambda/4\,monopole)} = 37.5\ \Omega \tag{1}$$

Since the current is the same as for a λ/2 dipole, the radiated power will also be the same, but because the ground plane cuts through the middle of the radiation pattern, the beamwidth will be half that of the dipole. Therefore, the directivity and the gain will be double that of the dipole.

$$G_{\lambda/4\,monopole} = 2 \times 1.64 = 3.2 \text{ or } 5\,\text{dB} \tag{2}$$

The radiation pattern of a λ/4 monopole at the ground surface can be considered as having the same shape as that of a λ/2 dipole for angles above zero. The theoretical radiation pattern is illustrated in Figure 12-22(b) and given by the Equation (3), seen previously for a half-wave dipole.

$$F(\theta)_{\lambda/4\,monopole} = \frac{1}{2}\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}, \quad \theta > 0 \tag{3}$$

If the monopole is raised above ground, say, at a height of d/2, as illustrated in Figure 12-23, the antenna acts as a kind of two-element array. The radiation from the top and the bottom element combine somewhat differently as the height above ground is modified. This gives rise to the **array factor.**

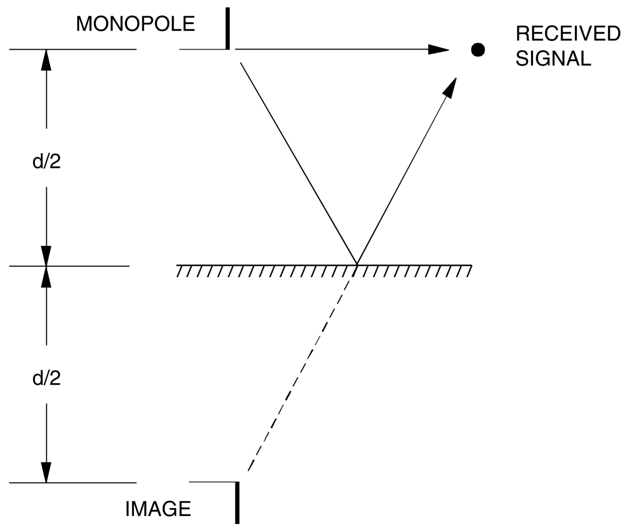


Figure 12-23. Combination of radiation from the monopole and its image

This is similar to that of a dipole above a perfectly conducting plane. This situation has not been mentioned before in this manual because we have so far only been considering dipoles in free space, not above ground.

Standard monopole

Figure 12-24 illustrates the Lab-Volt standard monopole. It is fed from a 50-Ω coaxial cable through a hole in a "large" ground plane.

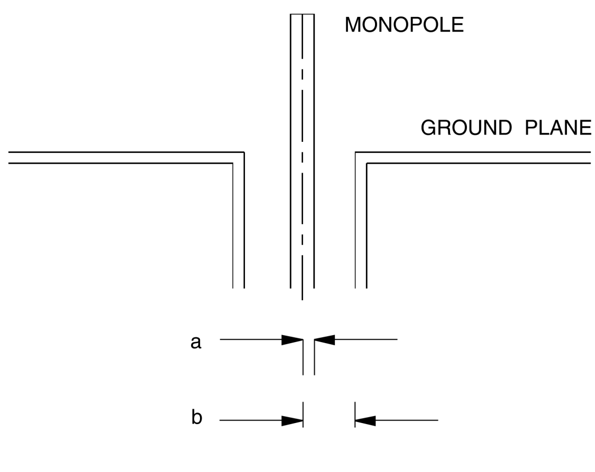


Figure 12-24. Coaxially-fed monopole and ground plane

The ground plane is an essential part of a monopole design. Ideally, it should be infinite in size. In practice, a radius of 5λ gives a condition close to ideal, and a radius of 0.5λ is a minimum. The Lab-Volt monopole comes with a ground plane of 0.5λ radius.

The coaxial cable feeding the antenna has an impedance of 50 Ω, and there is a transition from this impedance level to the 37.5-Ω impedance of the monopole. In this case the impedance after the transition is a function of the diameter a of the central conductor and the distance b between the central conductor and the edge of the hole in the ground plane. The relationship is given by Equation (4).

$$Z_o = 60 \log\left(\frac{b}{a}\right) \tag{4}$$

With a = 0.159 cm and b = 0.317 cm, the impedance is 41.5 Ω, which is an intermediate value between the 50-Ω impedance of the coaxial cable and the 37.5-Ω impedance of the monopole.

Procedure Summary

In this exercise you will plot the radiation patterns of a λ/4 monopole over a conducting ground plane and you will compare the directive gain of both a λ/2 dipole and a λ/4 monopole.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission support. Clip the Yagi antenna, polarized horizontally, onto the mast, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator.

☐ 3. Insert the monopole connector into the centre of the ground plane and attach it firmly using the two screws provided for this purpose under the plane. Insert the λ/4 wire into the centre of the connector.

☐ 4. Place the other antenna mast with horizontal clips on the sliding support of the Antenna Positioner. Clip the monopole antenna onto this mast, oriented to rotate in the E-plane.

Using the sliding support, ensure that your antenna is in line with the rotation centre of the Antenna Positioner. Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the intermediate SMA cable. Refer to step 11 of Exercise 1-1, to connect the SMA cable.

Figure 12-25 illustrates Steps 3 and 4.

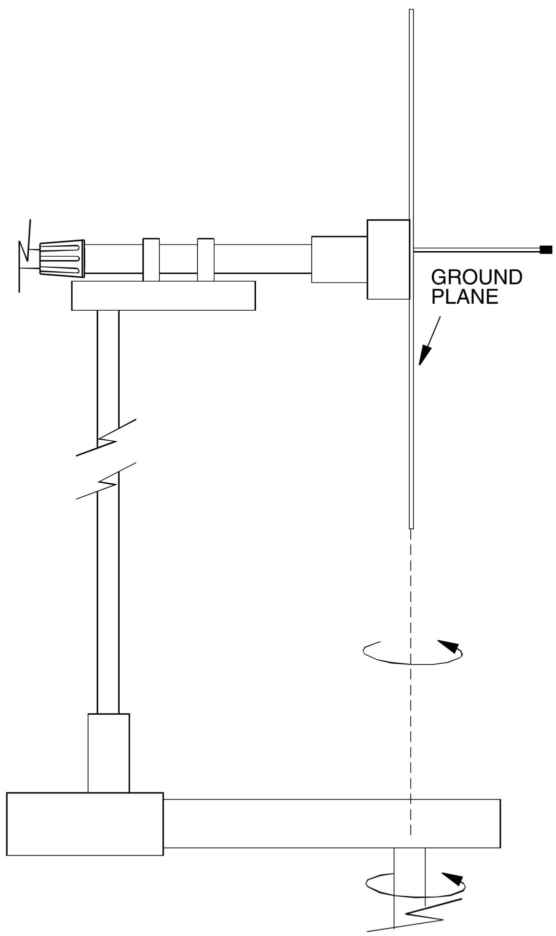


Figure 12-25. Set-up of the monopole in the E-plane

☐ 5. Position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

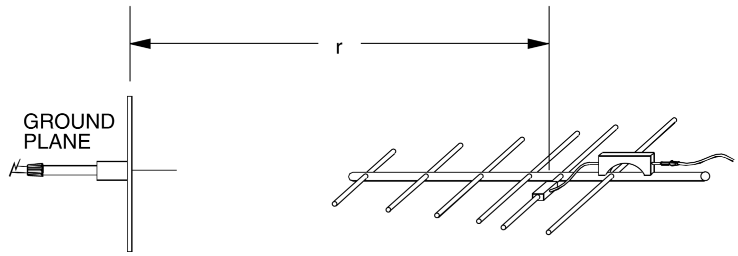


Figure 12-26. Distance r between the antennas

☐ 6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Use the Attenuation control to optimize reception of the signal.

Start the acquisition and store the radiation pattern in a new document (Document1).

☐ 8. Rotate the Yagi antenna so that it is vertically polarized.

Remove the mast with horizontal clips from the sliding support and replace it using the one with vertical clips. Clip your monopole onto this new mast, making sure that it rotates in the H-plane, and replace the intermediate cable with the short one. Refer to Figure 12-27.

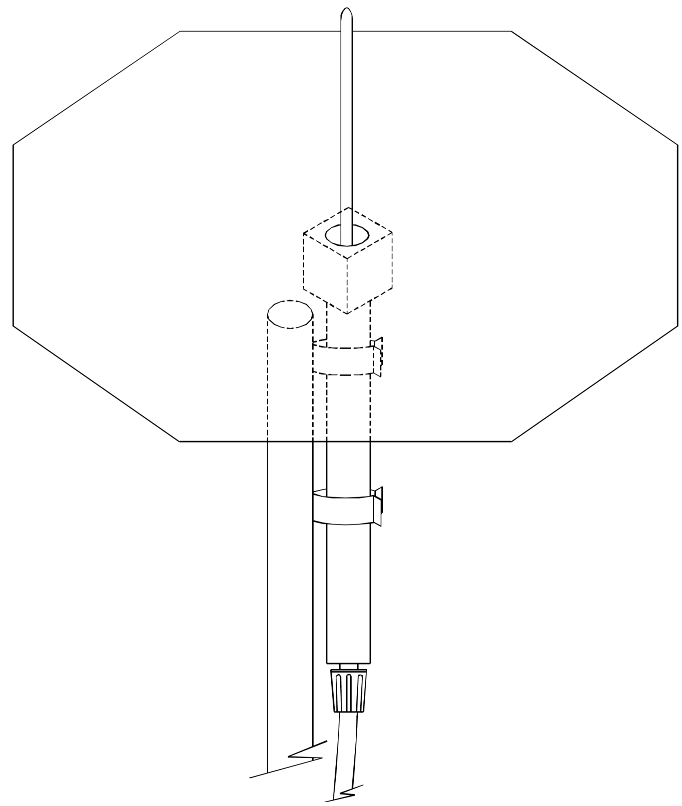


Figure 12-27. Set-up of the monopole for a rotation in the H-plane.

Perform a new acquisition and store it as the H-plane of Document1.

☐ **9.** Examine the spatial representations of these patterns with the E-H and 3-D options (refer to Exercise 1-4 to correctly position a non-symmetrical pattern).

Directivity

☐ 10. According to theory, the directivity of a monopole is supposed to be twice (3 dB over) that of a λ/2 dipole.

Set up a half-wavelength dipole and perform an acquisition of its E-plane, still keeping the same attenuation level. Store this pattern in Document3.

$$D \simeq \frac{101}{\text{HPBW (degrees)} - 0.0027\,[\text{HPBW (degrees)}]^2}$$

☐ 11. Compare this last result with the E-plane pattern of the monopole. Which antenna has the better directivity? Give the directivity difference.

____

Does this result agree with the theory? Explain why.

____

____

CONCLUSION

In this exercise, you plotted the radiation patterns of a monopole . You compared the E-plane patterns of the λ/4 monopole and of the λ/2 dipole.

REVIEW QUESTIONS

1. What theory is at the source of the standard monopole configuration? Explain.

____

____

2. Explain why the directivity of a monopole over an infinite ground plane is double that of dipole.

____

____

3. You are designing a 800 MHZ (UHF band) monopole antenna and you want a ground plane with a dimension close to the ideal, without being infinite. Calculate this dimension.

____

____

4. What parameters should be considered in evaluating the input impedance of the monopole?

____

____

Telecommunication Engineering Department

Advanced Communications Lab

EXP. 12 Characteristics of Optical Cables, Optical Sources and Detectors and Audio/Video Transmission over Fiber

Part One : Characteristics of Optical Cables, Optical Sources and Detectors

1. DESCRIPTION of the PANEL and ACCESSORIES

1.1 GENERAL DESCRIPTION

The educational system for the study of optical fibers consists in a panel containing all the electronics and part of the passive components, and a set of components and accessories (fig. 1.1).

1.2 DESCRIPTION of the SET of COMPONENTS and ACCESSORIES

The set of components and accessories consists in the following elements:

- 11 jumpers
- 1 switching power supply 12V/3A
- 1 Numerical Opening kit complete with LASER emitter
- 6 glass fiber optical cables, Graded-Index, 62.5/125μm, ST-ST, 3m length, identifier "4"
- 1 glass fiber optical cable, Step-index, 200/230μm, ST-ST, 3m length, identifier "3"
- 1 glass fiber optical cable, Step-index, 9/125μm, ST-ST, 3m-length, identifier "5"
- 1 plastic optical cable, 1000μm, ST-ST, 5m-length, identifier "2"
- 1 microphone
- 1 Optical Power meter in the Ist/IInd/IIIrd windows
- 1 LED source 850/1310nm
- 10 BNC-BNC coaxial cables
- 4 electrical connection cables
- 4 plugs

1.3 PANEL DESCRIPTION

The *FIBER OPTICS EDUCATIONAL PANEL mod. EFO41/EV* (fig.1.1) is divided into the following sections:

- **SPEAKER** (two separate sections)

− Audio amplifier with loudspeaker and volume regulation

- **TV-COLOR MONITOR**

− LCD display for video signals and ON switch

- **TEST GENERATORS**

− *AUDIO* generator for 1-kHz audio signal
− *VIDEO* generator for Color Bars video signal
− *PULSE 1* generator of TTL pulse signal with possibility to adjust the Frequency
− *PULSE 2* generator of TTL 2kb/s digital signal
− *DATA PATTERN* generator of TTL data signal with possibility to select the kind of signal 0, 1, 0/1, 4x0/4x1

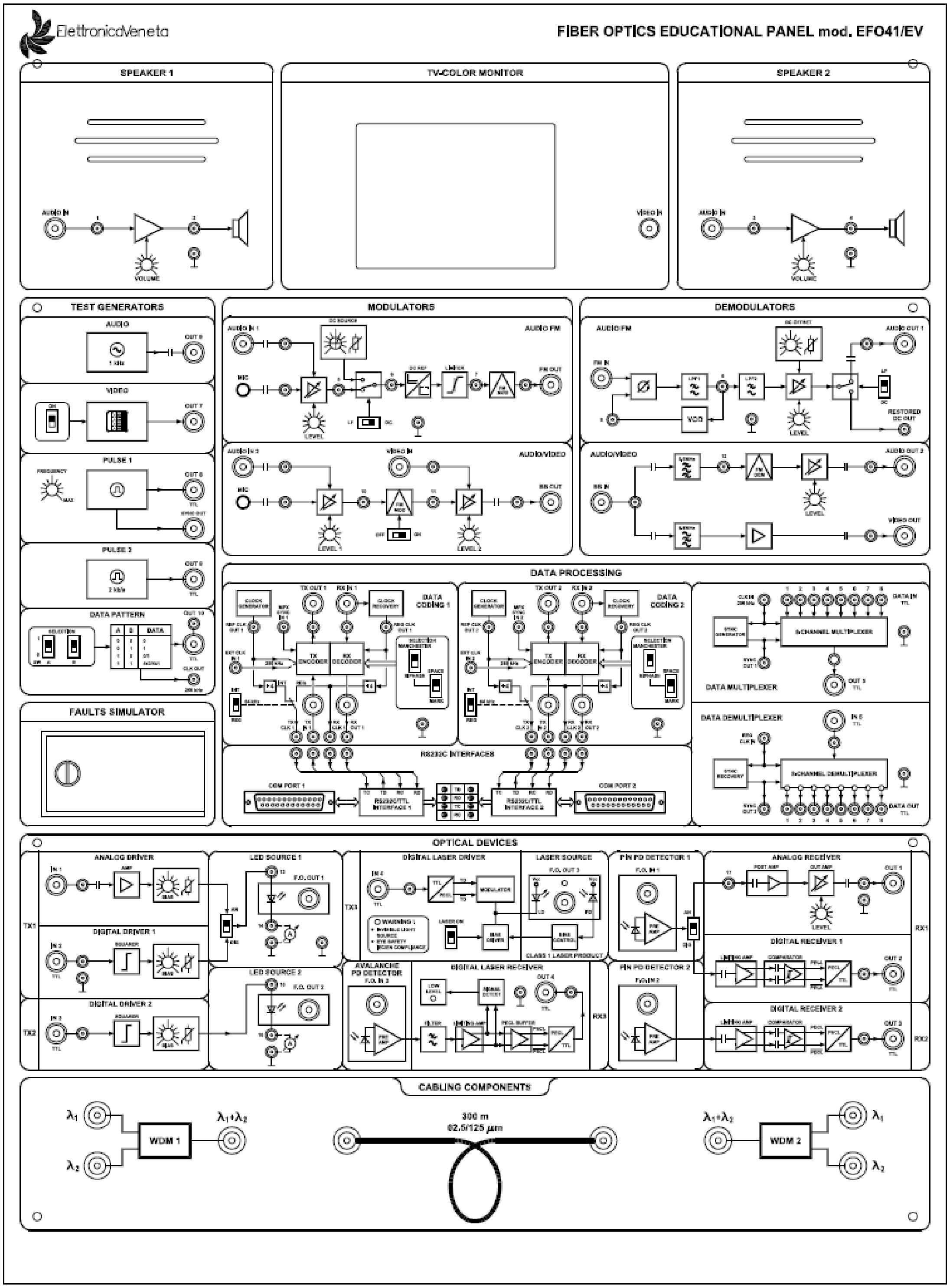


fig. 1.1 Fiber Optics Educational Panel

- **MODULATORS**

− *AUDIO FM* modulator providing the frequency modulated signal of the audio information or the DC source (d.c. voltage)
− *AUDIO/VIDEO* modulator providing the base band signal which is the sum of the video signal and the frequency modulated audio subcarrier

- **DEMODULATORS**

− *AUDIO FM* demodulator providing the frequency demodulated signal of the audio information or the DC source (d.c. voltage)
− *AUDIO/VIDEO* demodulator separating and providing the audio and video signals

- **DATA PROCESSING**

− *DATA CODING 1* coder/decoder of digital signals with possibility to select the Manchester/Biphase and clock coding
− *DATA CODING 2* coder/decoder of digital signals with possibility to select the Manchester/Biphase and clock coding

− *RS232C* interfaces containing two matching circuits for the TTL /serial levels with TD, RD, TC and RC state display
− 8-channel *DATA MULTIPLEXER* of digital signals
− 8-channel *DATA DEMULTIPLEXER* of digital signals

- **OPTICAL DEVICES**

− Bias *ANALOG DRIVER* circuit for LED source; for analog signals
− Bias *DIGITAL DRIVER 1* circuit for LED source; for digital signals
− Bias *DIGITAL DRIVER 2* circuit for LED source; for digital signals
− Processing and bias *DIGITAL LASER DRIVER* circuit for LASER source; for digital signals
− *LED SOURCE 1* circuit with 850nm LED source
− *LED SOURCE 2* circuit with 850nm LED source
− *LASER SOURCE* circuit with 1310nm laser source and photodiode for bias control
− *AVALANCHE PD DETECTOR* circuit with 1310nm detector
− *DIGITAL LASER RECEIVER* processing circuit; for digital signals
− *PIN PD DETECTOR 1* circuit with 850nm detector
− *PIN PD DETECTOR 2* circuit with 850nm detector
− *ANALOG RECEIVER* processing circuit; for analog signals
− *DIGITAL RECEIVER 1* processing circuit; for digital signals
− *DIGITAL RECEIVER 2* processing circuit; for digital signals

- **CABLING COMPONENTS**

− Wave-form division multiplex *WDM 1;* 850/1310nm
− Wave-form division demultiplex *WDM 2;* 850/1310nm
− Glass fiber optical cable, Graded-Index, 62.5/125µm, 300m

The different sections can be interconnected, as explained during the exercises, to carry out optical fiber circuits and communication systems. The panel is powered with +12V via the rear socket with the provided switching power supply. All the other voltages necessary to properly power all electronic sections are taken inside the panel.

THEORITICAL REVIEW AND QUESTIONS

OBJECTIVES

- To describe the constructional structure of the optical fiber
- To describe how light propagates inside the fiber
- To describe the Acceptance angle and the Numerical Opening
- To measure the Numerical Opening.

The main components characterizing an optical fiber communication system are (fig. 2.1):

- the optical fiber cable
- the electro-optical interface and the optical source
- the optical detector and the optical-electrical interface.

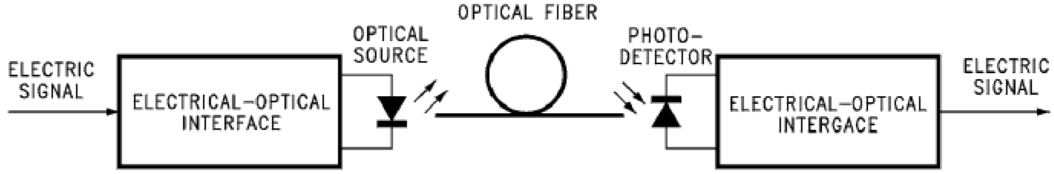


fig. 2.1 Optical fiber communication system

The basic structure enabling the light *propagation* is called *naked fiber*, and consists of *Core* and *Cladding*. As this structure is mechanically too fragile, it is strengthened by different protection layers, obtaining the *single-fiber optical cable*. In the center there is the *Core* (fig. 2.2), consisting in a cylinder with transparent material and with a given refraction index $n1$. Around it there is a layer - coaxial and in contact with the same *Core* - consisting in a transparent material but with refraction index $n2$ lower than the one of the *Core*. Note that the *Core* and *Cladding* are indiscernible, and are usually made with the same material (glass-glass or plastic-plastic). In some cases, e.g. in PCS fibers (Plastic Clad Silica), they can be of different material (Glass Core and plastic Cladding). Typical dimensions of *Core* and *Cladding* of optical fibers in the market are:

- **Plastic fibers:**

− CORE = 480, 1000 μm
− CLADDING = 500, 1000 μm

- **Step-index fibers:**

− CORE = 100, 200 μm
− CLADDING = 140, 230 μm

- **Graded-Index fibers:**

− CORE = 50, 62.5 μm
− CLADDING = 125 μm

- **Monomode fibers:**

− CORE = 9, 10 μm
− CLADDING = 125 μm.

In the standard use, the Core and Cladding dimensions are indicated with the values of the two diameters (expressed in μm) separated by a bar. E.g.: the indication *50/125 fiber* means a fiber which Core has a diameter of 50μm and Cladding of 125μm. The *naked* fiber is mechanically too fragile, and so more layers of covering are added to it in order to strengthen it. Typically as in (fig. 2.2).

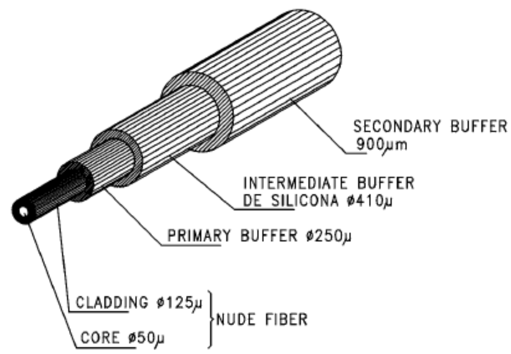


fig. 2.2 Optical fiber structure with covering

• *Primary covering*, in epoxy resin (250μm diameter for fibers with 125-μm Cladding)
• *Intermediate covering*, in silicone (diameter of 410 μm)
• *Secondary covering*, in plastic material (diameter of 900 μm).

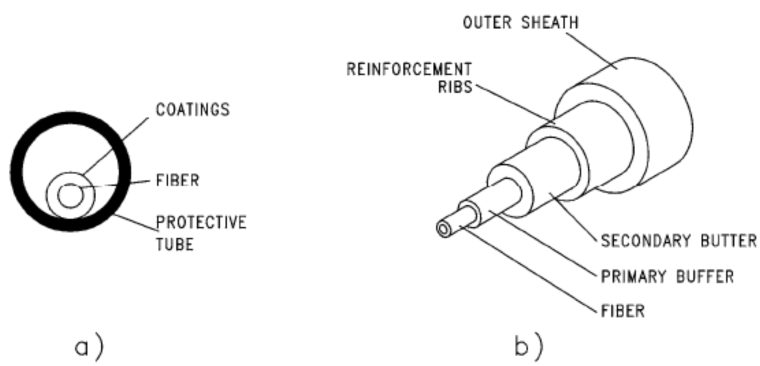


fig. 2.3 Structure of single-fiber optical cables: a) loosen cable; b) adherent cable

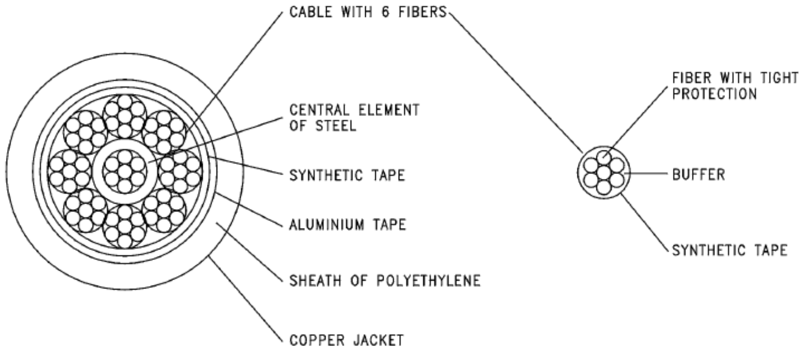


fig. 2.4 Structure of a multifiber optical cable

PROPAGATION MODES

An analysis of the propagation phenomenon made with the help of the Maxwell equations takes to the concepts of *Propagation mode*. Not considering a rigorous treatment, in these lines we are to examine the subject with simple considerations.

The *Propagation Mode* is a configuration in the electromagnetic field inside the fiber, as allowed by the geometry of the same fiber and the behavior of the refraction index.

The Normalized Frequency V is a parameter containing all main variables from which the propagation depends: the wavelength of the light energy, the Core ray, the Core and Cladding refraction indexes. It is defined by the relation:

$$V = \frac{2\pi}{\lambda} \cdot r \cdot \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{l} \cdot r \cdot NA \qquad [3.1]$$

with: λ = wavelength of the light energy
r = Core ray
n_1 = Core refraction index
n_2 = Cladding refraction index.

The solution of the Maxwell equations takes to the results appearing in the graphic of fig.3.1 showing the behavior, for some propagation modes, of the so called *Effective Refraction Index neff* as function of the *Normalized Frequency V*.

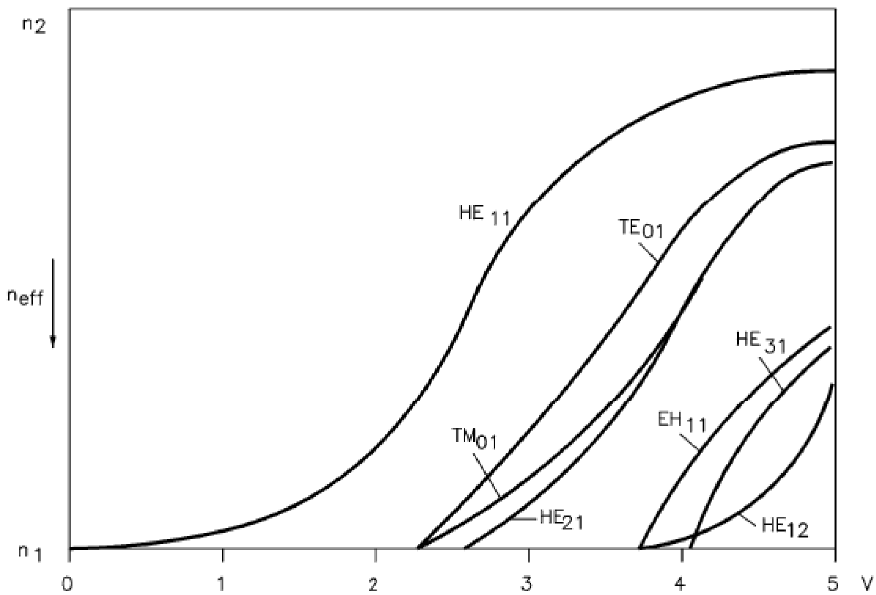


fig. 3.1 Propagation modes

Note the following aspects:

• neff is between n1 and n2 (n1>n2)

• for each propagation mode there is value of V, called *Cutting Frequency VC*, under which there is no propagation

• the first mode, called also "main", has VC=0, the second one VC=2.405. Superior modes have increasing cutting frequencies VC.

Given the value *V*, depending only on the fiber geometry and parameters, the light energy will propagate inside the fiber only via those modes having *Cutting Frequency VC* lower than *V*.

Consider an example with the following numerical values:

λ = 1.5 µm r = 5 µm NA = 0.15

You find:

V ≈ …………

From the graph of fig. 3.1 and considering V=3.14, you find out the following:

• the light energy propagates only according to the modes indicated with HE11, TE01, TM01, HE21

• the *Effective Refraction Index neff* corresponds to the HE11 modes and is lower than those related to the other modes.

This means that such mode propagates with higher speed than the others (*remember that the propagation speed of light inside a mean is inversely proportional to the refraction index of the same mean*). According to the number of active modes, the fibers are multimode or monomode.

The monomode fiber must have V<2.405, so that only the first mode (main one) propagates.

MODAL DISPERSION

A light pulse entering the fiber from different angles will result, after the path in the fiber, extended in time (fig. 3.4). This effect, due to different propagation modes of the light inside the fiber, is called *Modal or Intermodal dispersion*. The *Modal dispersion* is expressed in ns/km, and its effect increases when the fiber length increases. In a digital transmission, the transmitted signal consists in a set of pulses; it may happen that these pulses, by enlarging, intercross making decoding in reception impossible. Fig. 3.5 shows two examples of signals where the received pulses have been *enlarged* by modal dispersion. It is evident that the *Modal dispersion* limits the transmission capacity, i.e. the number of pulses that is possible to transmit in the time unit. It is logical to say that this parameter affects the fiber pass band.

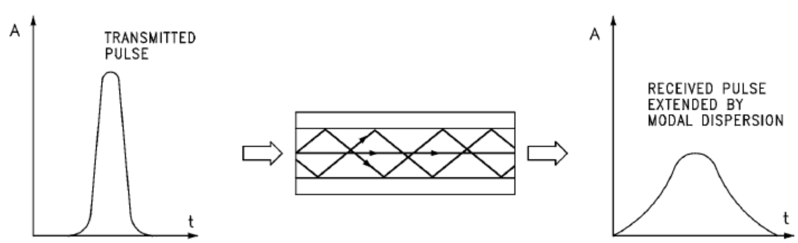


fig. 3.4 Pulse enlargement due to Modal dispersion

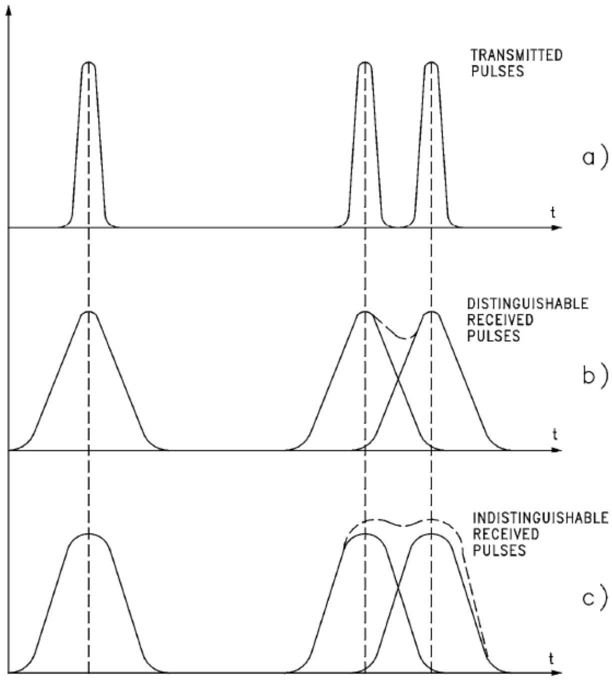


fig. 3.5 Effect of Modal dispersion on pulse transmission

CHROMATIC DISPERSION

Another cause for the pulse enlargement at the fiber output is given by the fact that the refraction index, and so the light speed in a given mean, depends on the wave-length of the light energy in transit (fig. 3.8). The commonly used light sources do not emit a chromatically pure radiation; the components at different wave-lengths, so, run at different speeds, contributing to the pulse enlargement (fig. 3.9). In this case, we speak of *Chromatic Dispersion* (even called *Material Dispersion* or *Spectral Dispersion*). The *Chromatic Dispersion* is expressed in ps/nm·km. E.g., if the fiber is characterized by a dispersion of 14 ps/nm·km and the light source has a spectrum of 70nm, the signal widens of about 1ns for each kilometer of fiber. It is evident that to minimize the effect of

Chromatic Dispersion it is necessary to use narrow spectrum sources, such as e.g. LASER diodes.

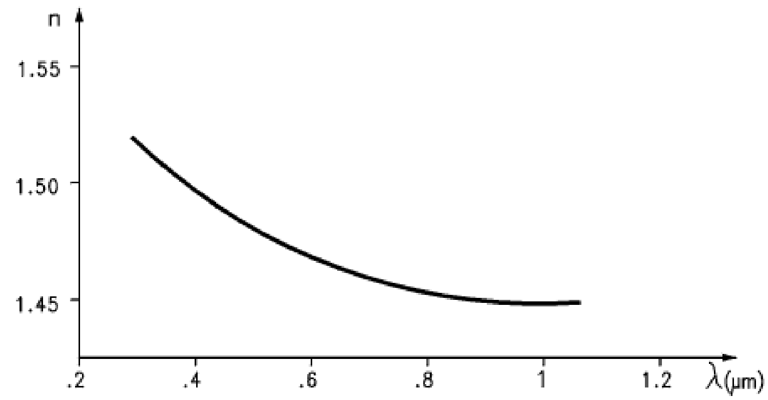


fig. 3.8 Variation of the refraction index as function of the wave-length

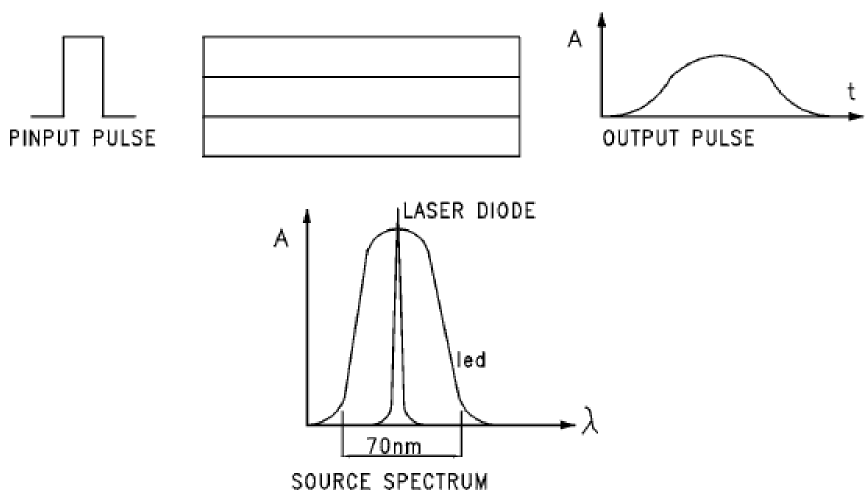


fig. 3.9 Pulse enlargement caused by Chromatic Dispersion

ATTENUATION

When the light is transmitted across an absorption mean, as the optical fiber, the light energy drops with the distance. The loss of a trunk of fiber (*Attenuation*) is given by the ratio between the injected power at an end PIN and the power detected on the other end POUT. It is usually expressed in decibel:

$$Att(dB) = 10\log\left(P_{OUT}/P_{IN}\right) \qquad [3.7]$$

The attenuation can be of some dB/**m** for plastic fibers, fractions of dB/**km** for glass fibers. The attenuation of the light signal introduced by the fiber depends on the wave-length and the material the fiber is made with. In glass fibers, the main causes of attenuation are the *Losses by Absorption* and the *Losses by Diffusion* which, if added, give intrinsic attenuation curves as the one shown in fig. 3.11.

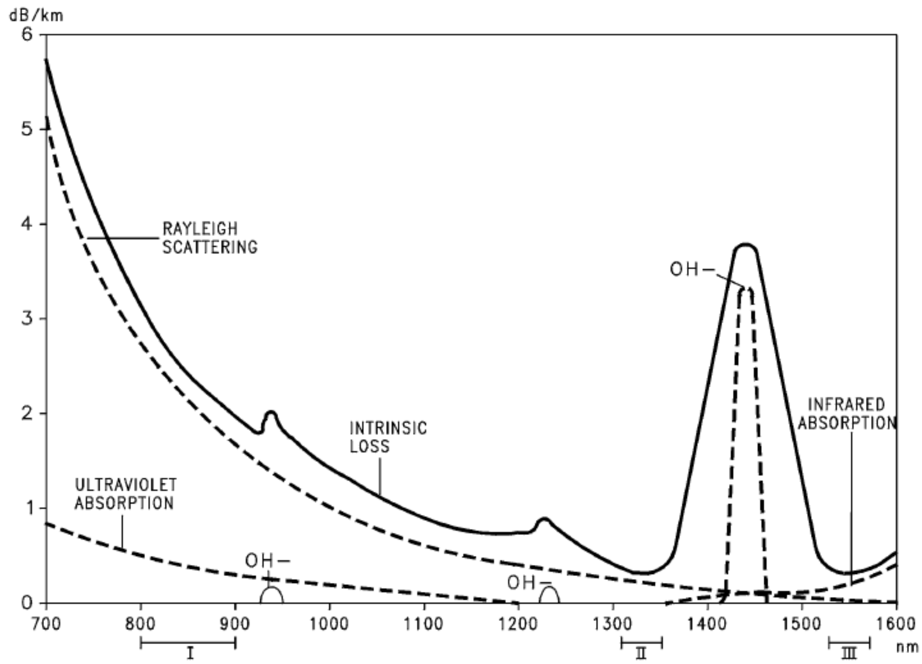


fig. 3.11 Typical attenuation curve of monomode glass fiber

In a fiber connection, other losses are caused by too narrow bending in the optical cable path (Bending Losses), or by junctions between more fiber trunks. These are obviously intrinsic losses of the fiber, but this depends on the cables lay-out. From the glass fiber attenuation curve (fig. 3.11) you can note that there are 3 zones with wave-lengths with minimum attenuation. These zones are called *Windows*:

1st window between 800 and 900 nm

2nd window around 1330 nm

3rd window around 1550 nm.

It is on these wave-lengths that the glass fiber is commonly used, and on the same lengths, source and detectors must have respectively maximum power and sensitivity. The plastic fiber is normally used at 660nm and, rarely, in 1st window.

BAND WIDTH

The band width of an optical fiber is directly related to the dispersion phenomena examined before. The effects of dispersion can be described in the time domain as well as in the frequency domain. In the first case we speak of delays in the run times of the light rays inside the fiber, in the second of *transfer function* and *pass band* of the fiber. The transfer function is the ratio between the output signal amplitude of a fiber with a given length in respect to the input signal amplitude, at variation of the frequency with which the optical source is modulated (fig. 3.12). For ease we define *band width Bw* the frequency value corresponding to an output reduction of 3dB in respect to the maximum value. The transfer function depends even on the light wave-length, and so fibers can be obtained with bandwidth optimized on particular spectral areas. For fibers with increasing length, the band restricts, as the delays caused by dispersion increase. The band is inversely proportional to the fiber length, and so it is expressed in MHz (or GHz) by units of length (MHz·km or GHz·km).

A fiber with:
Bw = 1000 MHz·km
Enables, e.g., the passage of signals
up to 1000 MHz if ………… km long, and
up to 1000/5=200 MHz if ……………. km long.

Typical band width values are:
• 10-100 GHz·km for monomode fibers
• 300-3000 MHz·km for monomode fibers
• 10-30 MHz·km for multimode Step-index and plastic fibers.

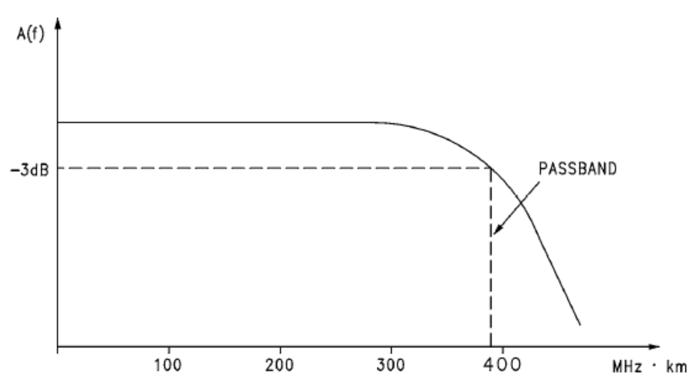


fig. 3.12 Fiber transfer function

SUMMARY CARD of OPTICAL FIBERS

The following table reports some typical data concerning plastic and glass optical fibers.

Fiber	Dimensions Core/Cladding [µm]	NA	Attenuation	Modal Dispersion	MHz·km Band	Applications
Plastic Step-index	500/530 980/1000	0.5-0.6	0.2dB/m (660nm)	very high	10	Analog and data transmissions at intermediate speed (10Mb/s) on short distances (<200m). Telemetry. 660nm wave-length
Step-index PCS (Plastic Clad Silica)	200/380 600/750	0.4-0.5	10dB/km (660nm)	high	20	Analog and data transmissions at intermediate speed (10Mb/s) on short distances (<2km). Telemetry. 660nm wave-length
Glass Step-index	100/140 200/230	0.3-0.4	7dB/km (850nm)	average	50 MHz·km	Analog and data transmissions at intermediate speed (10Mb/s) on average distances (<10km). Local Networks. Wave-length 850nm
Graded-Index	50/125 62.5/125 85/125	0.2-0.3	3dB/km (850nm) 1dB/km (1330nm)	low	1 GHz·km	Video and data transmissions at intermediate speed (200Mb/s) on average distances (<50km). Local networks. 850nm and 1330nm wave-lengths
Monomode	8-10/125	<0.1	.4dB/km (1330nm) .25dB/km (1550nm)	very low	10 GHz·km	Digital transmissions at very high speed (Gb/s) and long distance (<400km). 1330 and 1550nm

CHARACTERISTICS of the PROVIDED FIBERS

Optical cable included in the panel
• length: 300 m
• kind of fiber: glass, Graded-Index
• diameter: 62.5/125µm (Core/Cladding)
• attenuation: < 3.5 dB/km (850 nm); < 1.5 dB/km (1330 nm)
• numerical opening: 0.2
• acceptance angle: 11 °
• pass band: 600 MHz·km

Optical cable "2"
• length: 5 m
• kind of fiber: plastic, Step-index
• diameter: 1000µm (Cladding)
• attenuation: see fig. 3.13
• numerical opening: 0.46
• acceptance angle: 55 °

Optical cable "3"
• length: 3 m
• kind of fiber: glass, Step-index
• diameter: 200/230µm (Core/Cladding)
• attenuation: < 7 dB/km (850 nm)
• numerical opening: 0.35
• acceptance angle: 20 °
• pass band: 20 MHz·km

Optical cable "4"
• length: 3 m
• other characteristics as cable included in the panel

Optical cable "5"
• length: 3 m
• type of fiber: glass, monomode
• diameter: 9/125µm (Core/Cladding)
• attenuation: < 0.4 dB/km (1330 nm); < 0.3 dB/km (1550 nm)
• numerical opening: < 0.1
• acceptance angle: < 5 °
• pass band: > 5 GHz·km

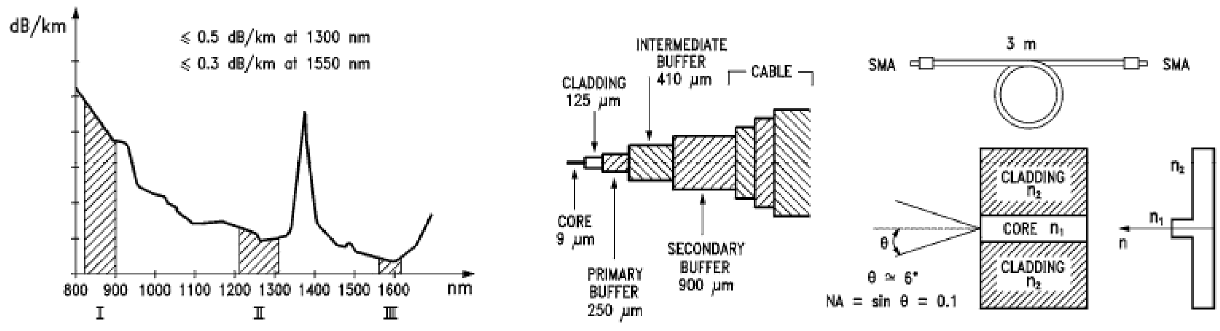


fig. 3.14 Attenuation curve and index profile – 9/125 Monomode Fiber

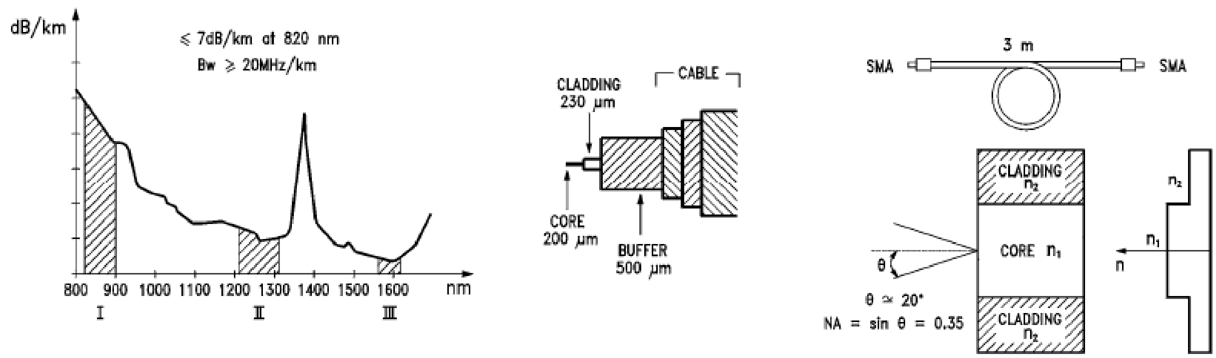


fig. 3.15 Attenuation curve and index profile – 200/230 Multimode Fiber

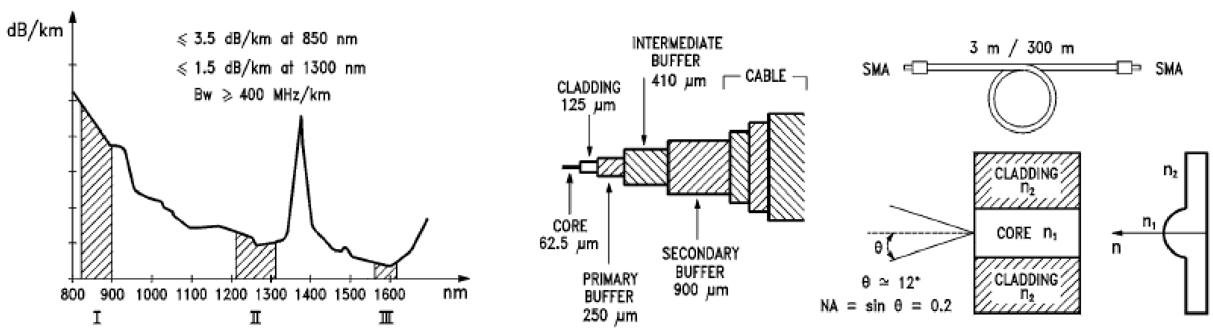


fig. 3.16 Attenuation curve and index profile – 62.5/125 Fiber Graded-Index

COUPLINGS

• To describe the methods normally used to couple elements of an optical fiber system: connectors; fusion junctions; mechanical junctions
• To describe the causes of power loss in the couplings
• To examine the characteristics of optical connectors
• To describe couplers for more fibers: the Splitter and the WDM (Wavelength Division Multiplexer). Operating principle, characteristics and use.

Junctions and connectors are integrating and important parts of an optical fiber connection. The connectors offer the possibility to quickly and easily power the optical power between fibers and the systems equipment. The junctions enable to permanently connect contiguous pieces of optical cable.
Other couplers are used for particular functions, such as dividing the signal to be transmitted or carrying out a transmission or reception multiplexing. They belong to the category of couplers and have specific names: Splitter and WDM. The Splitters are optical signal dividers, necessary when the same signal must be sent to different optical channels for backup function or because it must be sent to different receiving stations. The WDM are employed to enable the use of the same fiber for two or more luminous signals, that can “transport” information even of different kind. They are being used more and more because they enable a higher exploitation of the fiber present in the transport system. Junctions, terminations, Splitters and WDM inevitably absorb a part of the system power, introducing attenuations in this way.

JUNCTIONS

Losses in the junctions

The optical power losses in correspondence to a junction can be generally divided into:
• Intrinsic losses
• Extrinsic losses

The intrinsic losses consist in the difference of the junction fibers parameters, as schematically shown in fig. 4.2. The extrinsic losses come from the fibers physical misalignment in the junction point, due to the mechanism and to the junction technique. There are 3 kinds of misalignment, classified as described in fig. 4.1.

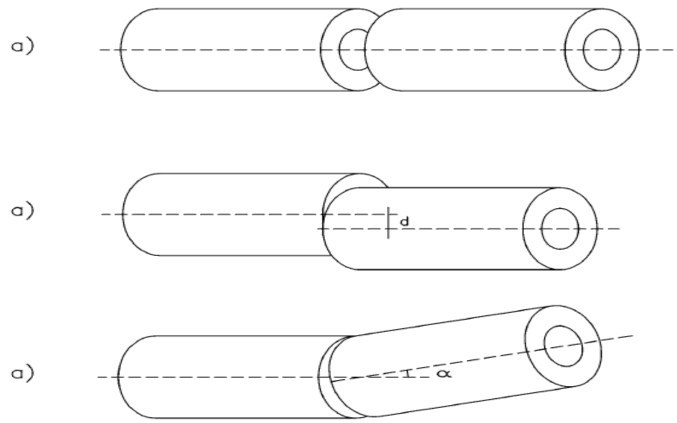


fig. 4.1 Extrinsic losses in the junctions
a. gap misalignment

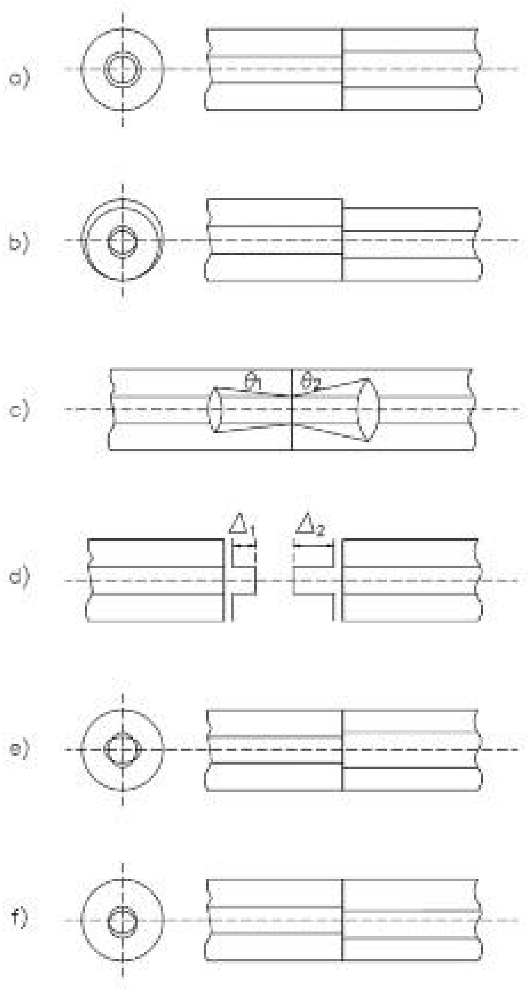


fig. 4.2 Intrinsic losses in the junctions

a. different diameters of the core | *b. different Cladding diameters*
c. different Numerical Opening | *d. different behavior of the refraction index*
e. Core ellipticity | *f. non concentricity between Core and Cladding*

CONNECTORS

The connectors are devices that can connect two optical fibers or an optical fiber to a source or a detector, in a stable but not permanent way. The connection system can consist in the male connector (mounted on the fibers) or the female one (or *receptacle*, mounted on the equipment or directly on sources and detectors), or by 2 male connectors connected via a double female adapter. This last kind of connectors are commonly called *Adapter* or *Coupling Receptacle* according to their functions, and are defined like this:

- *Adapter* or *Hybrid Adapter* when they adapt fibers using different termination connectors (e.g. *FC to ST*, *SC to FC*, *SC to ST*)
- *Coupling Receptacle* when adapting fibers using the same kind of termination connector (e.g. ST-ST, as the ones used on the *Educational Panel* fig. 4.4).

As function of the fiber they will be mounted on, there will be connectors for multimode or monomode fibers. It is evident that higher mechanical accuracy will be requested to the second ones, considering the smaller size of the monomode fiber and consequently the need to reduce the misalignments of the faced fibers via the same connectors to the minimum. The losses introduced by a connector are due to the same causes examined before for the junction. They depend on the kind of connector, and can take average values from 0.5dB (biconic connectors, ST connectors) to about 1dB (SMA connectors). There are different kinds of connectors, developed by different manufacturers or coming from evolutions of existing connectors. Among the most used ones, we can mention the ST, the SMA, the NTTFC, the NTT-PC, the biconic. Among plastic fibers, a connector developed by Hewlett-Packard, known as *Snap_In HP* connector, is much used (fig. 4.6).

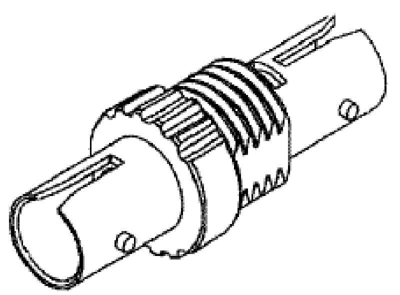


fig. 4.4 Coupling receptacle ST

COUPLER (or SPLITTER)

These are passive components used to distribute the optical power from a fiber to two or more fibers, with minimum loss, or to combine the light, from two or more fibers in a fiber. The *Couplers* are commonly called *Splitters.* It is very important to note that they operate only in a defined band wave-length range. They are defined 1x2, when they have an input port and two output ones. It is however important to remember that they are reversible. There are multi-port Splitters, too, defined 1xN (or also *Tree* or *Star Coupler*), because they have an input port and N output ports (N is a parameter to be defined when choosing the component). Two very important parameters in the choice of the component are:

- the coupling ratio (fig. 4.7), indicating the percentage of optical power on the output ports in respect to the total power present on all output ports
- the directivity (fig. 4.8), that is defined also *Near-end Cross-talk*, and is the quantity of power present at a given input port in respect to the starting input power.

The characteristics and typical values for the dividers are:

- Typically monomode component or a few cases for Graded-Index fibers
- Wave-length, 1310nm, 1480nm or 1550nm
- *Coupling Ratio* or *Split Ratio*, typical for a 1x2 are 50/50, 40/60, 30/70, 20/80, 10/90, 5/95, 1/99
- *Directivity*, good if over 50dB
- *Insertion Loss*, over 3-4 dB

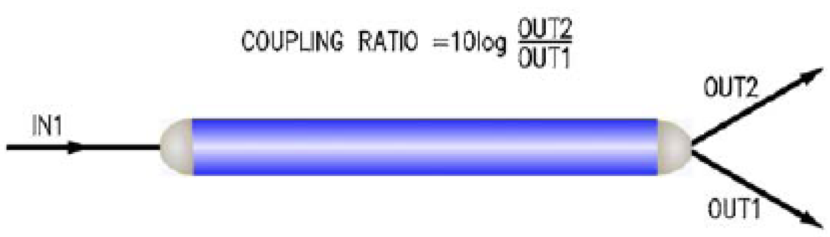


fig. 4.7 Coupling Ratio

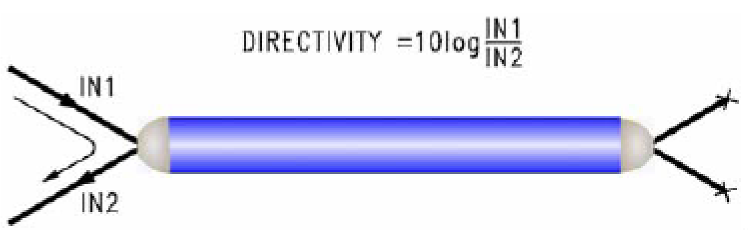


fig. 4.8 Directivity

WDM (Wavelength Division Multiplexer)

The WDMs are passive components that enable the use of the same optical channel (the fiber) to transfer different optical signals using different bands. They are the analogous to the systems using the FDM technique (Frequency Division Multiplexing) with electrical signals.

The purpose is the same: to use a single physical channel to transfer different signals carrying information of different kind. The WDM is a three-port component (e.g. in fig. 4.9 and 4.10): two as input and one as output (considering they are reversible, fig. 4.11), and the pair of two wave-lengths at which the component must operate is a very important parameter in the choice of the component.

If λ1 and λ2 are the two wave-lengths, each will be the useful band for only one of the input ports (e.g. λ1 for the port 1 and λ2 for the port 2), while the useful band of port 3 will be λ1 plus λ2. At the end, the signal inserted into port 1 will be present across the output of port 3 and the same can be said for the one inserted into port 2 that will be present at the output of port 3. In short, the WDMs use the principle of the optical band width multiplexing for which, the different wave-length of the present signals, enables a proper scrambling in

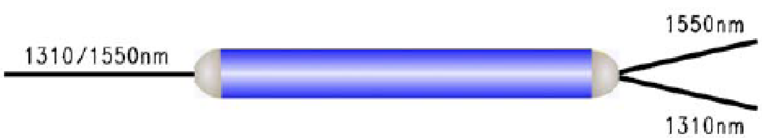


fig. 4.9 Example WDM 1310/1550nm

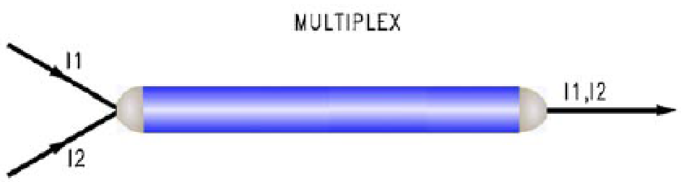


fig. 4.10 Multiplex: process for combining optical channels

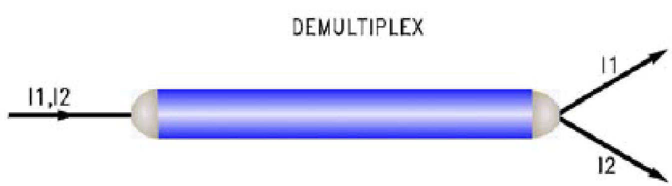


fig. 4.11 Demultiplex: process for separating optical channels

Characteristics of the provided WDMs

- Multimode
- Wave-length: 850nm/1310nm +/- 50nm
- Fiber: 62.5/125/250μm • Connector: ST
- Insertion loss: <0.8dB (850nm) / <0.6dB (1310nm)
- Insulation: >25dB • Directivity: >45dB

WDM amplification: amplifier for optical fiber

A particular professional application of the WDM is to carry out an optical power amplifier for optical fiber (fig. 4.12). It is commonly called *Fiber Optic Amplifier WDM* or *Pump EDFA* (Erbium-doped fiber amplifier) and, using a pump laser and a WDM,*,* it enables the signal amplification at the wished wave-length. They can be found as single components for OEM applications or as equipment ready for use in rack version.

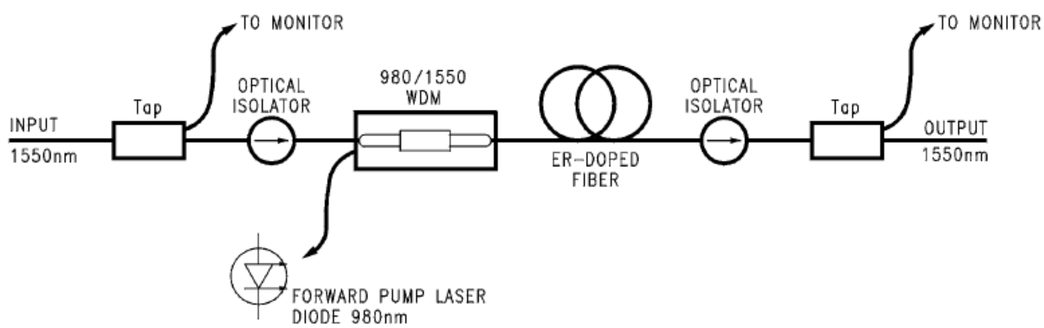


fig. 4.12 Optical fiber amplifier

ATTENUATION MEASUREMENTS

There are different methods to measure the attenuation of a fiber and among these the following are the most used:

- the cut-back method - the back-scattering method
- the insertion method.

Accurate measurements - e.g. in the laboratory for the certification of the parameters of a fiber - require the use of the *mode scrambler* described hereafter. This device is not used when high accuracies are not required. In these cases it can be changed with a so called *launch fiber*, that in practice enables to reach good results.

Scrambler Mode

Before describing the attenuation measurement methods, it is useful to indicate the propagation conditions to be carried out in a fiber to obtain an accurate measurement. The main problem, concerning multimode fibers, lies in the fact that in the starting trunk of fiber, called *transient state zone*, each mode has a different attenuation coefficient. This means that the attenuation depends on the excitation conditions, i.e. by which propagation modes they are excited and the way power is divided between them. The power distribution is definitive only in the so called *stationary state zone*, in which all modes have the same coefficient of loss and the attenuation measurement has meaning. As the *transient state zone* can reach some hundreds of meters, measurements of attenuation on fibers of shorter length could be wrong. Fig. 4.13 shows a diagram of the kilometric attenuations on fibers of different length. Note that if the length of the fiber being measured is lower than 1kilometer, for the reasons explained above, the found kilometric attenuation is superior than the one found measuring longer fibers working in balance conditions.

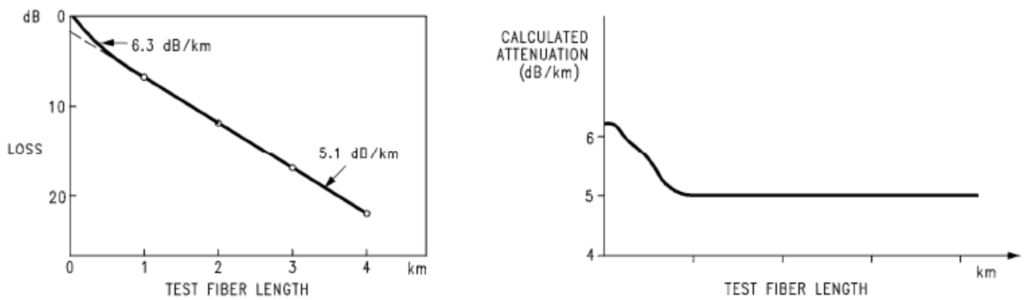
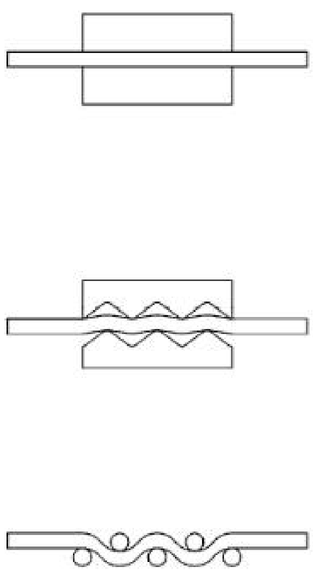


fig. 4.13 Loss and Attenuation curves



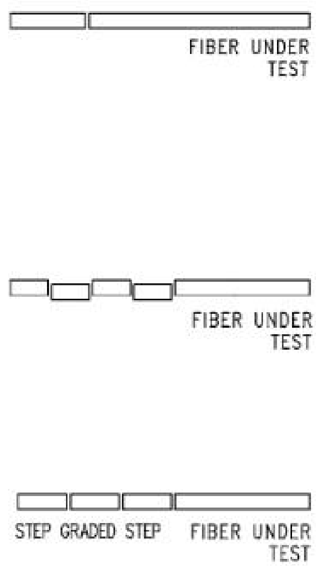


fig. 4.14

fig. 4.15

To take the fiber to balance conditions you can insert a *mode scrambler* between the source and the fiber under measurement. This creates strong perturbations on the fiber, forcing the stationary state to be obtained in a few meters. There are different kinds of *mode scrambler*, acting directly on the fiber under test, or before it. The first ones induce micro-bends in the first trunk of fiber, by compression of the same fiber with wrinkle surfaces (fig. 4.14). The second ones use a short piece of fiber with corrugated end, or partially faced trunks of fiber or alternations of Step-index and Graded-Index trunks (fig. 4.15). A simple but efficient *mode scrambler* can be carried out by manually causing some bending (ray of about 10 cm) in the first trunk of fiber (about 1 meter).

As mentioned before, for measurements not at laboratory level, the *mode scrambler* is changed with a launch fiber, which introduces a sufficient *scrambling* to carry out an acceptable measurement. The launch fiber is an optical cable some meters (3-5 about) long with fiber like the one to be measured.

Cut-back method

The attenuation measurement with the cut-back method is made in 2 phases:

1. The fiber being measured is connected to the source and to the detector, with eventual insertion of a *mode scrambler* at the beginning of the fiber. The received optical power **Px** is measured (fig. 4.17)
2. The fiber is cut after the *mode scrambler* (or some meters from the source if there is not *mode scrambler*) and the optical power **Po** is measured across the left short trunk of fiber (fig. 4.17). The total attenuation AdB introduced by the fiber, evaluated in decibel, results:

$$A_{dB} = 10 \log \frac{P_o}{P_x}$$

The kilometric attenuation is calculated by dividing AdB by the fiber length.

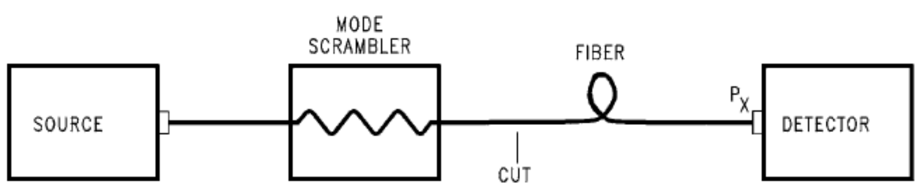


fig. 4.16

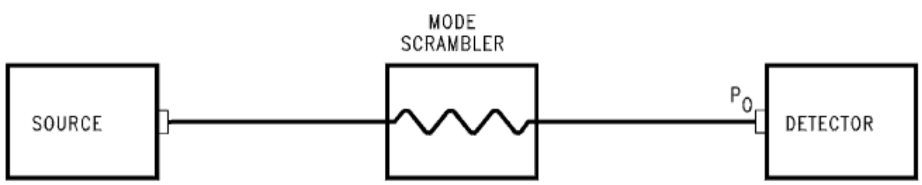


fig . 4.17

Back-scattering method

It is based on the physical principles according to which the light is diffused to all directions, even backward, when propagated in a mean with no homogeneity at microscopic level (fig. 4.18).

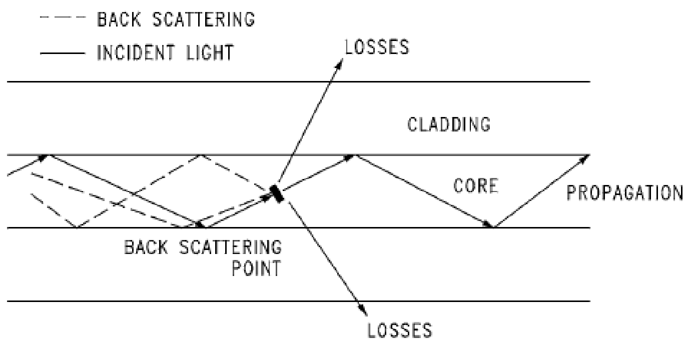


fig. 4.18

The instrument for this kind of measurement is the *optical reflectometer* (**OTDR - Optical Time Domain Reflectometer**), which block diagram is reported in fig. 4.19. The measurement technique consists in launching a set of periodic luminous pulses into the fiber, and in measuring the corresponding
back-scattered power (it is a technique analogous to the one used in pulse radars, where a short radio-frequency pulse is transmitted and you listen to the *echoes*).

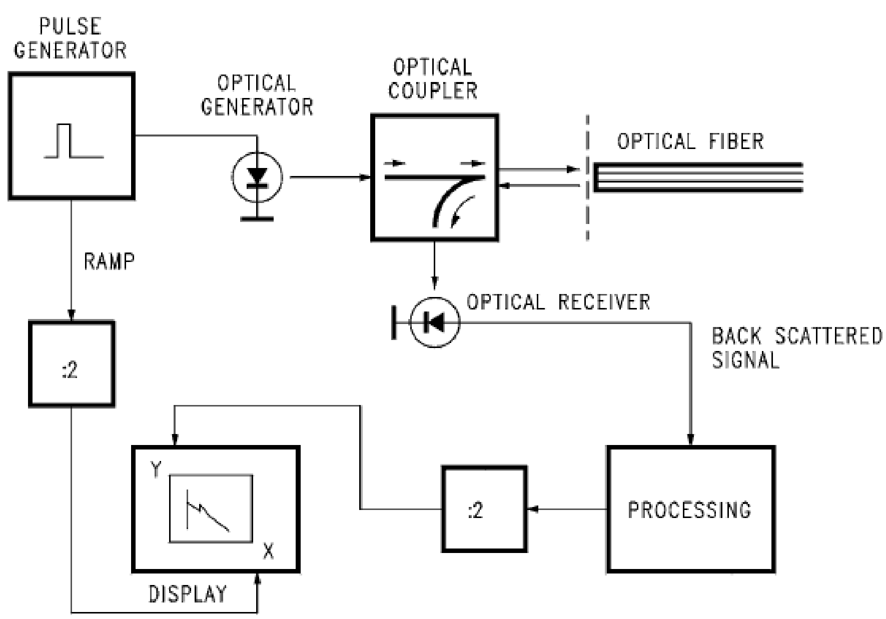


fig. 4.19

By measuring the back-scattering power appearing at the same end of the fiber, and calculating the time employed by the light energy to run the two directions of the fiber (delivery and return), it is possible to calculate and detect the losses along the fiber. The measurement is then represented on a X—Y plane, in which Y-axis there is back-scattering power, usually in **dBm**, and on the X-axis the distance (evaluated as product between the light propagation speed inside the fiber and the time elapsed). Note in the block diagram that two dividers by 2 have been inserted on driving the X-axis (time) and the Y-axis (attenuation), to indicate that the instrument considers that the measured run time actually corresponds to a double path (delivery and return), and so does the attenuation. Fig. 4.20 shows a typical graph obtained with the OTDR. Starting from distance zero, what you can see is the pulse emitted by the generator. Such pulse automatically cancels the *echoes* due to the starting part of the cable. The more the optical pulse emitted by the OTDR is narrow, the shorter will be the *masked* distance. However, an OTDR typically cannot explore cables that are some tens of meters shorter. The pieces at constant slope are the effective loss of the fiber. The kilometric attenuation can be evaluated making the difference between the powers measured in two points, and dividing the value by the distance between the same two points. The steps indicate where junctions or connectors are inserted. The junction shows a short shift, the connector a greater shift and
besides it shows a strong reflection (peak upward), too. The last is caused by the fact that the light, between connector and connector, *bounces* even out of the fiber, where there is an air separation. At the fiber's ends there is a peak with strong reflection.

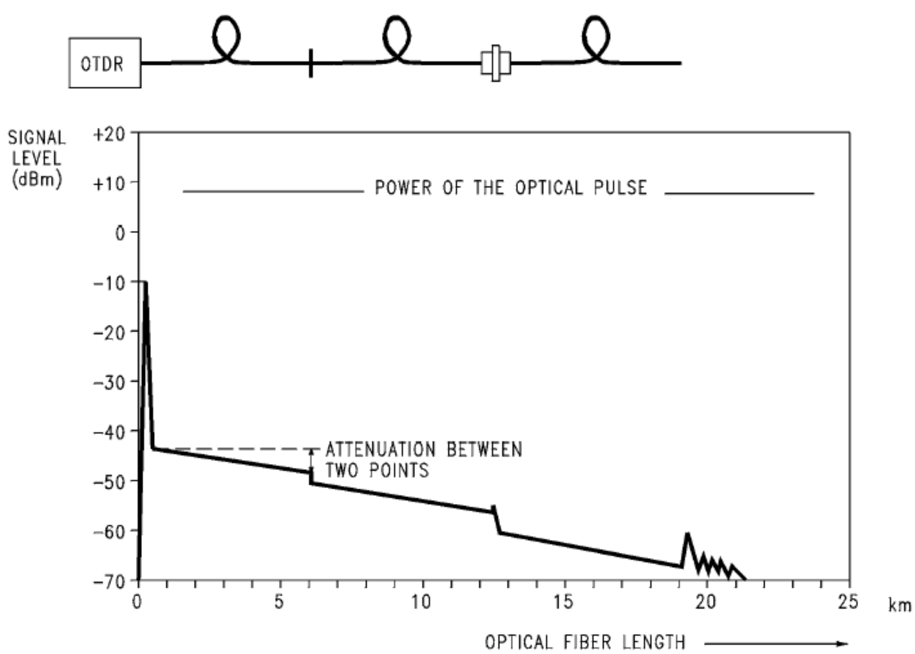


fig. 4.20

Insertion method

It is the simplest method that can be quickly executed, especially good for measurements during the installation or control phase on the field. It consists in connecting one end of the fiber to the source and the other end to the optical detector (fig. 4.21). The *mode scrambler* or the launch fiber can be inserted between source and fiber being measured. Note the power coupled across the input of the fiber being measured (calculated by subtracting the attenuation introduced by the *mode scrambler* from the power provided by the source) and the total attenuation due to the fiber insertion is evaluated by measuring the received optical power. If source and detector are not calibrated with accuracy, a variation of the last technique is the *method by substitution*, that includes the calibration, before the measurement, of the source and detector with a test fiber like the one to be measured.

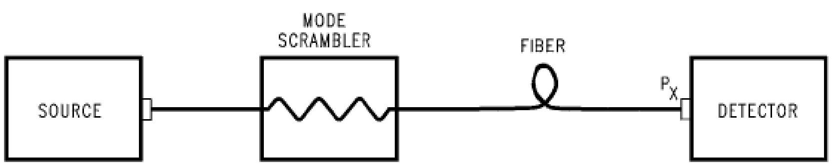


fig. 4.21

OPTICAL SOURCES

• To describe the parameters and the operation characteristics of LED and LASER diodes used as optical sources for fiber transmissions.

The commonly used optical sources are the light emitting diodes (*LED*) and the laser diodes (*LD*). Both can be made to generate radiations at different wave-lengths, in correspondence to the zones (windows) where the fibers show a minimum attenuation. The LEDs generally offers a good reliability at a reduced cost, the size is much reduced and they can be coupled well to the optical fibers. They are not absolutely monochromatic, though, and so they can cause chromatic dispersions inside the fiber.

The LASER diodes have extremely narrow emission spectra, to the advantage of the chromatic dispersion, and provide an optical power highly superior to the LEDs one.

They are more expensive than the LED and the power they emit is much affected by temperature variations. They must operate in temperature-regulated places, or they must be driven via an APC circuit (Automatic Power Control) stabilizing the emitted power with the temperature variations.

LED

The LED is a particular diode where the recombination process of the electron-hole pairs, after a direct polarization of the junction, causes light emission (fig. 5.1). The emitted optical power is function of the direct driving current. The LEDs in 1st window are currently based on gallium arsenide and on the ternary compound with aluminum (AlGaAs/GaAs), The LEDs in 2nd and 3rd window are obtained from indium-gallium arsenide-phosphorous compounds (InGaAsP/InP).

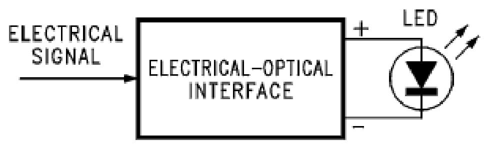


fig. 5.1 LED diode driving

The most significant parameters of a LED source are:

- *emission wave-length*
- *emission spectrum width*: the non-monochromatism is cause of chromatic dispersion, sensitive in 3rd window especially. Fig. 5.2a shows - for a LED operating in 2nd window - a typical diagram of the relative intensity as function of the wave-length
- *emitted optical power*: it is in the order of tens of μW, and depends on the direct driving current. Fig. 5.2b shows a typical diagram of the emitted power as function of the driving current. The manufacturer usually indicates the *optical power inserted into the fiber*, specifying the kind of fiber (62.5/125,100/140, monomode, etc.)
- *frequency response*: it has a low pass shape, and is detected by changing the frequency of a sine signal modulating the optical carrier. It can take values from some tens to some hundreds of MHz. Fig. 5.2c shows a typical frequency response of a LED. Sometimes, in alternative to the frequency response, the manufacturer provides the *pulse response* (fig. 5.2d).

Characteristic parameters

a) emission spectrum
b) emitted optical power / driving current
c) frequency response d) response to the pulse

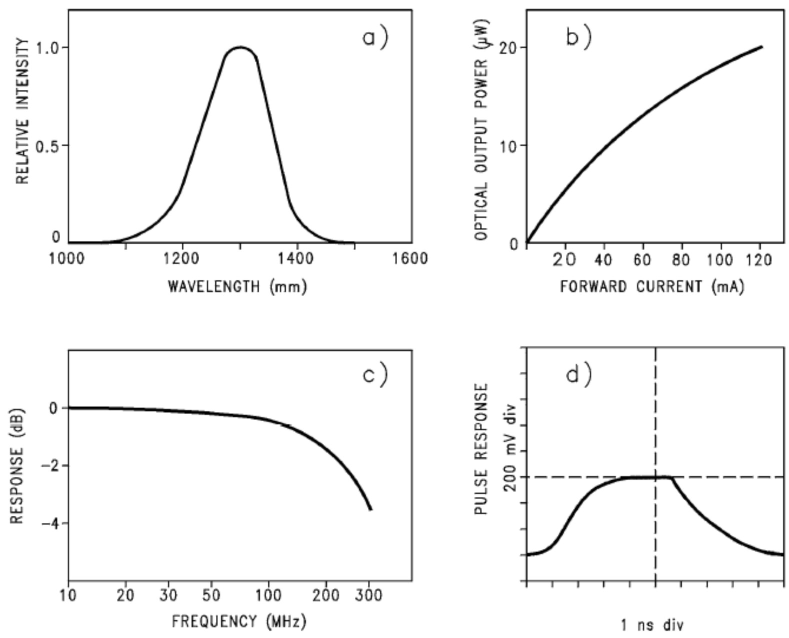


fig. 5.2 LED characteristic parameters
a) emission spectrum
b) emitted optical power / driving current
c) frequency response
d) response to the pulse

LASER DIODE

The electron-hole recombination phenomena is not the only way to generate photons, i.e. light radiation. If a photon with proper power strikes an excited atom, it can cause the emission of another photon: this is the so called *stimulated emission*. The characteristic of the new emitted photon is to be in phase with the incident one and to have practically equal frequency, which sets the bases to obtain a radiation amplification effect. The LASER diode (LD) is based on the last principles. The stimulated emission is made possible thanks to a higher doping in respect to the LEDs and to some constructional expedients, such as a positive reaction of a part of the emitted light inside the active zone started by reflection. The fact that incident photon and emitted photon have practically the same frequency makes the spectrum emitted by the LASER much narrower than the one emitted by the LED. The characteristic parameters of the LASER diodes are the same of the LEDs. Fig. 5.3 shows the graphs related to the emitted power and the spectral width of a LASER diode. In respect to the LED the following advantages must be underlined:

• much narrower spectral width (nanometers instead of tens of nanometers)
• much higher emitted power (mW instead of μW)
• much quicker response times (fractions of ns instead of some ns).

On the contrary, the LASER diode is much more sensitive than the LED to temperature variations, and so it must be thermostated or it must be driven via a circuit automatically changing the bias current so to stabilize the emitted power. This circuit is known as Automatic Power Control (APC).

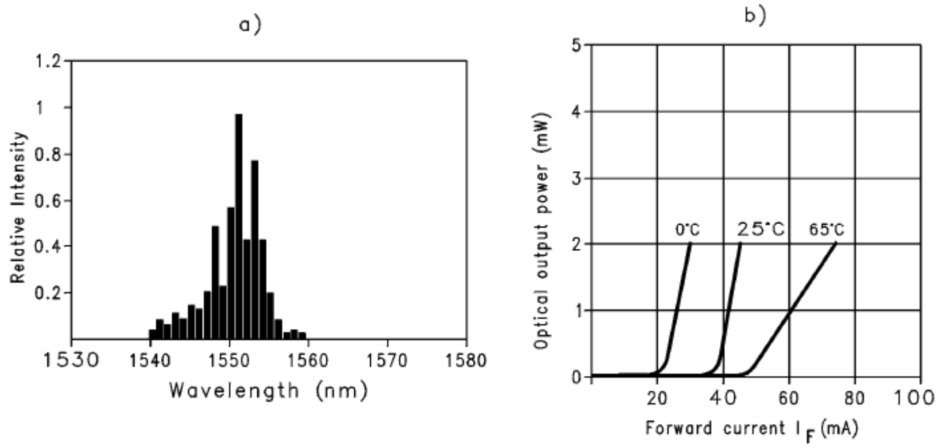


fig . 5.3 LASER diode characteristic parameters
a) emission spectrum
b) emitted optical power/ driving current

Characteristic parameters
a) emission spectrum
b) emitted optical power/ driving current

The LASER diode has an electrical behavior similar to the LED, and the emitted optical power depends on the direct current flowing in the same LASER. So, it is possible so to carry out optical fiber communication systems by directly modulating the LASER with an electrical signal. Consider, e.g., the transmission of a digital signal (fig. 5.4). In this case, the LASER is biased with a bias current IB around the threshold current ITH. The pulse driving current IP, due to the digital signal, takes a minimum value and a maximum value, in correspondence of which you obtain the minimum and maximum light emission. The *Output Optical Power/Driving current* characteristic of the LASER diode highly depends on temperature (fig. 5.3a). As you can note e.g. at 0°C and with IF=35 mA, the output power is 0.175 mW, and this quickly drops when the temperature increases if IF keeps constant. There are 0.075 mW at 25°C, and 0 mW at 65°C. To compensate the strong thermal dependence of the LASER diode, an external circuit is used controlling the bias current, so to stabilize the emitted power at temperature variation. This circuit must increase the bias current when the temperature increases, and vice versa. In some cases, besides, the temperature stabilizes, too, using a

temperature sensor and a cooler (*Peltier* cell) already mounted inside the container of the LASER diode.

SUMMARY of OPTICAL SOURCES

The following table sums up some typical data concerning LED and LASER Diode optical sources.

	LED	**LASER diode**
Emitted optical power	tens of mW	hundreds of mW
Wave-length	660nm and I/II^{a} window (typical)	II/IIIrd window (typical)
Emission spectrum	large (tens of nm)	narrow (few nm)
Circuit complexity	average / low	high
Frequency response	hundreds of MHz	tens of GHz
Mounting	receptacle pigtail (IInd window)	pigtail
Cost	average (hundreds US$)	High (thousands US$)
Applications	Telemetry. Analog and data transmissions at intermediate speed (10Mb/s) on short distances (<2km) with plastic fibers. Wave-length 660nm. Analog, data and local network transmissions, at intermediate speed (10Mb/s) on average distances (<10km), with glass fibers. Wave-length in Ist window. Video, data and local networks transmissions, at high speed (200Mb/s) on average distances (<50km), with glass fiber. Wave-length in I/IInd window.	Video, data and local networks transmissions at high speed (200Mb/s) on average/long distances (100km), with monomode fibers. Wave-lengths in II/IIIrd window. Digital transmissions (Gb/s) at very high speed and long distance (<400km) with monomode fibers. Wave-length in II/IIIrd window.

OPTICAL DETECTORS

• To describe the operating parameters and characteristics of Photodiodes and Avalanche Photodiodes used as optical detectors in optical fiber systems.

The photodetectors enable to transform an incident optical signal into an electrical signal. Necessary requirements for the photodetector are:

• high sensitivity, i.e. the capacity to absorb the maximum possible incident radiation
• high response speed, to properly detect very narrow luminous signals
• small size, low cost, reliability.

The photodetectors commonly used in optical fiber systems are the Photodiodes with PN and PIN junctions and the Avalanche Photodiodes (APD).

FIBER-TO-DETECTOR COUPLING

The luminous radiation from the fiber must strike the detector sensible surface as much as possible. The manufacturers provides Photodiodes and Avalanche Photodiodes (and so also the optical sources, examined in the last lesson) mounted on proper containers for fiber coupling.There are two kinds of mounting:

• with *receptacle* (fig. 6.10a): the manufacturer usually indicates the area of the sensible surface and/or the Numerical opening of the device
• with *pigtail* (fig. 6.10b): the manufacturer usually indicates the fiber used to carry out the *pigtail*, and its Numerical opening. In the first case, the fiber is coupled to the source via connectors (female on the source, male on the fiber). In the second case, at the connection, the fiber is directly welded to the receiver *pigtail*.

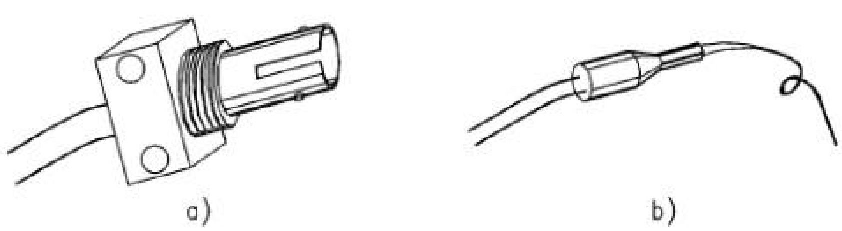


fig. 6.10 a. detector mounted on the receptacle
b. detector with pigtail

SUMMARY CARD of OPTICAL DETECTORS

The following table sums up some typical data concerning Photodiode and Avalanche Photodiode optical detectors.

	PHOTODIODE	AVALANCHE PHOTODIODE
Sensitivity	0.1-1 A/W	10-100 times higher than the photodiode
Wave-length	660nm and I/II/IIIrd window (typical)	II/IIIrd window (typical)
Circuit complexity	average / low	high
Frequency response	hundred of MHz	tens of GHz
Mounting	receptacle pigtail (II/IIIrd window)	pigtail
Cost	average (<500 US$)	high (<1000 US$)
Applications	Telemetry. Analog data transmissions at intermediate speed (10Mb/s) on short distances (<2km) with plastic fibers. Wave-length 660nm. Analog data and local network transmissions at intermediate speed (10Mb/s) on average distances (<10km), with glass fibers. Wave-length in Ist window. Video, data and local networks transmissions, at high speed (200Mb/s) and average distances (<50km), with glass fibers. Wave-length in I/II/IIIrd window.	Video, data and local network transmissions at high speed (200Mb/s) on average/long distances (100km), with monomode fibers. Wave-length in II/IIIrd window. Digital transmissions at very high speed (Gb/s) and long distance (<400km) with monomode fibers. Wave-length in II/IIIrd window.

ASSIGNMENT ONE

EXERCISE 1

Objective

- To get familiar in detecting and using the optical cables.
- To measure the Numerical Opening.

Necessary material

- Provided optical cables.
- 1 kit of Numerical opening complete with LASER emitter.

WARNING: carefully read the precautions provided in the first page.

Exercise 1.1: Characterization of the optical cables

1. Examine the provided optical cables.
2. Note what marked (Number) on each single cable and relate it to its type.
3. Lightly remove the caps from the connectors of all optical cables.
4. Check how the intensity of the luminous point decreases by connecting one end of the fiber to the LASER 660nm and insert the other end into the support with graduated base (fig. 2.10). Record your result in the following line

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Exercise 1.2: Measurement of the numerical opening

The numerical opening NA value can be obtained by measuring the transmitted power distribution at the fiber output or approximately, using a measurement bench like the one of fig. 2.10, where a visible radiation is injected into the fiber under test. At the fiber output, there is a luminous cone. The cone is projected on a surface and the diameter “D” of the cone on the surface and the distance “L” fiber-surface are measured. The numerical opening is calculated by the following formula:

$$NA \cong \arctan\left({}^{D}/_{2L}\right) \qquad [2.10]$$

where the arcsin must be calculated in radians.

1. Connect one end of the synthetic fiber to the LASER 660nm and insert the other end into the support with graduated base (fig. 2.10). T
2. he distance between the fiber and the graduated base is L=20 mm, the circles marked on the base are separated by 1 mm.
3. Activate the LASER by pushing the pushbutton.
4. Evaluate the diameter D of the lighted area (fig. 2.11).
5. Calculate the Numerical opening NA from the formula [2.10]. Insert your results in the following line.

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6. Compare the measured value with the one provided by the manufacturer (if possible).
7. Carry out the same measurement with all available optical cables. Insert your results in the following lines.

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8. Check how it is difficult to carry out measurements with the monomode 9/125 cable due to the reduced size.

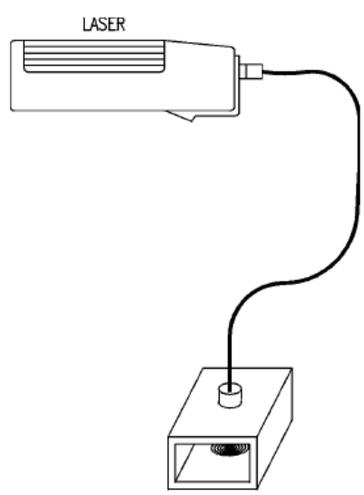

fig. 2.10 Lay-out of the components

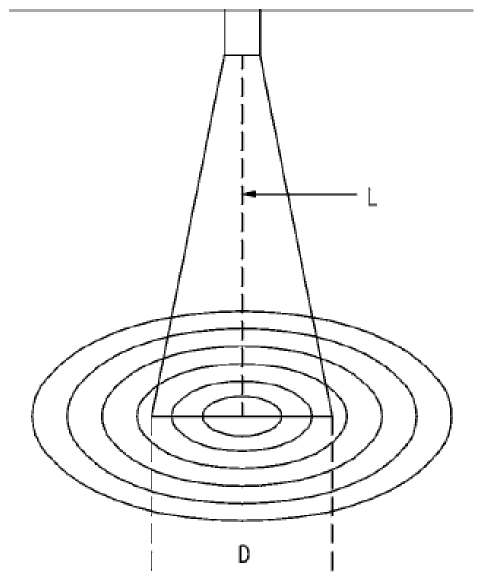

fig. 2.11 Example of measurement of the factor D

EXERCISE 2

Objectives

- To measure the attenuation.
- To measure the coupling losses.
- To get familiar with the use of the optical instruments: Source and optical power Meter.

Necessary material

- Optical source in the windows Ist/2nd 850/1310nm.
- Optical power meter including the windows Ist/2nd 850/1310nm.
- Provided optical cables.

Exercise 2.1: Measurement instruments & Direct measurement of the attenuation

This measurement is usually carried out on already installed cables, so that the two cable ends are not accessible in the same place. As in this case the absolute optical power is to be measured, a calibrated Optical Source and an Optical Power Meter are required.

- Connect the 3 m of the 62.5/125 optical cable with identifier “4” from the Source in 1st window to the Optical Power Meter (fig. 4.22).
- Turn the 2 instruments on.
- On the Meter, select the wave-length of 850 nm and the reading in dBm. Activate the LED on the Source and select the same wavelength (connector or selector according to the provided model): in these conditions the power inserted into the 62.5/125 fiber is

$$P_t = \ldots\ldots\ldots\ldots\ldots dBm$$

- Delicately move the optical cable connectors, and check that the measured optical power can change. Measure the power and explain why this happens.

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- Connect another fiber cable with identifier “4” to the first one. The value read on the Meter is the received optical power P_r.
- The loss L of the cable, including the fiber as well as the connectors, is:

$$L = P_t - P_r = \ldots\ldots\ldots\ldots\ldots\ldots dBm$$

- Invert the cable terminals and measure again. Do you find a different measure? If yes explain?

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- Now carry out the measurement at 1310nm.

$$L = P_t - P_r = \ldots\ldots\ldots\ldots\ldots\ldots dBm$$

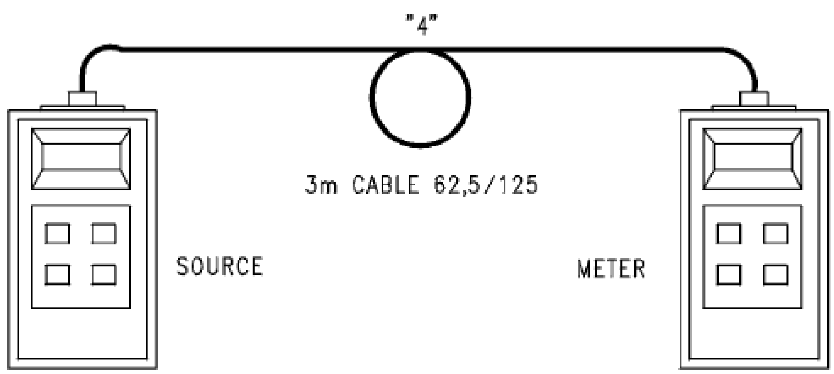

fig. 4.22

***Observation:* Make some comments on the accuracy of your measurements with relation to the length of the used fiber.**

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Exercise 2.2 Measurement for attenuation insertion

This measurement is usually carried out on cables to be installed, so that the two ends of the cable are accessible in the same place. An Optical Source, a Power Meter, an adapter and a reference cable are required (commonly called *launch fiber*) which is some meters long and with characteristics equal to the cable to be measured (fig. 4.23 and 4.24).

With our *Educational Panel* we can use the configuration of fig. 4.25 that uses the 300 meters of fiber contained into the panel that are accessible only with the two ST-ST adapters in the same panel.

- Connect a 62.5/125 fiber with identifier "4" from the Source in 1^{st} window to the Optical Power Meter (fig. 4.23).
- Turn the 2 instruments ON.
- On the Meter, select the wave-length 850 nm and the reading in dBm. On the Source, activate the LED and select the window 1.
- Read the received power $\boldsymbol{Pref}$ on the Meter.
- With two connectors and the two fibers, insert the 300 meters of 62.5/125 optical cable (fig. 4.25) and read the new received power $\boldsymbol{Pr}$**.**
- Not considering the attenuation introduced by the two adapters (the loss of each of them is around 0.5 dB), the loss L of the cable is:

$$\mathrm{L} = \mathbf{P_{ref}} - \mathbf{P_r}$$

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- Repeat the last measurements at 1310 nm and on the 200/230 and 9/125 cables if available. Record your results below.

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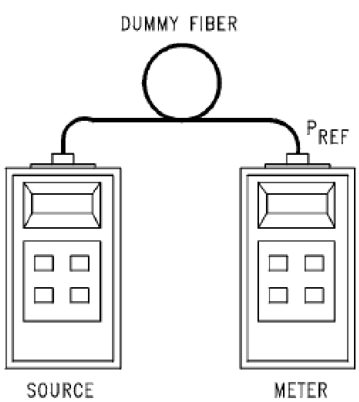

fig. 4.23

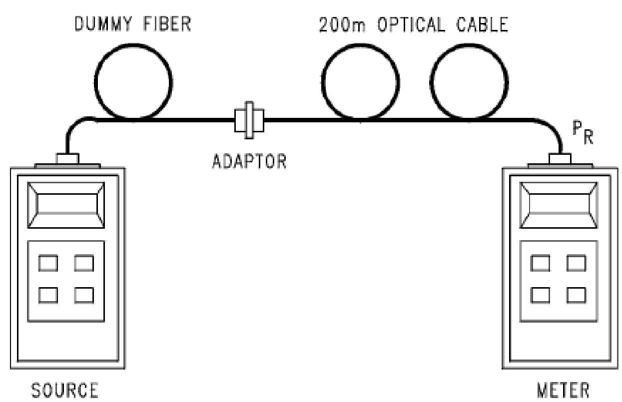

fig. 4.24

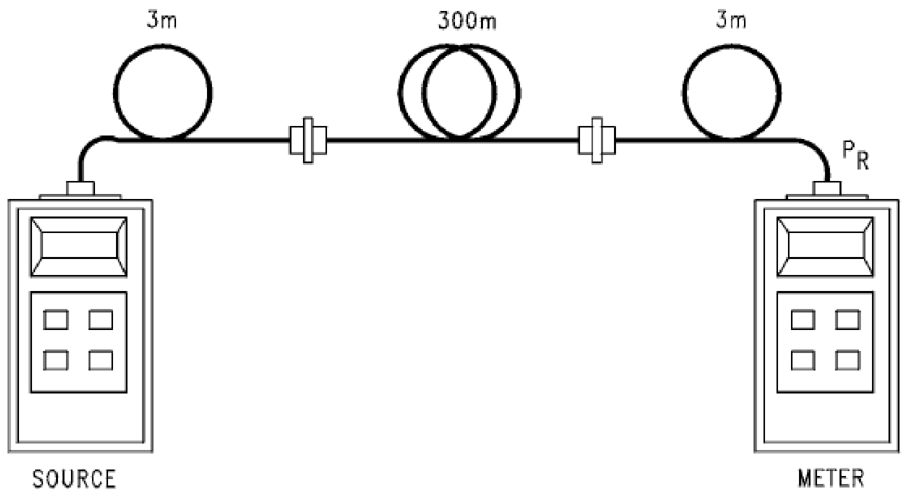

fig. 4.25

Consider to carry out these measurements also with the ***Substitution method*** using a launch fiber.

- The experiment is as seen before, but instead of carrying out a direct measurement of the received power and then making the difference between the measured values, you must reset the meter (key ***ZERO***) when the first calibration measurement is done, then, The Meter will directly provide the introduced fiber attenuation, as variation in respect to the 0dBm of the calibration.
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Exercise 2.3: Measuring the attenuation of the connectorized fiber

The total measured attenuation includes, in this case, the attenuation of the actual optical fiber as well as the attenuation introduced by the two connectors.

- Measure the attenuation on 300 meters of optical fiber as explained in the last exercises for the wave-length of 850nm.
- Consider there are connectors (0.5 dB each) or adapters (0.5 dB each) present in the path that is to be measured, that were not in the launch fiber.
- The kilometric attenuation of the fiber is calculated by dividing the loss L by the distance in kilometers (0.3 km).
- The same measurement can be repeated also at 1310nm.
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Exercise 2.4: Measuring the coupling losses

Keep the same conditions of the previous exercise (Source and Meter connected via 300-m fiber and panel connectors)

- Loosen one of the fiber connectors inserted into the ST-ST panel adapter, and separate it gradually from the same adapter (and, consequently, from the second ST connector inserted into the adapter inside the panel).
- Does the intensity of the received signal drops, and does it depends on the angle with which the connector is inserted into the adapter.

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- Loosen and separate the connector from the source and the detector, too. What happens to the received signal?

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Exercise 2.5: Measuring the insertion and the insulation loss of the WDM

This measurement is usually carried out in the laboratories of the component's manufacturer to check the characteristics (*Test Report).*

An Optical Source, a Power Meter and two 62.5/125 fibers with identifier "4" and one of the two WDMs present in our *Educational Panel* are required.

Measurements at λ1 (850 nm)

- Turn the 2 instruments ON.
- On the Meter, select the 850-nm wave-length and the reading in dBm. On the Source, activate the LED and select the window I.
- Connect a fiber directly from the Source to the Meter (fig. 4.23).
- Read the received power $\boldsymbol{Pref}$ on the Meter and this is our reference reading.
- Connect a fiber from the Source to the common port λ1+λ2 of the WDM (fig.4.26).
- Connect the other fiber from the Meter to the port λ1 of the WDM (850 nm).
- Read the received power $\boldsymbol{Pr1}$ on the Meter.
- The difference $IL850$

$$IL_{850} = P_{ref} - P_{r1}$$

What is the insertion loss of the WDM at 850 nm?

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(It would be more correct to subtract the loss of the two adapters included in the measurement set from this measurement).

- Disconnect the second fiber from the port λ1, and connect it to the port λ2 of the WDM (1310 nm), keeping it connected to the Meter.
- Read the received power **Pr2** on the meter.
- The difference IL850 is

$$I_{850} = P_{ref} - P_{r2}$$

What is the insulation of the WDM at 850nm?

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(It would be more proper to subtract the loss of the two adapters included in the measurement set from this measurement).

Measurements at λ2 (1310nm)

- On the Meter, select the 1310-nm wave-length and the reading in dBm. On the Source, activate the LED and select the window II.
- Connect a fiber directly from the Source to the Meter (fig. 4.23)
- Read the received power **Pref** on the Meter that is our reference reading
- Connect a fiber from the Source to the common port λ1+λ2 of the WDM (fig. 4.26)
- Connect the other fiber from the Meter to the port λ2 of the WDM (1310nm)
- Read the received power **Pr1** on the Meter
- The difference IL1310 is

$$IL_{1310} = P_{ref} - P_{r1}$$

What is the insertion loss of the WDM at 1310nm?

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(It would be more proper to subtract the loss of the two adapters included in this set from this measurement).

- Disconnect the second fiber from port λ2 and connect it to the port λ1 of the WDM (850nm), keeping it connected to the Meter
- Read the received power **Pr2** on the Meter
- The difference IL1310 is

$$I_{1310} = P_{ref} - P_{r2}$$

What is the insulation of the WDM at 1310nm?

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(It would be more proper to subtract the loss of the two adapters included in this set from this measurement).

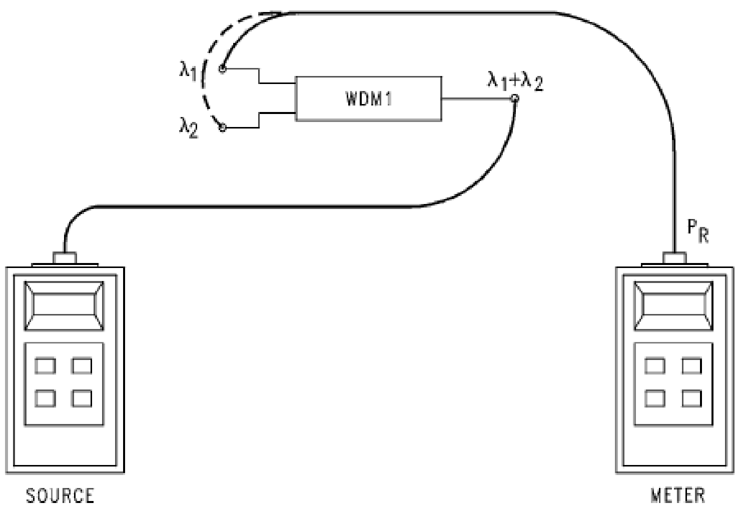

fig. 4.26

EXERCISE 3

Objective

- To measure the emitted power

Necessary material

- *Educational Panel*
- Provided optical cables
- Optical Power Meter
- Ammeter and Voltmeter

Exercise 3.1: Optical power emitted by the LED

The *Educational Panel* is provided with three driving sections, an analog and two digital ones, for the two present LED sources.

- Power the panel with the provided power supply
- Use the *ANALOG DRIVER* and *LED DRIVER 1* sections
- Disconnect the jumper between TP14 and ground and insert a tester configured as ammeter (range in mA)
- Use another tester configured as voltmeter between TP13 and ground (range about 2V)
- Set the AN/DIG switch to ***AN***
- In this configuration, the 850nm LED is used biased directly with the *BIAS* potentiometer
- Connect the Optical Power Meter to the *F.O. OUT 1* output and set it for 850-nm wave-length and measurement in dBm
- Measure the voltage VF across the LED and the direct bias current IF flowing across it
- Check that the optical power emitted by the LED. What happens when the direct current increases?

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Exercise 3.2: LED characteristic curves

- Set the measurement unit as in the previous Exercise
- With the cable "3" (200/230 fiber), connect the *F.O. OUT 1* to the Power Meter
- Change the *BIAS* potentiometer
- Measure the current IF crossing the LED, the voltage VF across it and the optical power Pout detected by the Optical Power Meter
- Record your results in a table and make a graph of Pout versus IF and another for IF versus VF.
- Change cable "3" with cable "4" (62.5/125 fiber) and "5" (9/125 fiber), and check what happens to the measured power. Expaline why this happens.
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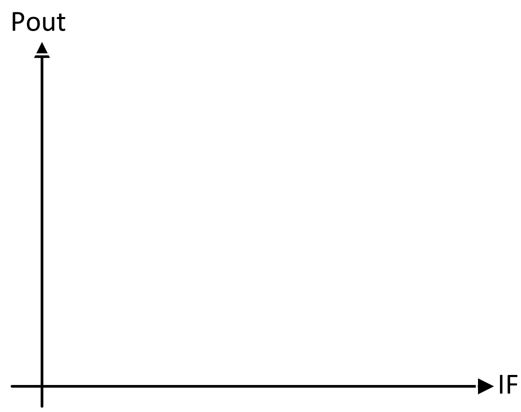
IF (mA)	VF (mV)	Pout (dBm



Exercise 3.3: LASER characteristics

The device used in the *Educational Panel* is a component defined ***Transceiver*** because it integrates, into a single container, the function of the optical transmitter and receiver for monomode fibers. In fact, as seen in fig.5.10 there are two receptacles for the separate sections Tx and Rx, for the SC connectors. The connection fibers toward the panel carry out the SC-ST matching. It is a device born to be used in SONET (Synchronous Optical NETwork), FDDI (Fiber Distributed Data Interface), ATM (Asynchronous Transfer Mode) and Fast Ethernet applications.

fig. 5.10 LASER Transceiver

The transmitter uses a *Multiple Quantum Well* LASER in Class I for the eyes' safety. The receiver contains a detection circuit for the input signal when the level overcomes a minimum threshold. The nominal characteristics are the following:

Transmitter

- Wave.length (λc): 1261 nm to 1360 nm
- Sprectral width: 7.7 nm
- Average optical power: -20 to -14 dBm (monomode fiber)

Receiver

- Sensitivity: -31 dBm max
- Maximum input power: -8 dBm min
- Signal non detection threshold: -45 dBm

The device being integrate, does not allow the de-activation of the APC circuit, consequently it is possible to measure the LASER response curve

- Via the cable "4" connect the *F.O. OUT 3* output to the Power Meter that must be set for 1310nm wave-length and measurement in dBm
- Activate the laser with the ***LASER ON*** switch
- Check the optical powered emitted by the LASER is about (in dBm)
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EXERCISE 4

Objective

- To measure the attenuation
- To measure the coupling losses
- To get familiar with optical instruments: Source and optical power Meter

Necessary material

- *Educational Panel*
- Optical power meter including the windows Ist/2nd 850/1310nm
- Provided optical cables
- Voltmeter or Oscilloscope

Exercise 4.1: Detector responsivity

The *Educational Panel* is provided with three reception sections, an analog and two digital ones, for the two present PIN photodiode detectors.

- Power the *Educational Panel*
- Use the *LED SOURCE 1* and *PIN PD DETECTOR* sections with both *AN/DIG* switches set to ***AN***
- In this configuration, the 850nm LED is used, biased directly through the *BIAS* potentiometer (clockwise rotation to increase the transmitted optical power)
- Connect a voltmeter (or the oscilloscope in DC) to TP17, where the voltage provided by the detector is measured.

Without input signal, there is a bias voltage equal to
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Consider that the measured voltage is proportional to the current provided by the photodiode

- Via the fiber with identifier “4” (62.5/125), connect the source to the detector
- What happens when the *BIAS* changes, the detected voltage ranges between
  ………………………………………………………………………………………
  …………………………………..(V) and …………….(V)…………………………….

- Change the fiber with the one with indicator “3” (200/230) and see what happens when the *BIAS* changes, the detected voltage ranges now between

  ………………………………………………………………………………………
  ……………………………(V) and ……………….(V) only in the first third of travel of the *BIAS* control.

It is evident that most amplitude of the fiber enables a higher light or optical power transmission. Beside, once 1/3 of the whole travel is overcome there is the detector saturation

- Change the fiber with the one with indicator “2” (plastic) and record the voltage range again.

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In this case the detected voltage slightly shifts from the value in the detector when there is no signal.
What is the cause of that?
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- Change the fiber with the one with indicator "5" (9/125) and check what happens when the *BIAS* changes?

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Avalanche photodiode

- Power the *Educational Panel*
- Use the *DIGITAL LASER DRIVER* and *LASER SOURCE* sections for the transmitter, and *AVALANCHE PD DETECTOR* and *DIGITAL LASER RECEIVER* for the receiver
- In this configuration the LASER at 1310nm is used, driven directly from a modulator
- The oscilloscope in DC at TP of *OUT 4*, where the voltage provided by the detector is measured
- Without input signal, what is the signal is present across this output
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ATTENTION !!!
The laser diode is a source of invisible light !!!
When the laser is active (switch to LASER ON):
Do not look
inside the F.O. OUT 3 output or
inside the optical fiber if connected to it!!!

- With a BNC-BNC coaxial cable, connect the *OUT 10* output of the *DATA PATTERN* to the *IN 4* input of the *DIGITAL LASER DRIVER*
- Using the fiber with identifier "4" (62.5/125), connect the source (*F.O. OUT3*) to the detector (*F.O. IN 3*)
- With the switches *SW A/B*, select the wished pattern and check that it is impossible to receive a continuous voltage level (all 0 or 1), but only alternatively (0/1 or 4x0/4x1)
- By slowly extracting the connector from the detector (*F.O. IN 3*), i.e. by attenuating the received signal, check what happens to the LED *LOW LEVEL*
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- Check, in these conditions, what happens to the detected square signal too
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- Change the fiber with the one with indicator “5” (9/125) and see what happens to the signal received.
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Explain why this happens?
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- Change the fiber with the one with indicator “3” (200/230) and make your observations
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Explain why is that so?

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- Change the fiber with the one with indicator “2” (plastic) and make your observations
  ……………………………………………………………………………………………………….
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Explain why?

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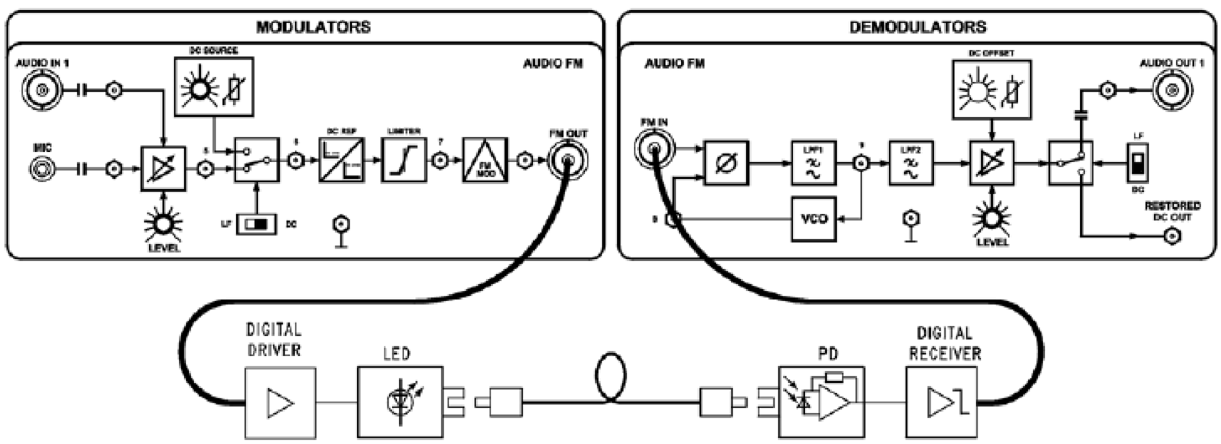
Part Two : Audio/Video Transmission over Fiber

OBJECTIVES

- To describe how the audio signal can be multiplexed with the video signal using a frequency translation
- To describe how the multiplexed audio signal can be separated by the video signal
- To describe the Intensity Modulation (linear modulation) of an optical source

INTRODUCTION to AUDIO / VIDEO TRANSMISSION

The optical fiber transmission system examined in this lesson can be used for the transmission of analog signals. Its frequency response ranges from 50Hz to 6MHz about, and so it is proper for video signal transmission. The electrical signal linearly modulates in intensity the optical power emitted by the source. In this case we speak of *Intensity Modulation* (IM). The connection block diagram is shown in fig. 10.1.



The analog signal is applied to an amplifier via a.c. coupling, that eliminates the continuous component. The transmission LED is biased in the central zone of the characteristics "*Output optical power/driving current*", and is then driven by the amplified analog signal. This changes the driving current in continuum, and consequently a modulation will be obtained with intensity equal to the optical power emitted by the LED (fig. 10.2).

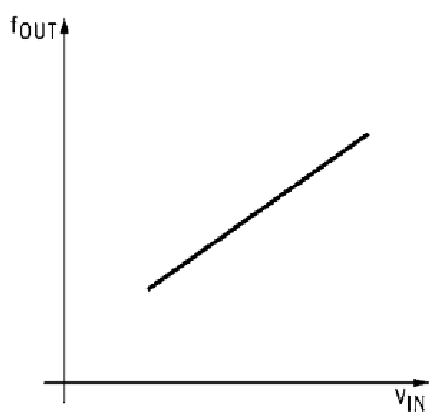


fig. 10.2 Voltage / frequency characteristic of the FM Modulator

The reception optical detector consists in a PIN photodiode. The photodetector current output is amplified by a transimpedance amplifier, providing a voltage output. Next amplification stages adjust the amplitude of the received signal. To carry out a complete video+audio communication system, there are a video signals generator, an audio generator, an audio+video multiplexer, an audio+video demultiplexer, and audio amplifier on the panel. The audio+video multiplex is carried out by adding the video to the audio subcarrier that is a 5.5-MHz carrier frequency modulated by the audio signal.

DEVICES for AUDIO / VIDEO TRANSMISSION

Analog transmitter with LED *TX1* source

In consists in the following sections:

- *ANALOG DRIVER* it constitutes the LED bias stage with input voltage – output current law the most linear possible. The bias regulation is possible with the *BIAS* potentiometer*,*
- *LED SOURCES 1* constitutes the stage containing the luminous source with output of ST *F.O. OUT 1* connector. Here there is a jumper on TP14 to carry out the bias current measurement. The ***AN /DIG*** switch must be to ***AN***

Analog receiver with photodiode detector *RX1*

It consists in the following sections:

- *PIN PD DETECTOR 1* constitutes the reception stage containing the PIN photodiode optical detector, with input of ST *F.O. IN 1* connector. The current output of the photodetector is amplified by a transimpedance pre-amplifier (mounted in the same container of the photodiode) providing a voltage output proportional to the input current.
- *ANALOG RECEIVER* constitutes the stage processing the signal of the last stage. In particular there are two *POST-AMP* and *OUT AMP* amplifiers*.* The last with gain control.

AUDIO/VIDEO Multiplexer of MODULATORS

Refer to the diagram with functional blocks of fig. 11.3. ***AUDIO IN 2 / MIC:***These are the two available alternate inputs (not the d.c. dis-coupling via capacitor), for audio signal and from microphone. Then there is an amplifier with level regulation ***LEVEL1****.* ***FM MOD:*** It is the audio subcarrier frequency modulator. The audio signal modulates a 5.5-MHz carrier in frequency, and the result of the modulation is then added to the composite video signal. The maximum frequency deviation allowed, for an audio signal of 1Vrms amplitude, should be ±50 KHz. There is a switch to turn off the modulator. ***VIDEO IN:*** It is the input of the composite video. It is compatible also with color video signals provided by other sources outside the *Educational Panel.* ***AMPLIFIER:*** It is the output amplifier that matches the level of the signal obtained with the potentiometer ***LEVEL2.*** The provided signal is the sum of the composite video signal and the audio subcarrier (above the video frequencies, see fig. 11.4). This signal is called Base band and is provided across the *BB OUT* output*.*

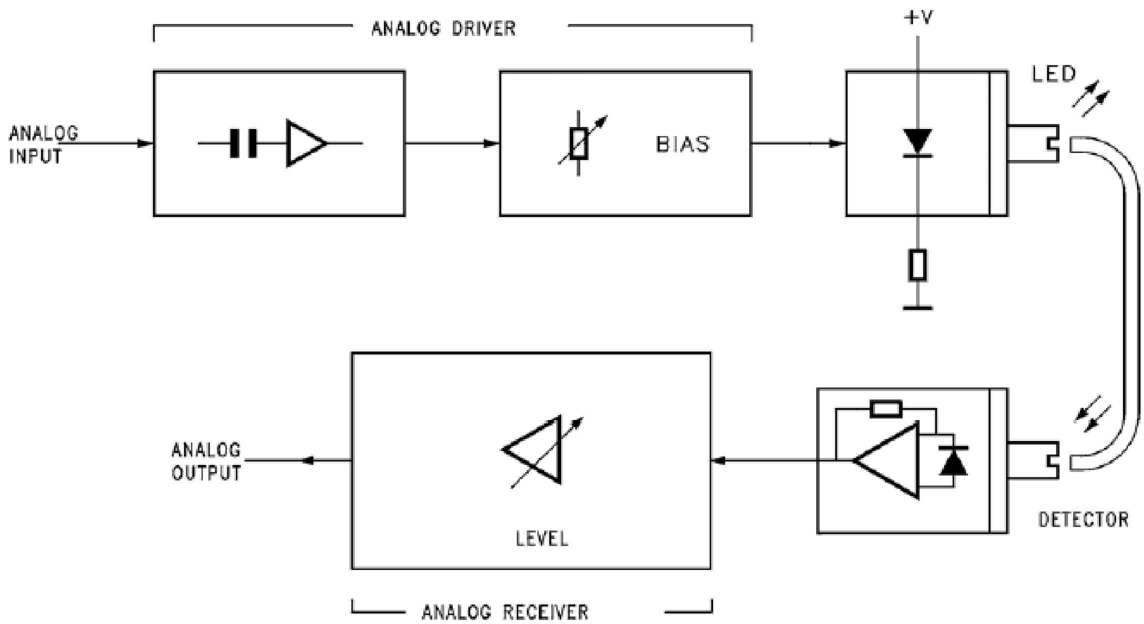


fig. 11.1 Communication system with Intensity modulation of the source

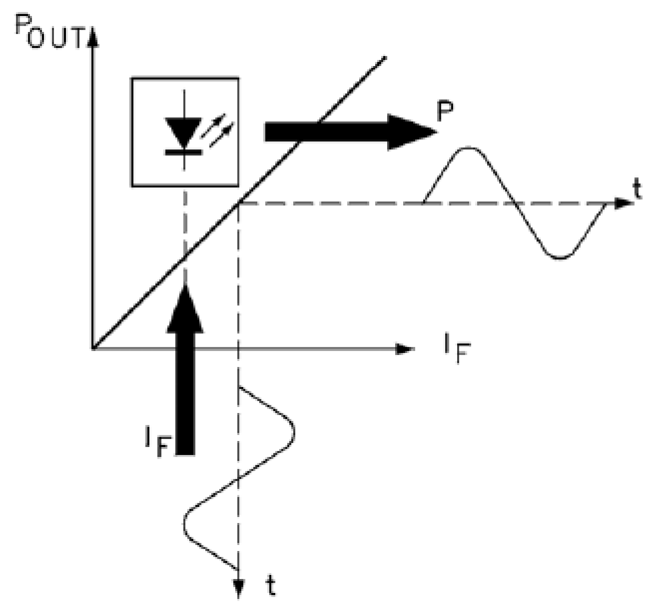


fig. 11.2 Linear variation of the emitted optical power intensity

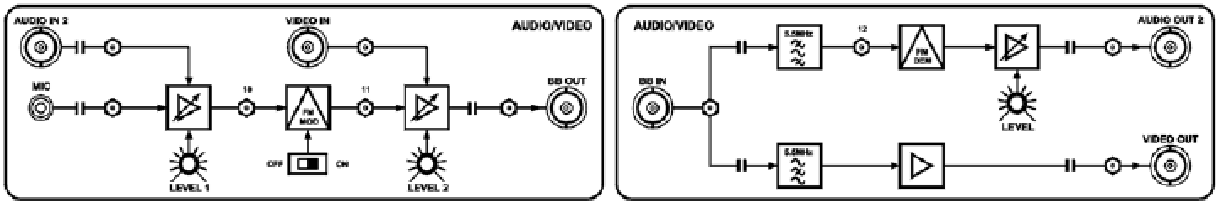


fig. 11.3 AUDIO / VIDEO MODULATOR - DEMODULATOR

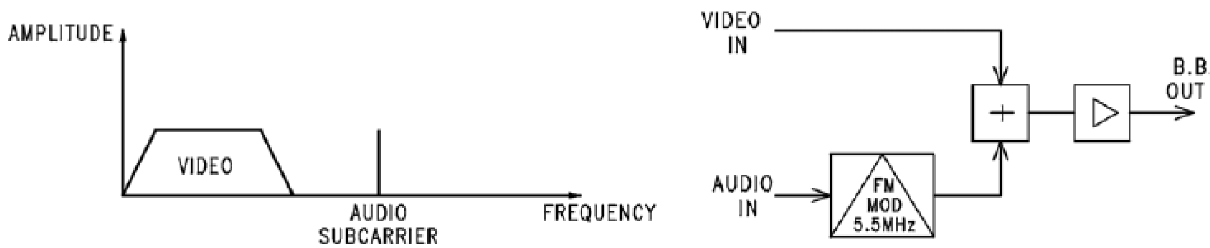


fig. 11.4 Signal Multiplex Audio / Video

AUDIO/VIDEO DeMultiplexer of DEMODULATORS

Refer to the diagram with functional blocks of fig. 11.3.

BB IN: It is the input of the Base band signal (composite audio + video).

AUDIO OUT 2: It is the audio output. The path of the audio signal extracted by the base band is the following:

- Band pass filter at 5.5 MHz extracting the single subcarrier from the base band
- frequency demodulator *FM DEM*
- amplifier with ***LEVEL*** control

VIDEO OUT: It is the composite video output.The path of the video signal extracted from the base band is the following:

- band pass filter at 5.5 MHz removing the audio subcarrier from the base band
- level matcher amplifier

AUDIO and VIDEO test generators

The *AUDIO* section provides a 1-KHz sine signal. It is possible to use the microphone source included in the set of accessories, as audio source. The *VIDEO* section provides a test video signal. It consists in Color Bars

EXERCISES

Objective

- To carry out an audio+video communication system consisting of: audio and video source; audio/video multiplexer and demultiplexer; analog transmitter and receiver on optical fiber; loudspeaker.

Necessary material

- *Educational Panel*

— Oscilloscope
— Tester
— Provided optical cables

Exercise 1: AUDIO / VIDEO Multiplexer

- Power the panel with the provided power supply
- Use the *AUDIO/VIDEO* section of *MODULATORS*
- With a BNC-BNC cable, connect the *OUT 7* output of the *VIDEO* generator to the *VIDEO IN* input
- Turn *ON the* switch of the VIDEO generator and the command of the *FM MOD*
- Connect the oscilloscope to the input and examine the Color Bars video signal.
- See the signal across TP11.

What kind of signal you observe, determine it's amplitude and frequency?

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It is the subcarrier frequency of the FM modulator used to transmit the audio signal overlaid to the video

- Note when the signal in *BB OUT* activates or not the *FM MOD*: Describe what you see.

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Exercise 2: Analog transmitter and working point of the LED

- Use the *ANALOG DRIVER* and *LED SOURCE 1*
- Set the AN/DIG switch to ***AN***
- Remove the jumper in TP14 and connect the tester in amperometric mode between TP14 and ground
- Adjust the *BIAS* potentiometer to obtain a bias current of 60 mA and re-insert the jumper again
- Connect the oscilloscope to TP13 to see the LED working point
- With a BNC-BNC coaxial cable, connect the output *AUDIO OUT 6* to the *AUDIO IN 2* input of the *AUDIO/VIDEO MODULATOR*
- With a BNC-BNC coaxial cable, connect the *OUT 7* output of *VIDEO* to the *VIDEO IN* input of the *AUDIO/VIDEO MODULATOR*
- With a BNC-BNC coaxial cable, connect the *BB OUT* output of the *AUDIO/VIDEO MODULATOR* to the *IN 1* input of the *ANALOG DRIVER*
- Adjust *LEVEL 2* to obtain a signal with proper amplitude
- With the oscilloscope, observe the voltage modulating the LED where the Video and Audio information is overlaid (5.5MHz FM)
- Increase and drop the *BIAS* current and describe what you see (TP13).

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Exercise 3: Creating the connection

- Complete the wiring started in the last exercise to carry out a complete connection

- With the fiber with identifier “4” (62.5/125), connect the source (*F.O. OUT 1*) to the *F.O. IN 1* input of the PIN photodiode detector
- Set the AN/DIG switch to ***AN*** even in the reception section
- With a BNC-BNC coaxial cable, connect the *OUT 1* output of the *ANALOG RECEIVER* to the *BB IN* input of the *AUDIO/VIDEO DEMODULATOR*
- With a BNC-BNC coaxial cable, connect the *AUDIO OUT 2* output to the *AUDIO IN* input of the *SPEAKER 2*
- With a BNC-BNC coaxial cable, connect the *VIDEO OUT* output to the *VIDEO IN* input of *TV COLOR MONITOR*
- Turn on the TV Monitor with *POWER*
- Adjust the *BIAS* again to get 60mA and re-insert the jumper
- Adjust the *LEVEL 1* to get 2Vpp in TP10

By setting the *FM MOD ON o*bserve and plot the signal in TP11, What is the shape, frequency and peak to peak voltage?

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- Adjust *LEVEL 1* to get 100mVpp
- Observe in *BB OUT*, when the FM modulator overlaid to the Video signal of the audio subcarrier turns ON.

Describe the effect on signal?

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- Adjust *LEVEL 2* to get 1Vpp in *BB OUT*
- Adjust the *LEVEL* of the *ANALOG RECEIVER* to the maximum to get 1Vpp across the *VIDEO OUT* output of the *AUDIO/VIDEO DEMODULATOR*
- With the oscilloscope observe (and plot) the wave-form in the different measurement points.

How the wave-form in TP13 is changed in respect to the starting signal?

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