ECE 584
Microwave Engineering
Laboratory Notebook

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2004

Electrical and Computer Engineering

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Contents

I. Introduction

1. General Comments

Lab Organization:
There are a total of six laboratory experiments described in this manual. The first three involve basic microwave measurement techniques for power, frequency, wavelength, standing wave ratio, impedance, and S parameters. The last three experiments deal with the characterization of some basic microwave components, extending the techniques learned in the first group of experiments. Each group of students will have two weeks in which to complete each of the six experiments. The first three experiments will be set up during the first six weeks of the semester, and the last three experiments will be set up during the following six weeks. Every two weeks each group will rotate to a new experiment station.

Be sure to completely read the description of each experiment before beginning the experiment. This will help you to see the overall plan of action, and should decrease the likelihood that you will do the procedure incorrectly, or forget to do part of the procedure.

Some of the laboratory experiments will involve material that is out of sequence with the classroom lecture, and you will be covering topics that have not yet been discussed in class. You will need to read some text material (*Microwave Engineering*, 3rd edition, by D. M. Pozar) ahead of the lecture schedule so that you have a better understanding of the experiments you are performing. Prior to going to your first lab, you should read over the description of the first three experiments in the lab handbook. Also, make sure you read pages 3-10 of the lab handbook, since they contain general information that you need to know.

You will be performing Labs 1, 2, and 3 through the first half of the semester, and Labs 4, 5 and 6 will be completed during the second half of the semester. Each Lab Section will have six lab groups, with two students in each group (some groups may consist of three students in special situations). Each lab group will take two consecutive Lab periods to complete each of the six lab experiments.

There will be two bench setups for each of three experiments on any given lab day, so two lab groups will start with Lab 1, and the other two groups will start with either Lab 2 or Lab 3. <u>For this reason, it is very important that you read over the first three experiments (slotted line, vector network analyzer, Gunn diode) prior to coming to your first lab.</u> You also need to study ahead in the text material, as required for these labs.

Lab Reports:
Lab reports are required of individual students, and are due two weeks after the corresponding experiment has been completed. Students are encouraged to keep a lab notebook to record original data, equipment layout, and notes about the experiment. Reports should be neat and clearly organized, and should include original data sheets. Graphs should be neatly drawn, either using a computer graphics package, or by hand with a straightedge and French curve. Each graph axis of a graph must include a title and units. Organization of the lab report is left to the student, but a suggested report outline follows:

1.	Introduction	(purpose of experiment)
2.	Procedure	(equipment used, configuration, unexpected problems)
3.	Results	(measured data, relevant calculations)
4.	Discussion	(interpretation of results)
5.	Conclusions	(what was learned, recommendations)

In some of the experiments topics for optional work are suggested - you should consider these options, if time permits. Students are also encouraged to try out their own "what if. . . " ideas. period. You are encouraged to keep a lab notebook, with careful notes about the experiment setup, measurements, expected (or unexpected) results, problems encountered, etc. Completed lab reports are required of each student, and are due two weeks after each experiment is completed. The Teaching Assistant will collect lab reports at the beginning of the lab period.

Care of Equipment:
Please be very careful with the microwave test equipment, as it is very delicate, and expensive to repair or replace. (Microwave network analyzers cost approximately $70,000 each; microwave connectors and adapters range in cost from $35 to $90 each.) If you suspect something is not operating correctly, report it to the lab technician or Teaching Assistant. Be especially careful when using connectors to avoid breaking pins and cross-threading. If at any time you are uncertain about lab safety, please ask the Teaching Assistant before proceeding.

Lab Support:
There will be a Teaching Assistant assigned to each of the Lab Sections to help with questions about experiment setup and measurements. In addition, our Research Engineer (Mr. Eric Knapp) will be available to maintain the microwave lab equipment. Any problems with basic measurement equipment (e.g. network analyzer, signal sources, VSWR meters, etc.) should be reported to Mr. Knapp at 545-4699 or at knapp@mirsl.ecs.umass.edu.

2. Microwave Radiation Hazards

Excessive exposure to electromagnetic fields, including microwave radiation, can be harmful. Although the power levels used in our Microwave Instructional Lab are very low and should not present a health risk, it is still prudent to,

- be aware of the recommended safe power limits
- be aware of the power densities with which you will be working
- use good work habits to minimize exposure to radiated fields

The question of what is a "safe" radiation level is controversial; like highway speed limits, all we can say with total certainty is that less is safer. Microwave radiation is nonionizing, so the main biological effect is induced heating, which may occur relatively deep inside the body to affect sensitive organs. Health risks increase according to the power density and the duration of the exposure. The eye is the most sensitive organ, and studies have shown that cataracts can develop from exposures as short as 1.5 hours to power densities of 150 mW/cm^2. Thus, using a safety factor of more than 10, the current US safety standard, C95.1-1991, recommends a maximum exposure power density of 10 m W/cm^2, at frequencies above 10 GHz, with lower levels at lower frequencies. By comparison, the power density from the sun on a clear day is about 100 mW/cm^2, but most of this power is beyond the microwave spectrum, and so does not enter deeply into the body.

The sources used in the Microwave Instructional Laboratory, such as sweep generators and Gunn diodes, have power outputs in the 10 - 15 m W range. In most cases, there is little danger of being exposed to radiation at these power levels because our experiments use coaxial lines or waveguide, which provide a high degree of shielding. It is possible, however, to encounter power densities near the US recommended limit at the end of an open-ended coaxial cable or waveguide. Such power densities exist only right at the open end of the coax line or waveguide, due to the $1/r^2$ decrease of radiated power with distance. For example, at a distance of 10 cm from a waveguide flange with an input power of 20 mW, the Friis formula gives the power density as,

$$S = \frac{PG}{4\pi R^2} = \frac{(20)(2.5)}{4\pi(10)^2} = 0.04 \ \text{mW/cm}^2$$

which is seen to be far below the recommend safety limits.

Even though there should be little danger from microwave radiation hazards in the lab, the following work habits are recommended whenever working with RF or microwave equipment:

- ***Never look into the open end of a waveguide or transmission line that is connected to other equipment.***

- ***Do not place any part of your body against the open end of a waveguide or transmission line.***

- ***Turn off the microwave power source when assembling or disassembling components***

3. Overview of Microwave Test Equipment

A key part of the microwave laboratory experience is to learn how to use microwave test equipment to make measurements of power, frequency, S parameters, SWR, return loss, and insertion loss. We are fortunate to have a very well-equipped microwave laboratory, but most of the equipment is probably not familiar to students. Here we briefly describe the most important pieces of test equipment that will be used in the laboratory experiments. More detail on the operation of this equipment can be found in the Operation Manuals in the Microwave Instructional Lab. The Appendix of this manual contains a list of the major pieces of equipment in the Microwave Instructional Lab.

Sweep Generator:
The source of microwave power for most of our experiments will be supplied by a microwave sweep generator. We have several sweep generator models, including the HP8620 mainframe and the HP8350 mainframe, each of which uses plug-in modules to cover specific frequency bands. These generators can be used as a single-frequency source (CW), or as a swept source, where the frequency is varied from a specified start and stop frequency. The HP8620 model uses manually adjustable knobs and buttons to specify the frequency, while the newer HP8350 units use electronically adjustable frequency ranges. The HP8350 also includes digital readouts for frequency and output power. Both sweep generators have a switch on the plug-in unit to turn the RF power on and off. To obtain the best frequency stability it is recommended that the AC power for the sweep generator be left on during the lab period, and the RF power switched off at the plug-in module when re-arranging components.

Power Meter:
We can measure microwave power with the HP436A power meter. This meter uses a sensor head that converts RF power to a lower frequency signal measured by a calibrated amplifier. Before using, the HP436A should first be zeroed by pressing the *zero* button, then calibrated by connected the sensor head to the calibration connector on the front panel. A calibration dial on the front panel should be set to the value indicated on the calibration data listed on the sensor head. The HP436A can be set to display power in mW or dBm.

Frequency Counter:
We have several microwave frequency counters, including the HP5342A, the HP5350B, and the HP5351A. These give precise measurement of frequency using a heterodyning technique, followed by a high-speed digital counter.

Spectrum Analyzer:
The spectrum analyzer gives a frequency domain display of an input signal, and allows measurement of power of individual frequency components. This is especially useful when a signal contains components at several frequencies, as in the case of a Gunn diode, or the output of a mixer. We have two HP8559A microwave spectrum analyzers.

Vector Network Analyzer:
The vector network analyzer is one of the most useful measurement systems in microwave engineering, as it can be used to measure both magnitude and phase of a signal. It is usually arranged to measure the S parameters of a one- or two-port network, but this data can easily be converted to SWR, return loss, insertion loss, and phase. We will primarily use the HP8753 vector

network analyzer in our work. This is a state-of-the-art analyzer, with an internal microprocessor for error correction and instrument control, and data display. See the Appendix for details on the calibration procedure for the HP8753.

Scalar Network Analyzer:
The scalar network analyzer, the HP8757, is similar to the vector analyzer, but measures only the magnitude of a reflection or transmission.

SWR Meter:
The standing wave ratio is measured using the HP415 SWR meter in conjunction with a slotted waveguide line and detector carriage. The RF input to the line is modulated at 1 kHz by the microwave sweeper source. The amplitude of the electric field in the slotted line is sampled by a small adjustable probe, which drives a detector diode. The output of the detector is a low-level 1 kHz signal, which is amplified, filtered, and displayed by the HP415 SWR meter. The scale on the SWR meter is calibrated to read SWR directly.

4. Resources

Here we list some of the many resources that can help you with your work in the microwave laboratory:

- Manuals for laboratory equipment - kept on the shelves in the Microwave Instructional Laboratory

- Serenade Manuals - a copy is available in the Microwave Instructional Laboratory

- Your textbook - describes *S*-parameters, operation of network and spectrum analyzers, microwave couplers and resonators, and more

- The library - many good references on microwave measurements and microwave theory

- Lab Teaching Assistant - for help with procedures, faulty equipment, etc

II. The Experiments

1. The Slotted Line

Introduction:

In this experiment we will use a waveguide slotted line to study the basic behavior of standing waves, and to measure SWR, guide wavelength, and complex impedance. Slotted lines can be made with any type of transmission line (waveguide, coax, microstrip, etc.), but in all cases the electric field magnitude is measured along the line with a small probe antenna and diode detector. The diode operates in the square-law region, so its output voltage is proportional to power on the line. This signal is measured with the HP415 SWR meter. To obtain good sensitivity, the RF signal is modulated with a 1 kHz square wave; the SWR meter contains a narrowband amplifier tuned to this frequency. The HP4l5 has scales calibrated in SWR, and relative power in dB. This experiment also introduces the student to common waveguide components such as waveguide-to-coax adapters, isolators, wavemeters, slide-screw tuners, detectors, and attenuators.

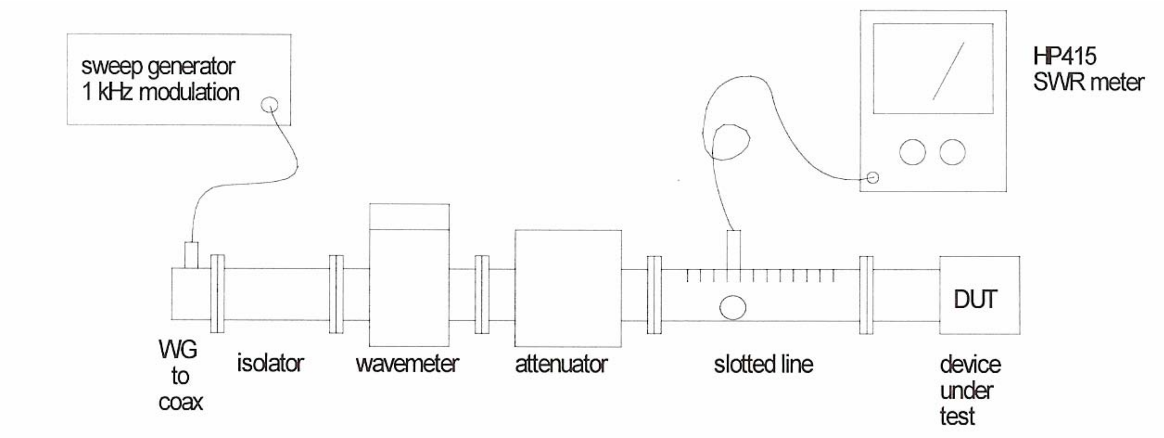
While the slotted line is cumbersome to use and gives less accurate results when compared with the automated vector network analyzer, the slotted line is still the best way to learn about standing waves and impedance mismatches. Before doing the experiment, read pages 69-72 of the textbook for a general description of the slotted line. Make sure that you understand the difference between "guide wavelength" and "wavelength". There is a discussion on pages 101, 109, and 113 on this topic. There is a manual in the lab describing the operation of the SWR meter; it is often non-intuitive. The detector diode must operate in the square law region for good behavior and accurate results. If the power level is too high, the small signal condition will not apply and the output will be saturated, while for very low power, the signal will be lost in the noise floor. Attenuation and impedance are discussed on pages 109-115, and there is also a very useful example there to help with your calculations later.

Equipment Needed:

HP8620 or HP8530 sweep oscillator and X-band plug-in
coax-to-waveguide adapter
waveguide isolator
cavity wavemeter
precision attenuator
slotted line and detector
HP415 SWR meter
waveguide matched load
frequency counter (optional)
waveguide section (1m long)
fixed waveguide attenuator (3 to 10 dB)
slide-screw tuner
blank waveguide flange
waveguide iris

Procedure:

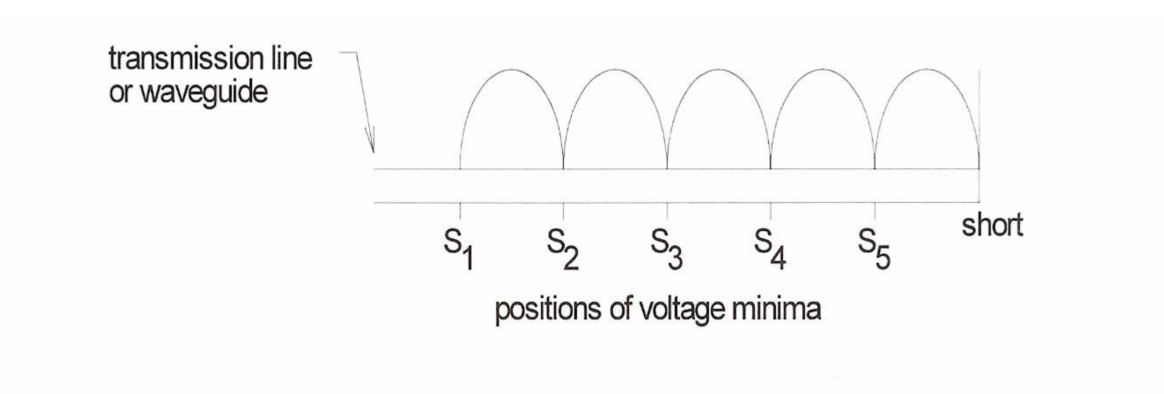
1. Setup:
Set up the equipment as shown below. We are using X-band waveguide, with a=0.9", and a recommended operating range of 8.20 - 12.40 GHz for dominant mode operation.



2. Measurement of Guide Wavelength:
Set the source to a CW frequency in the above range, and measure the frequency with the frequency counter or wavemeter. Do not rely on the scale reading on the sweep generator, as this may not be accurate.

The wavemeter is a tunable resonant cavity, and is used by tuning it until a dip is registered on the SWR meter; the frequency is then read from the scale of the wavemeter. Be sure to detune the wavemeter after frequency measurement to avoid amplitude fluctuations that may occur when the wavemeter is set to the operating frequency.

Place the blank flange on the load end of the slotted line; use two or more screws to get good contact. Set the attenuator near zero dB. Adjust the SWR sensitivity for a reading near midscale, then adjust the carriage position to locate several minima, and record these positions from the scale on the slotted line. Note that voltage minima are more sharply defined than voltage maxima, so the minima positions lead to more accurate results. See the sketch below.



Since the voltage minima are known to occur at spacings of $\lambda_g/2$, the guide wavelength can be determined. Do this for several frequencies.

3. Measurement of SWR:
Measure the SWR of the following components at two frequencies, at least 2 GHz apart:

a) a fixed attenuator with a short at one end
b) a matched load
c) an open-ended waveguide
d) a blank flange (short circuit)

After measuring the operating frequency, connect one of the above loads to the end of the slotted line. Adjust the probe carriage for a maximum reading on the SWR meter, then adjust the gain and sensitivity of the meter to obtain exactly a full-scale reading. Now move the probe carriage to a voltage minimum, and read the SWR directly from the scale. If the SWR is greater than about 1.2, increase the gain of the meter by 10 dB, and read the SWR on the SWR=1 to 3 scale.

To obtain accurate results with the slotted line, it is critical that the signal level be low enough so the diode is operating in the square-law region. This can easily be checked by decreasing the power level with the attenuator and verifying that the power reading (in dB) indicated on the SWR meter drops by the same amount. If it does not, reduce the received power level by reducing the penetration depth of the probe. Alternatively, the power level can be reduced at the sweeper, but it is usually best to work with a minimum probe depth, and maximum source power to maintain a good signal to noise ratio.

If the probe is extended too far into the waveguide the field lines can be distorted, causing errors. This can be checked by re-measuring the SWR with a smaller probe depth; if the same SWR is obtained, the probe depth is ok. Otherwise, the process should be repeated with progressively shallower probe depths, until a suitable depth is found. This is generally a more serious issue when low SWRs are being measured.

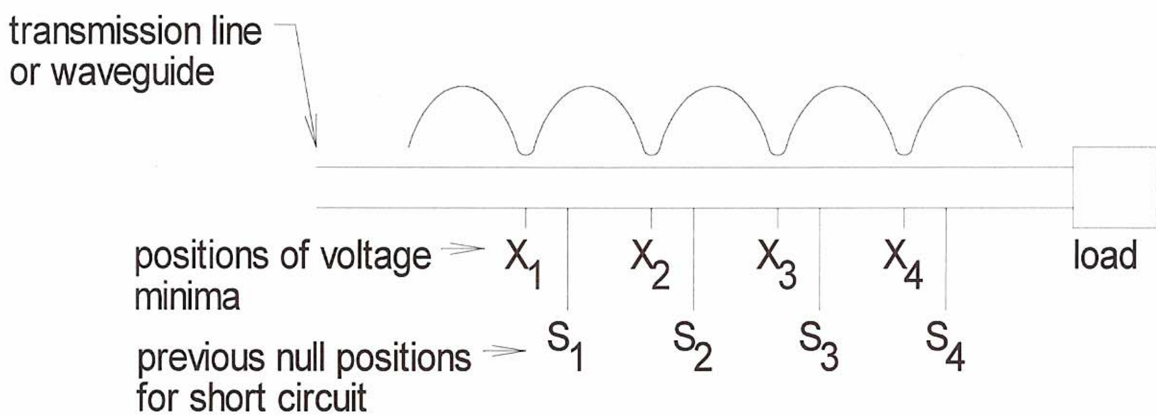
If the SWR is greater than about 3 to 5, accuracy can be improved by measuring the SWR with the precision attenuator. First, move the probe carriage to a voltage minimum, and record the attenuator setting and meter reading. Then move the probe to a maximum, and increase the attenuator to obtain the same meter reading. The difference in attenuator settings is the SWR in dB.

4. Measurement of Attenuation:
The above technique can also be used to measure attenuation. Attach the (two-port) device to be tested before the slotted line, with a matched load after the slotted line. Adjust the probe carriage for a maximum reading, and record this value and the attenuator setting. Now remove the device under test. Adjust the probe carriage for a maximum, and increase the attenuator setting to obtain the previous reading on the SWR
meter. The difference in attenuator settings is the attenuation of the component. This is called the comparison method of attenuation measurement.

Use this technique to measure the attenuation of the fixed attenuator, and a 1m length of waveguide, at several frequencies.

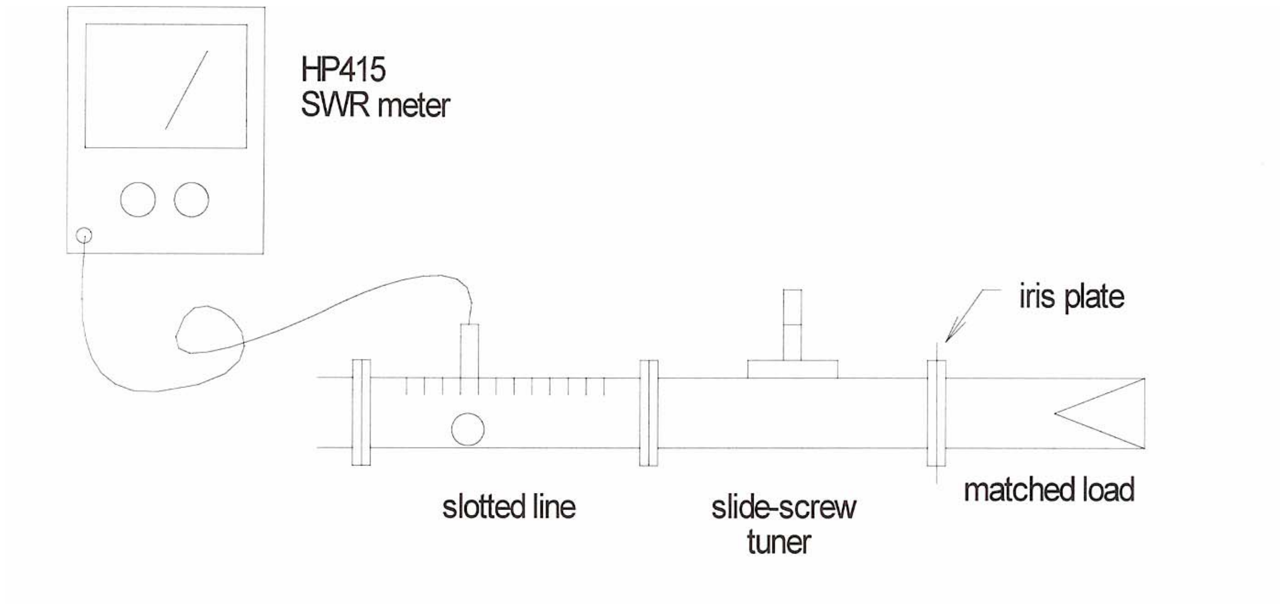
5. Measurement of Impedance:
The previous measurements involved only the magnitude of reflected or transmitted waves, but we can also measure phase with the slotted line.

First terminate the slotted line with the blank flange, and accurately measure the positions of the voltage minima. Next, place the component to be measured on the slotted line, and measure the SWR and the new positions of the minima. The SWR determines the magnitude of the reflection coefficient, while the shift in the position of the minima can be used to find the phase. Then the normalized (to the waveguide characteristic impedance) load impedance can be found. This can be done with a Smith chart, or by direct calculation.



Measure the impedance of the iris (the flat plate with a round hole), backed with a matched load at several frequencies using the above procedure.

6. Tuning a Mismatched Load (optional):
Use the iris backed with a matched load as a mismatched impedance, and place the slidescrew tuner between the slotted line and this impedance, as shown in the figure below. Measure the SWR. Now adjust either the depth or position of the slide-screw tuner, and re-measure the SWR. Keep iterating until you obtain an SWR<1.1, indicating a reasonably good impedance match. Leave the tuner at this setting, and measure the SWR versus frequency. (Remember how tedious this procedure is when you do Experiment 4 on the network analyzer!)



Write-up:

Measurement of Guide Wavelength:

Compare the frequencies read on the sweep generator, the wavemeter, and the frequency counter (if available). Determine the guide wavelength from the measured minima positions; average your results for different adjacent pairs of minima. Using the measured frequency, calculate the guide wavelength and compare with the above results. Discuss reasons for discrepancies.

Measurement of SWR:

Tabulate the measured SWR for each component, versus frequency. Indicate which measurement technique was used. Discuss the results of checking for the square-law region of the detector, and the effect of probe depth.

Measurement of Attenuation:

Compare the measured attenuation for the fixed attenuator with its specified value. Compare the measured attenuation for the 1 m long waveguide section with the calculated value. Discuss reasons for differences.

Measurement of Impedance:

Calculate the normalized impedance of the iris-load from the slotted line data, and plot on a Smith chart versus frequency.

Tuning a Mismatched Load:

Plot the measured SWR versus your tuning iterations. Plot the resulting SWR versus frequency.

2. The Vector Network Analyzer

Introduction:

In this experiment we will learn to use the HP8753 Vector Network Analyzer to measure the magnitude and phase of reflection and transmission coefficients (S parameters) of one and two-port networks. Such measurements are of critical importance in the design and testing of microwave circuits.

A discussion of the scattering matrix is presented in Section 4.3 of the text. Make sure you understand this material, because the experiment is based on measurements of S parameters. In Part 4 you will measure the reflection and transmission coefficients of a circulator. The text has a general discussion about circulators on pp. 308-311. Reflection and transmission coefficients are discussed on pp. 58-63. For Part 5 of this experiment you need to review Smith charts and understand their use. See text pp. 64-69, and the supplemental notes on the Smith chart handed out in class.

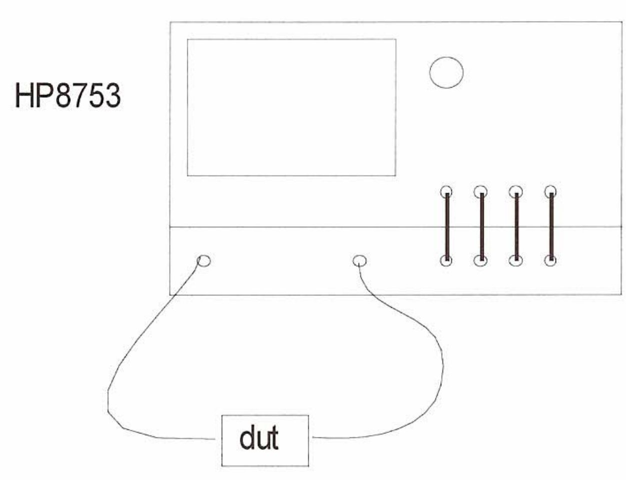
Equipment Needed:

HP8753 Network Analyzer
HP85047A test set
plotter with HP-IB input
coaxial low-pass filter, f_c = 2.2 GHz
coaxial circulator
coaxial matched loads and shorts
coaxial attenuator
coaxial connector with "50 Ω" resistor
"black boxes" with unknown networks

Procedure:

1. Setup:

Connect the device under test to the network analyzer. A one-port network may be connected to either port.



2. Calibration:

Set the frequency sweep to cover 1.5 to 5.5 GHz. Perform a full two-port calibration as described in the discussion in the Appendix. You may omit the isolation test. Measure the return loss of a matched load, and verify that the return loss is at least 20 dB over the band. Connect a 10 dB or 20 dB coaxial attenuator between the two ports and verify that $|S_{12}|$ drops by the proper amount.

3. Measure the low-pass coaxial filter:

Connect the filter between the measurement ports, measure $|S_{11}|$ and $|S_{12}|$ from 1.5 to 5.5 GHz, and plot your results. Also take a look at $|S_{21}|$ and $|S_{22}|$. Redo the $|S_{11}|$ measurement with a matched load connected to the output filter port, and compare with the first result. Be sure to use scales ranges (dB/div) to get meaningful results. Note that the HP8753 has the capability of displaying Γ, SWR, Z, and Y in various formats. Try some of these options.

4. Measure the coaxial circulator:

Using the same procedure as above, measure $|S_{21}|$, $|S_{32}|$, and $|S_{13}|$, and then the reverse paths $|S_{12}|$, $|S_{23}|$, and $|S_{31}|$, for the circulator. Use appropriate scales, and always terminate the unused of the three ports with a matched load. Check $|S_{11}|$, $|S_{22}|$, and $|S_{33}|$. Remove the matched load and re-measure $|S_{11}|$, $|S_{12}|$, and $|S_{21}|$. Use a scale of 0.5 or 1 dB per division to get accurate results for the insertion loss measurements.

5. Measure the input impedance of the "50 Ω " resistor:

Connect the coaxial connector with the 50 Ω carbon resistor to the input port, and measure the impedance from 1.5 to 5.5 GHz. Plot the result on a Smith chart format. Move your hand near the resistor and see if there is any effect.

6. Determination of "Black Box" networks:

Several "black box" microwave networks having two or three ports are available in our lab. Measure the S parameters of one of these networks at a frequency range within the range that is indicated, and try to determine the type of circuit or component that is inside the box. Is the network reciprocal? Lossless? Matched? Are any of the ports isolated? Do this for one or two boxes, as time permits.

7. Optional work:

There are lots of other possible measurements you can make, such as:

- Measure the input impedance of the filter using the Smith chart display
- Measure the attenuation vs. frequency of a piece of coaxial cable
- Measure the S-parameters of other components in the lab
- Measure the group delay of the filter

Write-up:

Return loss of matched load:

What were the best and worst return losses measured over the sweep range? List the frequencies where these occurred, and the corresponding SWRs. Complete the following table to convert between return loss, reflection coefficient magnitude, and SWR:

Return Loss	$\|\Gamma\|$	SWR
0 dB		
1 dB		
2 dB		
3 dB		
5 dB		
l0 dB		
20 dB		

Low-pass filter:

What is the measured 3 dB cutoff frequency for the filter? What is the roll-off of the attenuation of this filter in the stop-band (dB/octave)? What is the frequency range for which $|S_{12}|<20$ dB? What is the frequency range for which the input SWR is less than 2.0? Is there any difference in $|S_{11}|$ when the output is terminated with a matched load versus having port 2 connected to the network analyzer? What causes this difference?

Circulator:

Over what frequency range is the insertion loss less than 0.5 dB? Over what frequency range is the return loss greater than 20 dB? What is the minimum isolation over this latter range? What is the effect on the above quantities when the matched load is removed? Why does this happen?

"50 Ω" resistor:

The size of the short-circuit calibration "ball", or locus, gives an estimate of the uncertainty in the reflection coefficient measurement. Estimate this uncertainty for your measurements of the 50 Ω resistor. Explain why this impedance does not look like an ideal 50 Ω load.

Black boxes:

Discuss your measurements, and how you arrived at your idea of what is inside the box. Draw a circuit diagram of the network.

Optional work:

Present and discuss your results for any additional measurements you may have made. If you measured the attenuation of a coaxial cable, you may want to compare it to a calculated value, or data from the manufacturer. The Appendix of our text also has a table of data for commonly used cables.

3. The Gunn Diode

Introduction:
Here we will study the characteristics of a Gunn diode oscillator, and make power and frequency measurements. We will measure the *V-I* characteristics of the diode, and its output power using a power meter and a spectrum analyzer. We will use standard X-band waveguide components, a microwave power meter, and a microwave spectrum analyzer (for frequency and power measurement). Then we will use the Gunn diode as an RF source to study the basic operation of a microwave mixer.

The Gunn diode is a very useful source because it is simple, rugged, and compact. With a DC bias supply, the Gunn diode can generate 100 mW of power. From the DC V-I characteristics, we will see that the Gunn diode has a negative differential resistance region. The Gunn diode is described in the text on pp. 521, 609-611. It is a very common microwave source and is widely used. There is a discussion about mixers on pp. 510, 615-630 of the text. Read this material before doing the experiment so that you will understand the basic operation of a mixer.

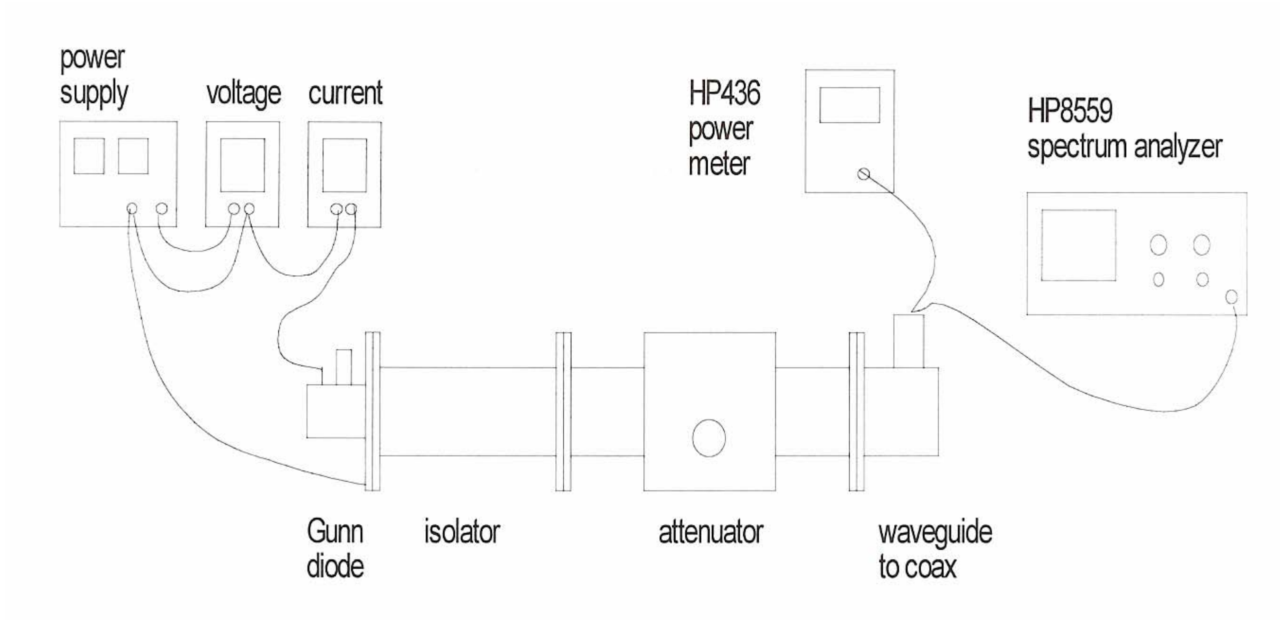
Note: Be very careful with the polarity of the bias voltage applied to the Gunn diode, as reversing the bias voltage will destroy it. Positive voltage should be connected to the pin terminal of the diode, and negative to the case.

Equipment Needed:

Gunn diode with X-band waveguide flange
waveguide isolator
variable attenuator
waveguide to coax adapter
HP436 power meter
HP8559 spectrum analyzer
DC power supply
DC voltmeter
DC ammeter
microwave mixer
1-10 MHz oscillator

Procedure:

1. Setup:
Arrange the equipment as shown below. The power supply should be set to provide a voltage limit of 8 volts, and/or a current limit of 300 mA. Be careful to use the correct polarity when connecting the power supply to the diode: positive to pin terminal, negative to case. The output of the waveguide-to-coax adapter is connected to the power meter, or spectrum analyzer, as needed.



2. Measure DC V-I characteristics:
Vary the DC voltage to the diode from 0-8 V in 0.5 V steps, and measure the diode current. Use a finer voltage step near the "knee" in the V -I curve.

3. Measure power output:
Use the HP436 power meter to measure the RF power delivered by the Gunn diode (set the attenuator to zero), versus voltage, over its operating range. At a relatively strong operating point, check the calibration of the waveguide attenuator using the power meter, over the range of 0 to 20 dB.

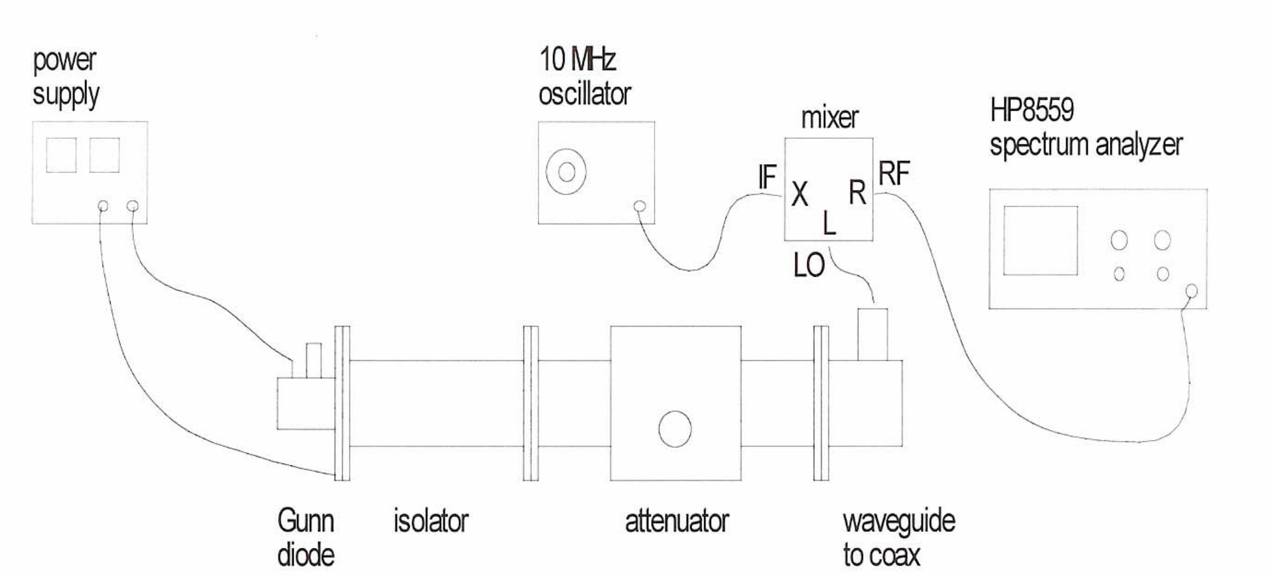
4. Using the spectrum analyzer:
A spectrum analyzer is a sensitive receiver that rapidly tunes its RF operating frequency over a relatively narrow bandwidth (SPAN) to give a display of power vs. frequency. Connect the spectrum analyzer to the waveguide to coax adapter, in place of the power meter. Set the *center frequency* of the spectrum analyzer to 9.5 GHz, and the *frequency span* to about 100 MHz/div. If necessary, adjust the *resolution BW* for a clean, stable display. Measure the power level and frequency versus bias voltage over the operating range of the diode.

5. Tuning the diode:
The small tuning screw on the flange of the Gunn diode can be used to adjust the resonant frequency of the Gunn diode, from about 9 to 10 GHz. For several positions of this screw, adjust the bias voltage, power, and operating frequency, f. (Use care when tuning the diode.) For each case, use the spectrum analyzer to check for a second harmonic at $2f$, and record this power level. Also, check the frequency range near f and $2f$ for other spurious signals. The spectrum analyzer may show spurious signals from its local oscillator; check for this by using the *signal identifier* button.

6. Basic mixer operation:
We will study mixers in more detail later in class, but for now all we need to know is that a mixer forms the sum and difference frequencies of two sinusoidal input signals. Thus, a mixer can be used

for the operations of modulation and demodulation, or frequency upconversion and down-conversion.

In the setup below, the local oscillator (LO) input is supplied by the Gunn diode (operating at about f_{LO} = 10 GHz, with a power level between -5 dBm and 10 dBm). The modulating signal, applied at the X input of the mixer) is supplied by an oscillator operating at about f_{IF} = 10 MHz. The RF output of the mixer will consist of the local oscillator signal and two sidebands at the frequencies $f_{LO} \pm f_{IF}$. This is called a double sideband modulated signal.



Connect the equipment as shown above, but first set the Gunn diode output power between -5 dBm and 10 dBm, using the spectrum analyzer to measure the output power. (The Gunn diode may have to be tuned to a new frequency to obtain enough power.) Then connect the waveguide-to-coax adapter to the mixer, and view the output of the mixer on the spectrum analyzer. Adjust the IF oscillator power level as high as possible, keeping only two sidebands visible. Note the effect of a change in IF frequency. Set the IF oscillator to square wave output and observe the spectrum.

7. Temperature stability (optional):
Set the operating point of the Gunn diode for a strong signal, and monitor the signal with the spectrum analyzer set to a small frequency scan, such as 500 kHz/div. Now heat the diode by holding a soldering iron or heat gun near (but not touching!) the Gunn diode, and observe the shift in frequency.

Write-up:
V-I characteristics: Plot the measured V -I curve. Mark the region of the graph where the diode generates RF output power.

Power output:
Plot the output power measured with the HP436, versus bias voltage. On this same graph, plot the power output as measured with the spectrum analyzer. Use a dBm scale. Explain why there is a difference between these two measurements.

Attenuator calibration:
Plot the measured attenuation of the attenuator versus the actual attenuator setting on a dB - dB scale.

Frequency measurement:
Plot the frequency of the diode output signal versus bias voltage.

Frequency tuning:
Plot the frequency and power level of the diode output versus screw position (using the number of half-turns, for example). Also plot the power level of the second harmonic on this same graph.

Mixer operation:
Discuss the operation of the mixer, and the observed mixer output spectrums. Explain the spectrum that results from square wave modulation.

Temperature stability (optional):
Discuss the results of this test, and suggest a way to avoid such frequency drift versus temperature.

4. Impedance Matching and Tuning

Introduction:

In this experiment we will study two types of matching or tuning techniques: the stub tuner and the quarter-wave transformer. We will first use the network analyzer and a stub tuner to tune a mismatched load at a single frequency, and then over a broad frequency range. Next we will design and fabricate a quarter-wave transformer to match a 500 line to a 250 load, and test this circuit. You should complete Experiment #2, on the Network Analyzer, before doing this experiment.

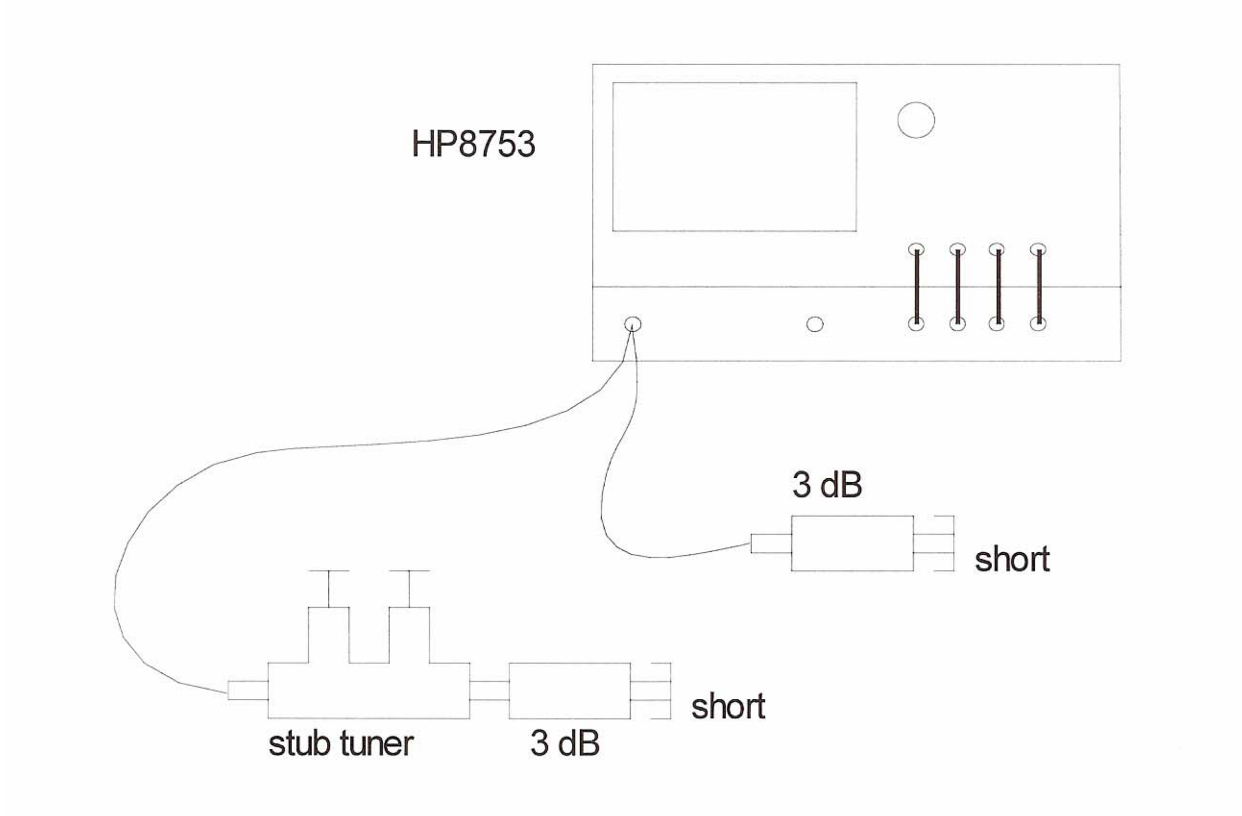
Equipment Needed:

HP8753 Vector Network Analyzer
HP85047A 6 GHz S-parameter test set
plotter with HP-IB input
3 dB coaxial attenuator
coaxial short
microstrip substrate with SMA connector
25 Ω chip resistor (or two 50 Ω resistors)

Procedure:

1. Setup:

Arrange the equipment as shown below. Set the sweep oscillator to sweep from 2-4 GHz, and calibrate the HP8753 Network Analyzer. Since we will only be making reflection measurements in this experiment, it is only necessary to do a one-port calibration. Store the Cal Set in memory.

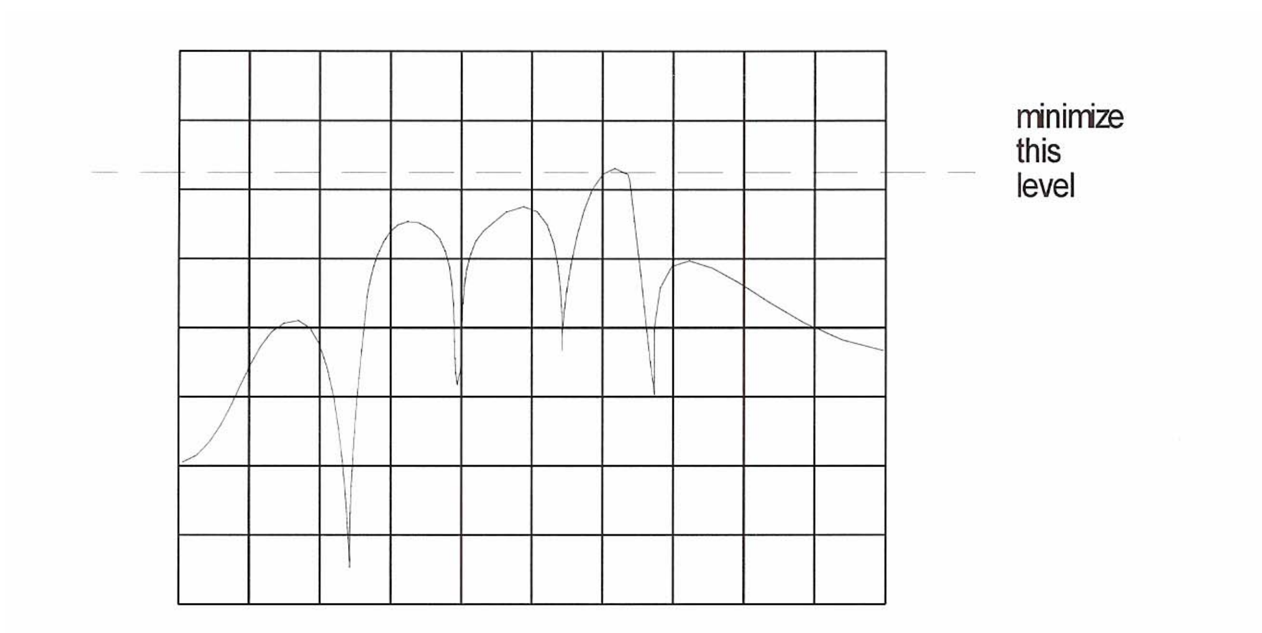


2. Single frequency tuning:

Our mismatched load will consist of a 3 dB coaxial attenuator backed with a short circuit. Connect this load to the analyzer (without the stub tuner), and measure the return loss. Now insert the stub tuner, as shown above, and tune for the best possible return loss at 3 GHz. Record the response, and measure the positions of the stubs (and the stub separation). Repeat this tuning procedure at 2.5 GHz and at 3.5 GHz. It will be helpful to learn how to use the frequency markers on the network analyzer for this work.

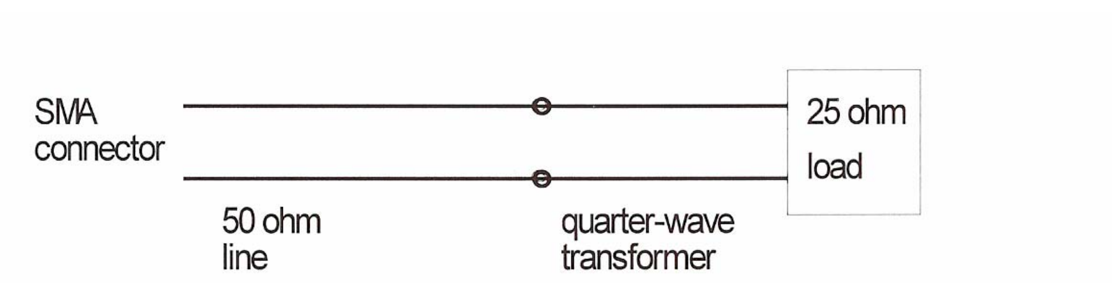
3. Broadband tuning:

Reduce the sweep range to 3-4 GHz, and calibrate again, and store the calibration. Measure and record the return loss of the mismatched load. Now insert the stub tuner, and adjust to achieve the lowest possible maximum return loss over the frequency band. Record this result. Repeat for a sweep range of 2-4 GHz. You don't need to calibrate again, since you should be able to recall the previously saved Cal Set for the 2-4 GHz range.



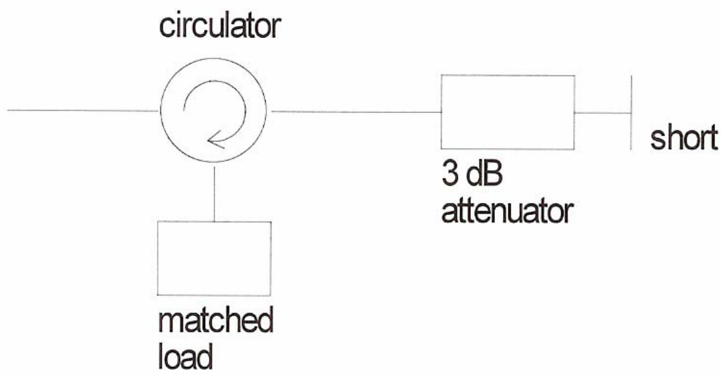
4. Quarter-wave matching transformer:

Design a quarter-wave matching transformer to match a 25 Ω load to a 50 Ω microstrip line at 3 GHz. Using the thickness and permittivity for the substrate (obtain from Teaching Assistant), calculate the necessary dimensions for a microstrip implementation of the circuit shown below:



Fabricate the circuit using copper tape and an Xacto knife. This is not a very accurate process, but if you are careful, and as precise as possible, reasonably good results can be obtained. Measure the return loss of your circuit from 2-4 GHz.

5. Optional work:
a) Use a circulator as shown below to "match" the load over a frequency range of 2-4 GHz. Measure the return loss.



b) Use the Fourier Transform menu and look at the time domain reflection response of the quarter-wave transformer. Try to identify the discontinuities and their locations. Repeat with the stub tuner.

Write-up:
Single-frequency tuning:
Calculate the return loss of the 3 dB attenuator and short circuit combination. Does this mismatch vary with frequency? Compare with your measured result. Tabulate the return losses which were achieved for the single-frequency tuning step. What additional information do you need to be able to calculate the tuning stub lengths for matching at a given frequency?

Broadband tuning:
List the worst return losses obtained for single-frequency tuning, the 3-4 GHz tuning, and the 2-4 GHz tuning. Discuss the implications of this trend.

Quarter-wave transformer:
Calculate the return loss of the quarter-wave transformer and 25 Ω load from 2-4 GHz, and plot. Compare with your measured results, and discuss the differences. How could your matching circuit be improved?

Optional work:
Using your measured load impedance, distance between stubs, stub lengths, and distance between the first stub and load, calculate the input impedance seen by the network analyzer. Compare with the measured return loss. For the circulator matching network, compare the worst return loss with the corresponding return loss from the broadband tuning step. Which is better? Discuss the advantages and disadvantages of the circulator tuning technique.

5. Cavity Resonators

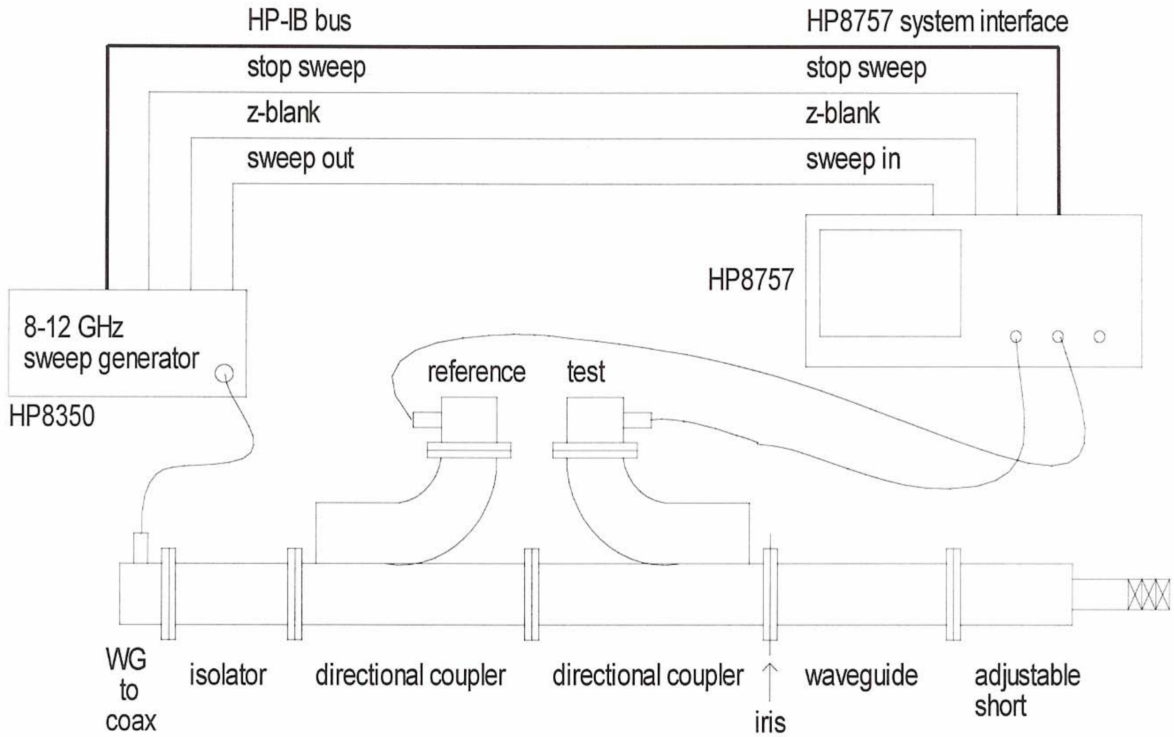
Introduction:
Here we will construct a cavity resonator in waveguide and study its characteristics using the network analyzer and a frequency counter. Resonant circuits can be made with discrete elements (inductors and capacitors), or from distributed elements (transmission lines and cavities). The Q of a resonator depends on loss; since waveguide has very low loss, a resonator made from waveguide can have a very high Q.

Equipment Needed:

HP8350 X-band sweep generator
HP8757 Scalar Network Analyzer
two waveguide directional couplers
short section of waveguide
waveguide iris plate
waveguide adjustable short
blank flange
waveguide isolator
three waveguide-to-coax adapters
slide-screw tuner

Procedure:
1. Setup:
Arrange the equipment as shown below. Set the sweep range from 8-12 GHz. The scalar network analyzer is similar in function to the vector network analyzer, but only measures magnitudes of reflected and transmitted power, versus frequency. Instructions on the operation and calibration of the HP8757 scalar analyzer are outlined in the Appendix. For further details, consult the HP8757 operator's manual. To calibrate the analyzer at the plane of the iris, follow the procedure dictated by the Cal menus, and use a shorting plate and the open waveguide for the short and open, respectively. Like the calibration of the vector network analyzer, calibration of the scalar analyzer must be done for each frequency range. It is faster to store the "short" response in Memory and normalize the display by using *Display-Mem*.

The interconnection of cables between the sweep generator and the scalar network analyzer allows the display to sweep at the same rate as the sweep generator, and for frequency markers to be used on the display.



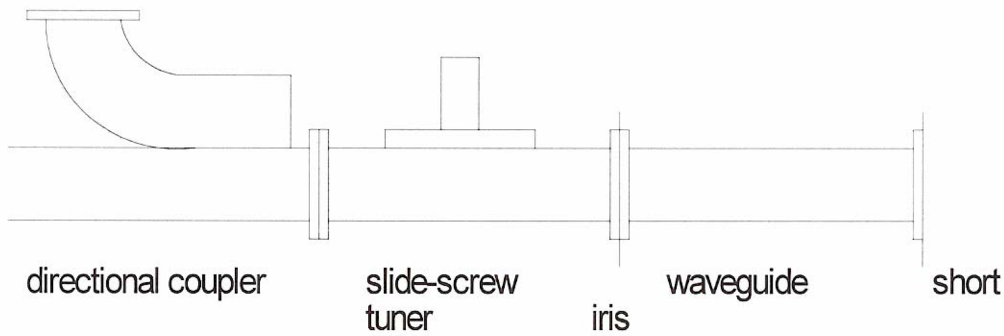
2. Measure resonant frequencies:
Build the resonant cavity shown above with the iris plate, the short length of waveguide, and a blank flange in place of the adjustable short. Use the frequency markers to accurately measure the resonant frequency of each resonance between 8 and 12 GHz. Define a resonance as any dip in the response with a return loss greater than 10 dB. Measure the physical length of the cavity.

3. Measure Q:
For each of the above resonances, use the frequency markers to measure Δf between the half-power points (return loss = 3 dB). on the response. Use a reduced sweep range for accuracy in this measurement. From this data the loaded Q of the resonator can be determined from $Q_L = f_0/\Delta f$.

To see the effect of an increase in loss, place a small piece of absorber material inside the cavity, near the shorting plate end, and re-measure the Q of a few of the resonances. Remove the absorber when finished.

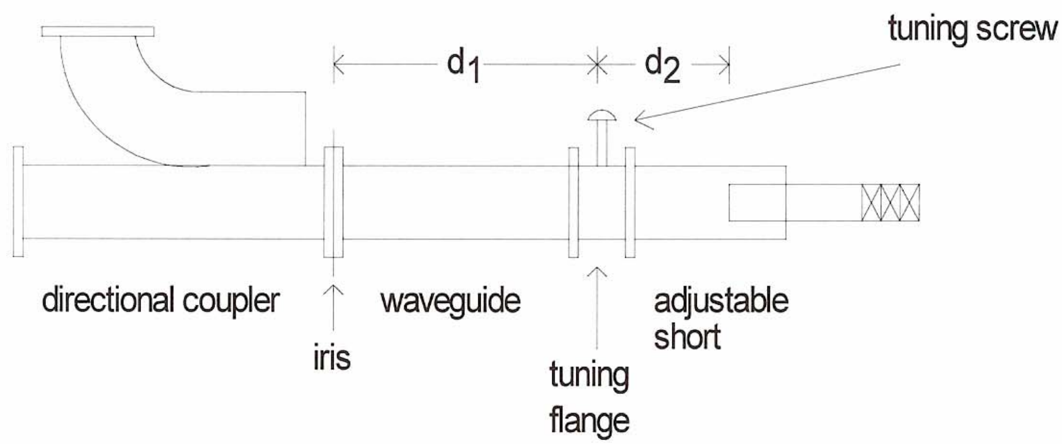
4. Tuning the cavity:
Replace the blank flange with the adjustable short. Initially, adjust the short to obtain a strong resonance at 10 GHz with the adjustable short near the middle of its mechanical range. Now adjust the short to tune the resonance from 9.5 to 10.5 GHz, in 100 MHz steps. Record the resonant frequency versus short position as given by the micrometer reading.

5. Match the cavity:
Replace the adjustable short with the blank flange, and insert a slide-screw tuner ahead of the iris plate, as shown below. Retract the tuning screw, and pick a resonance near 10 GHz. Record the return loss. Now use the tuner to maximize the return loss at the resonant frequency. Note the new return loss, and any change in resonant frequency or Q.

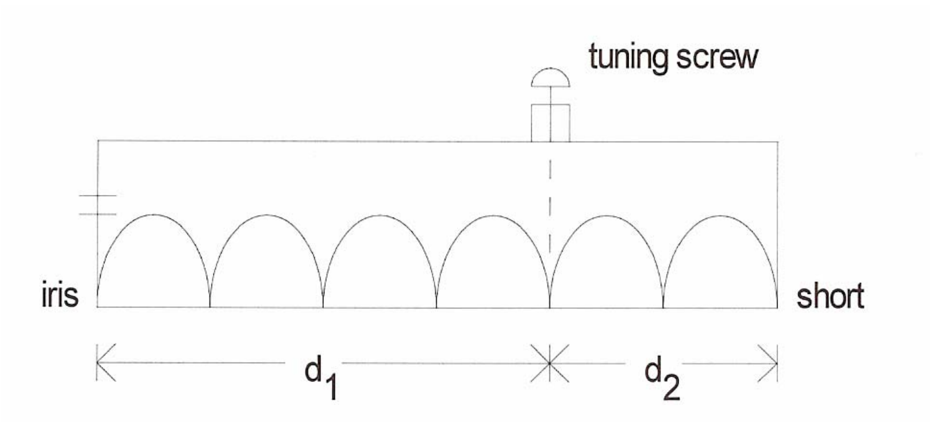


6. Optional:

Place the thick flange with a tuning screw between the waveguide and the adjustable short, as shown below.



Measure the distance between the iris and the tuning screw, d_1. Choose a frequency so that $d_1 = n\lambda_g/2$, where n is an integer and λ_g is the guide wavelength. Now set the movable short so that $d_2 = m\lambda_g/2$, where m is a different integer. The total cavity length is now $d = d_1 + d_2 = (m + n)\lambda_g/2$, and a tangential component of the electric field should exist at the tuning screw location, as shown below for $n = 4$ and $m = 2$:



Measure the resonant frequency versus depth of the tuning screw. Next, devise a similar procedure to place an H-field null at the tuning screw location. An H-field null corresponds to an E- field maximum at the tuning screw location. Measure the resonant frequency versus tuning screw depth for this case.

Write-up:

Setup:

Give a qualitative explanation of what goes on in this experiment. Explain why you see more than one resonance, and explain the function of the iris.

Resonant frequencies:

Using the length of the cavity, calculate the resonant frequencies and compare with the measured values. Identify the modes according to the TE_{10n} notation. Discuss reasons for differences between measured and calculated results.

Q:

Tabulate the measured *Q* and measured resonant frequency for each of the resonant modes. Is there a trend which is evident from the data? For one or two cases, calculate the unloaded *Q* of the cavity, and compare with the measured loaded *Q*. Are the results reasonable? Discuss the effect of placing absorber in the cavity.

Tuning the cavity:

Plot the measured resonant frequency versus short position. Can you predict this variation theoretically?

Matching the cavity:

Discuss the change in resonant frequency, loaded *Q*, and return loss when the cavity is matched with the slide screw tuner.

Optional work:

Plot the resonant frequency versus tuning screw depth for the two cases of an E-field and an H-field null at the tuning screw position. Which case gives a greater tuning range? Why?

6. Directional Couplers

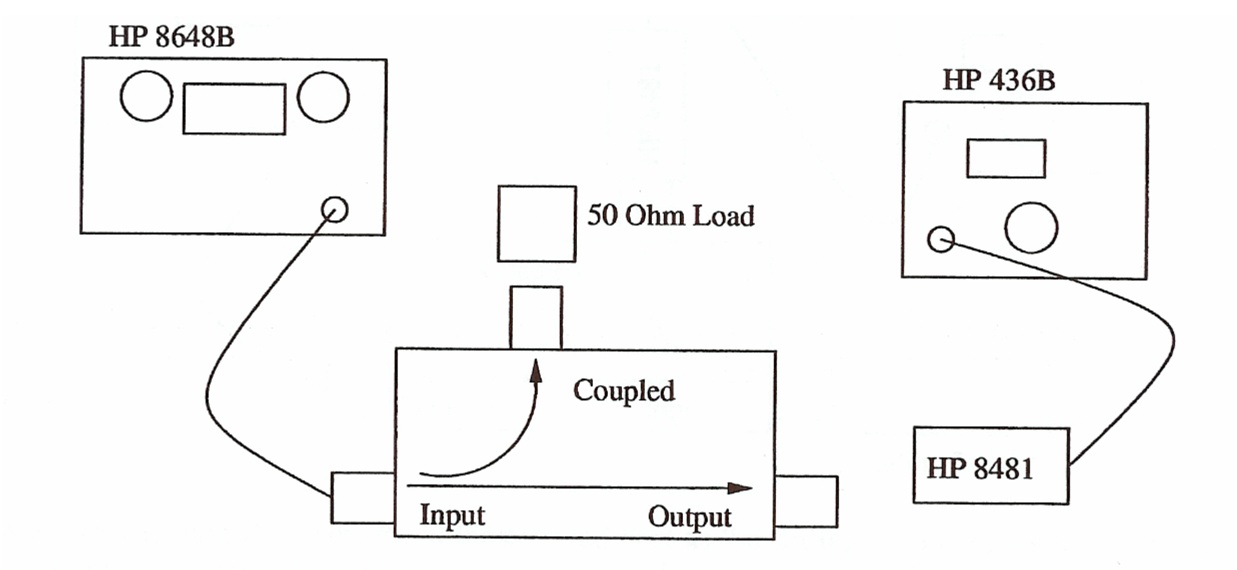
Introduction:
In this experiment we will characterize a coaxial (stripline) directional coupler in terms of its insertion loss, coupling, and directivity. Along with the return loss, these quantities constitute all the non-zero elements of the S-matrix of the coupler. We will also learn some special measurement techniques for measuring the low-level signals associated with coupler directivity. The directivity of a directional coupler is very important in many applications (such as reflection measurements), and is difficult to measure directly because it involves a very low level signal.

Equipment Needed:

HP8648B Synthesized Signal Generator
HP436B power meter with 8481 and 8484 sensors
Coaxial 10 dB directional coupler
Coaxial matched load
Coaxial sliding matched load
Coaxial double stub tuner
HP 8753C Network Analyzer

Procedure:

1. Setup:
Arrange the equipment as shown below, with the coupler in the forward direction. Set the source to a CW frequency between 2.5 and 3.0 GHz, and a power level of +13 dBm.



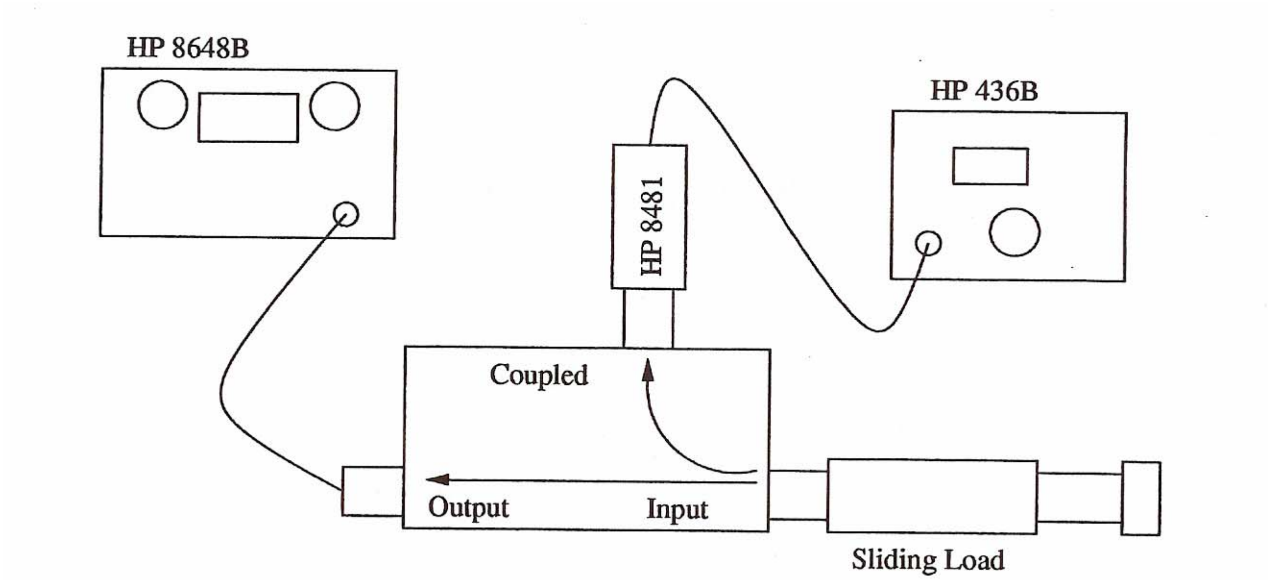
2. Measure insertion loss:
Remove the directional coupler and measure the incident power, P_i, at the end of the input cable. Reinstall the coupler and place a coaxial matched load on the coupled port. Measure the through power, P_t. The insertion loss of the coupler can be determined as,

$$L = \frac{P_t}{P_i} \qquad (L < 1)$$

3. Measure coupling:
Place the matched load at the through port, and measure the power at the coupled port, P_c. The coupling factor can be determined as,

$$C = \frac{P_i}{P_c} \qquad (C > 1)$$

4. Measure directivity (method #1):
Re-arrange the equipment with the coupler in the reverse direction, as shown below. Don't change the frequency or power settings on the generator, as you will need the previously measured values of incident power, coupled power, and through power.



Measure the output power, P_o, at the coupled port as the sliding load is moved. Record the minimum and maximum values of the output power.

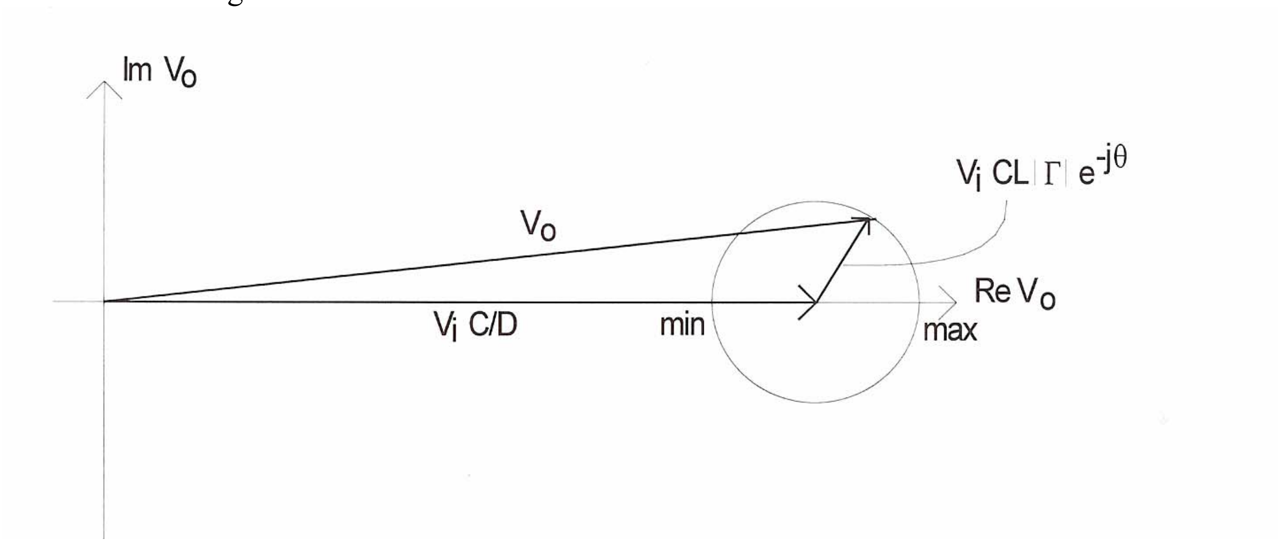
Part of the difficulty in measuring directivity is that even a small reflection from the through port will overshadow the small directivity signal. In the above setup the reflection, Γ, from the small mismatch of the sliding load is added to the directivity signal at the output of the coupled port. The phase of the reflection from the load can be changed by sliding the load, and made to add in phase or out of phase with the directivity contribution. The voltage at the output port is thus given by,

$$V_o = V_i \left[\frac{C}{D} + C|\Gamma| L e^{-j\theta} \right],$$

where

D is the coupler directivity ($D > 1$)
C is the coupling factor ($C > 1$)
Γ is the (unknown) reflection coefficient of the sliding load ($|\Gamma| < 1$)
L is the through loss of the coupler ($L < 1$)
θ is the electrical path length through the sliding load

As the sliding load is moved, θ changes, so the resultant phasor output voltage, V_o, traces a circle, as indicated in the figure below:



The maximum output power is then,

$$P_{\max} = \left[\frac{C}{D} + C|\Gamma|L\right]^2 P_i .$$

And the minimum output power is,

$$P_{\min} = \left[\frac{C}{D} - C|\Gamma|L\right]^2 P_i .$$

If we define the following quantities,

$$M = \frac{P_c}{P_{\max}} = \frac{C^2 P_i}{P_{\max}} = \left(\frac{D}{1+|\Gamma|LD}\right)^2 ,$$

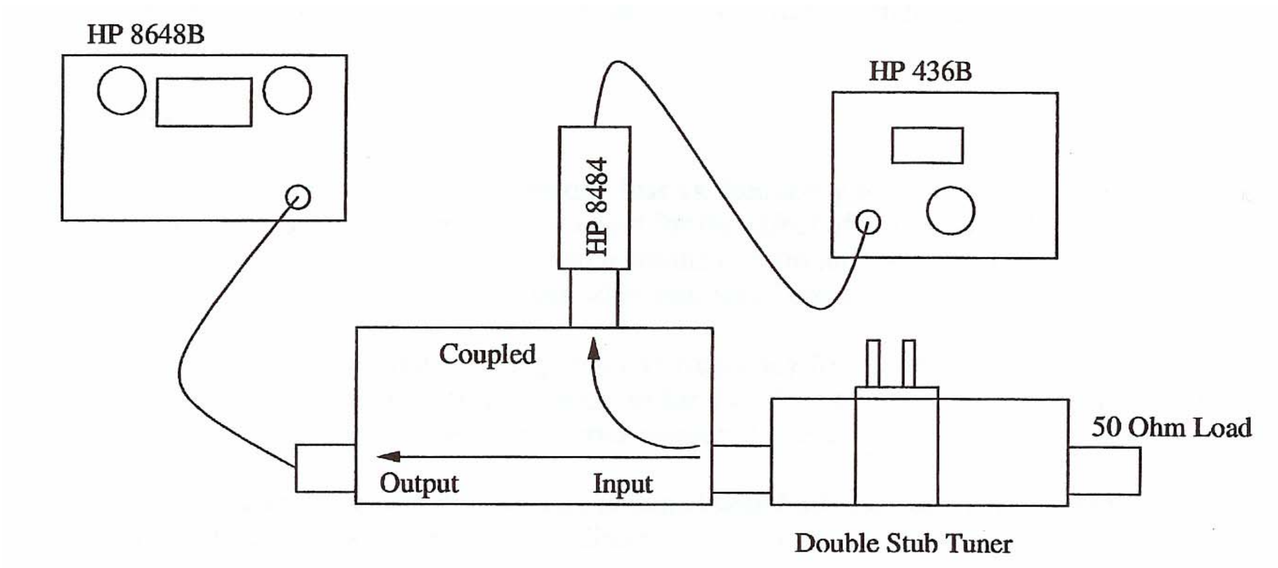
$$m = \frac{P_{\max}}{P_{\min}} = \left(\frac{1+|\Gamma|LD}{1-|\Gamma|LD}\right)^2 ,$$

then the directivity can be determined as

$$D = M\left(\frac{2m}{1+m}\right).$$

This method requires that |Γ <1/*D*.

5. Measure directivity (method #2):
In the previous method the residual reflection from the load was accounted for by using a sliding load. In this method, the reflection from the load is adjusted to cancel the directivity signal. A separate measurement of this reflection then gives the directivity. Arrange the equipment as shown below.



When replacing the HP8481 sensor with the HP 8484 sensor, be sure to turn off the AC power to the power meter. When you connect the sensor for calibration, insert the 30 dB attenuator and adjust the level for -30 dBm.

As before, the output voltage at the coupled port is given by,

$$V_o = V_i\left[\frac{C}{D} + C|\Gamma|Le^{-j\theta}\right].$$

Now tune the double stub tuner to null the output power at the coupled port (this will require only a small reflection). Then $V_o = 0$, so the directivity is given by,

$$D = \frac{1}{L|\Gamma|}.$$

We have already measured *L* and *C*; use the Network Analyzer to measure |Γ|. Repeat the above measurements at two other frequencies.

6. Stripline coupler design:
Use calipers to measure the width, length, and separation of the striplines in the opened coupler. Also measure the distance between the two ground planes. Determine the even and odd mode characteristic impedances (see text), and then the coupling factor:

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}.$$

Also determine the center frequency of the coupler, assuming a line length of $\lambda/4$. After calculating C, obtain the actual value from the Teaching Assistant.

Write-up:
Insertion loss:
Plot the measured insertion loss versus frequency, for the frequencies which were measured. Use a signal flow graph to account for the effect of a mismatched load on the insertion loss measurement, and apply your results to estimate the error in your measured insertion loss due to this effect. Discuss other sources of error.

Coupling:
Plot the measured coupling factor versus frequency, for the frequencies which were measured. Use a signal flow graph to account for the effect of mismatched coupled and through ports, and estimate the error in your measured coupling due to these effects.

Directivity:
Plot the measured directivity obtained with both measurement methods versus frequency. Discuss possible reasons for discrepancies, and the relative advantages and disadvantages of each method.

Stripline design:
Compare your calculated values with the actual values. Discuss the reasons for any discrepancies. Calculate the impedance of the stripline.

III. Appendices

Appendix 1: List of Major Equipment in the Microwave Instructional Lab.

Signal Generators:	
HP 8350B sweeper main-frame	3
HP 83540A RF plug-in 2 - 8.4 GHz	1
HP 83592B RF plug-in 0.1 - 20 GHz	1
HP 83545A RF plug-in 8 - 12.4 GHz	2
HP 8648C 3.2-GHz synthesized sweeper	2
Network Analyzers:	
HP 8753C Vector Network Analyzer	3
HP 8753B Vector Network Analyzer	1
HP 8510C Vector Network Analyzer	1
HP 8514A S- parameter test set	3
HP 8756A Scalar Network Analyzer	1
HP 8757C Scalar Network Analyzer	1
Wiltron 560 Scalar Network Analyzer	1
Frequency Counters:	
HP 5350 Frequency Counter	2
HP 5351B Frequency Counter	1
HP 5342A Frequency Counter	1
Power Meters and Sensors:	
HP 436A power meter	5
HP 8481A power sensor -30 to 20 dBm	7
HP 8481D power sensor -70 to -20 dBm	3
SWR Meters:	
HP 415E SWR meter	6
Noise Measurement:	
HP 8970S noise figure test set	1
HP 3048 phase noise test set	1
Power supplies:	
HP E3610A power supply	2
HP E 3611A power supply	2
Lambda LL901 power supply	2
Multimeters:	
Fluke 8840A	3
Keithley 177	1