

# ELEC 453/6391 Microwave Experiments

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## **Background**

During 1997-2002 I created the following six experiments for the course Microwave Engineering ELEC 453/6391 at Concordia University.

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# Contents

<b>1</b>	<b>Impedance Measurements Using a TEM Slotted Line</b>	<b>1</b>
1.1	Equipment . . . . .	1
1.2	Setup . . . . .	1
1.2.1	SWR Meter . . . . .	1
1.3	Measurement of Standing Waves . . . . .	2
1.4	Impedance Measurement . . . . .	3
1.4.1	Variable Length Stub . . . . .	3
1.4.2	Transmission Line and Load . . . . .	3
1.5	Questions . . . . .	3
<b>2</b>	<b>Impedance Measurements Using a Slotted Waveguide</b>	<b>7</b>
2.1	Equipment . . . . .	7
2.2	Introduction . . . . .	8
2.3	Setup . . . . .	8
2.4	Measurement of Standing Waves . . . . .	9
2.5	Impedance Measurement . . . . .	9
2.5.1	Open Ended Waveguide . . . . .	10
2.5.2	Irises . . . . .	10
2.6	Questions . . . . .	10
2.7	Iris Formulas . . . . .	11
<b>3</b>	<b>Diodes: Gunn, Varactor, and PIN</b>	<b>14</b>
3.1	Equipment . . . . .	14
3.2	Introduction . . . . .	15
3.3	Bias Voltages . . . . .	15
3.4	Power Meters . . . . .	16
3.5	Spectrum Analyzer . . . . .	17
3.5.1	Hardcopy of Spectrum . . . . .	17
3.6	FM setup . . . . .	17
3.7	AM setup . . . . .	18

3.8	Questions . . . . .	19
<b>4</b>	<b>Doppler Radar and Friis Transmission</b>	<b>22</b>
4.1	Doppler Radar . . . . .	22
4.1.1	Equipment . . . . .	22
4.1.2	Introduction . . . . .	22
4.1.3	Setup . . . . .	23
4.1.4	Storage Scope . . . . .	24
4.1.5	Questions . . . . .	24
4.2	Friis Transmission . . . . .	25
4.2.1	Equipment . . . . .	25
4.2.2	Introduction . . . . .	25
4.2.3	Setup . . . . .	26
4.2.4	Questions . . . . .	27
<b>5</b>	<b>Network Analyzer I</b>	<b>29</b>
5.1	Equipment . . . . .	29
5.2	Introduction . . . . .	29
5.3	Microstrip Line . . . . .	30
5.4	Stub Matcher . . . . .	30
5.5	Network Analyzer . . . . .	31
5.6	Impedance Measurement . . . . .	32
5.7	Simulation . . . . .	32
5.8	Questions . . . . .	33
<b>6</b>	<b>Vector Network Analyzer II</b>	<b>36</b>
6.1	Equipment . . . . .	36
6.1.1	X Band Reflectometer . . . . .	36
6.1.2	Network Analyzer, Bench #2 for 5.9-12.4 GHz . . . . .	36
6.1.3	Network Analyzer, Bench #1 for 2.0-8.2 GHz . . . . .	37
6.2	Introduction . . . . .	37
6.3	X Band Reflectometer . . . . .	38
6.3.1	Measuring $\Gamma$ . . . . .	38
6.4	Network Analyzer, 5.9-12.4 GHz . . . . .	39
6.4.1	Irises A, B, C, D . . . . .	39
6.4.2	Slide Screw Tuner . . . . .	39
6.4.3	Waveguide Cutoff . . . . .	39
6.5	Network Analyzer, 2-8 GHz . . . . .	39
6.5.1	27 $\Omega$ Resistor . . . . .	40
6.5.2	Microstrip Line I . . . . .	40

6.5.3	Microstrip Line II . . . . .	40
6.5.4	Quadrature Hybrid . . . . .	40
6.6	Questions . . . . .	40
<b>A</b>	<b>GPIB Instrument Control</b>	<b>43</b>

# Lab #1 Impedance Measurements Using a TEM Slotted Line

## 1.1 Equipment

- Microwave 2 GHz oscillator, e.g. HP8672A, HP8690B, or Wavetek 2002A
- 1 kHz audio oscillator
- HP 805A TEM slotted line (0.5-4 GHz) and 1N23 crystal detector
- HP 415 SWR meter, oscilloscope, two BNC cables, BNC tee
- Loads: short circuit load, matched load, VSWR 2:1 load
- GR 874D20 20 cm variable length stub, GR-N adapter, N type tee, 50 $\Omega$  load, male-male N adapter
- Approx 50 cm length of RG214U coax cable, N female tee, two N 50 $\Omega$  loads.

## 1.2 Setup

Connect the oscillator to the slotted line, using coax and N connectors. At the other end of the slotted line, terminate it with the matched load (labelled as 1:1; it's 50 $\Omega$ ). Connect the crystal detector output to the SWR meter and scope. Set the oscillator to 2.0 GHz. We need AM, so set the modulation for a 1 kHz square wave.

### 1.2.1 SWR Meter

The probe in the slotted line picks up the E field and feeds the signal to a crystal detector.

An RF voltage  $v(t) = A \cos \omega t$  incident on a crystal detector will cause a diode current  $i_D \propto A^2$ . If this is connected to a detection circuit, the voltage would be  $v_D \propto A^2$ . Hence, the square root of the detector voltage is proportional to the RF amplitude, i.e.  $\sqrt{v_D} \propto A$ .<sup>1</sup> In other words, a 2X increase in the RF voltage leads to a 4X increase in the RF power and a 4X increase in  $v_D$ .

The HP415 SWR meter is calibrated to work with a square law detector. It's essentially an audio amplifier with a bandpass filter at 1 kHz. To use the SWR meter, connect it to the probe, and set it to "high impedance" crystal. Adjust the penetration depth of the probe to about halfway in. The probe/crystal assembly has a matching network that needs to be tuned. Rotate the black knob on the probe carriage for maximum output. Adjust the audio oscillator frequency to obtain maximum output; it must match the passband of the HP 415.

To measure SWR, the procedure is as follows. Set the EXPAND switch to NORM. Slide the probe to  $V_{max}$  and adjust the SWR meter gain so that it reads SWR=1.0, on the 1.0 to 4 scale. Then slide the probe to  $V_{min}$  and read the SWR directly from the scale. If the meter drops below 3.2, then rotate the RANGE-DB switch clockwise and read on the 3.2-10 scale. The pattern continues for higher SWR readings.

It is interesting to note that the HP805 slotted line can be used over 0.5-4.0 GHz. This limit is determined by the probe matching network. Also, the HP415 SWR meter has a very narrow bandwidth, centered about 1 kHz. This greatly reduces noise problems in measuring small voltages. You will find it is much better than the scope for taking voltage readings.

### 1.3 Measurement of Standing Waves

On the scope, you should see the detector output; it has a d.c. component, which is proportional to the RF carrier power. Superimposed, you should see the 1 kHz signal. It is most convenient to directly read the SWR on the HP415.

Note that you should keep the crystal voltage down to 100 mV or less. Use the 30 dB range or lower, on the HP415. If the signal is too strong, the crystal will no longer obey a square law characteristic, and the SWR readings will be inaccurate.

Now replace the  $50\Omega$  load with the short circuit. Slide the probe carriage back and forth, observing the high SWR on the scope. Record the locations

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<sup>1</sup>Pozar, Sec. 10.2

of two or three null positions. Since the nulls are  $\lambda/2$  apart, deduce the wavelength.  $\lambda(cm) = 30/f(GHz)$

Get the standard 2:1 SWR load, or use two  $50\Omega$  loads with a tee. Measure the SWR. If the result is not good, reduce the RF signal level and try again.

#### 1.4 Impedance Measurement

We will use the Smith chart to find the impedance of the load. This involves 3 steps: (1) Record the null positions with a short circuit load. (2) Now replace the short with the unknown impedance and measure the SWR. Draw the corresponding constant SWR circle. (3) (a) If the unknown's minima are shifted towards the load by X wavelengths, relative to the short circuit nulls, then on the chart, move X wavelengths towards the generator, measured from  $Z=0+j0$  (b) if the unknown's minima are shifted towards the generator by X wavelengths, relative to the short circuit nulls, then on the chart, move X wavelengths towards the load, measured from  $Z=0+j0$ .

See Pozar Example 2.4, you can solve it by using the above method.

##### 1.4.1 Variable Length Stub

Connect the stub to a GR-N adapter and to the side arm of an N type tee. Connect one end of the tee to a  $50\Omega$  load and the other end of the tee to a male-male N adapter and slotted line. Record the SWR, and two or three voltage minima positions. Repeat this for at least **ten** stub lengths, every  $1cm$ . Use a Smith chart to plot  $Z(\ell)$ .

##### 1.4.2 Transmission Line and Load

Measure the impedance of the RG214U coax, 50 cm long, terminated by a female N adapter with a pair of  $50\Omega$  loads. At low frequencies, it is equivalent to a  $25\Omega$  load. Take **ten** readings over the frequency range 2.0-2.2 GHz. Be careful to retune the probe matching network, each time you change the frequency. Use a Smith chart to plot  $Z(f)$ .

#### 1.5 Questions

Your group is required to write up and submit answers to these questions. Hand in the work at class time. It will be marked like homework.

1. When the generator is set to 2 GHz, what is the measured wavelength and frequency?



2. For the 50 cm RG214U coax, show that the electrical length is  $\ell/\lambda = 2.50f$  where  $f$  is in GHz.
3. Calculate the upper frequency limit for RG214U coax, whereby the  $TE_{11}$  mode is suppressed. Use Appendix J to get  $b$ . Since  $Z_0 = 50\Omega$ , you can use the formula  $Z_0 = (\eta/2\pi) \ln(b/a)$  to get  $a$ . Then from Pozar Example 3.3,  $f = v/(\pi[a + b])$ .
4. For the stub +  $50\Omega$  load, use a Smith chart for plotting the locus of the theoretical reflection coefficient

$$\Gamma(\ell) = \frac{j \cot \beta \ell}{2 - j \cot \beta \ell}$$

where  $\ell =$  stub length. On the same chart, plot your measured values of  $\Gamma$ . Explain any differences between theory and experiment. Give a table of measured SWR's and minima shifts  $\Delta$ .

5. For the 50cm coax line with  $25\Omega$  load, use a Smith chart for plotting the locus of the theoretical reflection coefficient

$$\Gamma(f) = -0.33 e^{-j4\pi \ell f/v}.$$

Since the cable is polyethylene, the velocity factor of the cable is  $v/c = 1/\sqrt{2.25} = 0.667$ . Also plot the measured values of  $\Gamma$ . Give a table of measured SWR's and minima shifts  $\Delta$ .

6. Suppose you made a 1 cm error in measuring a null position. How much of an error would there be in the phase of the reflection coefficient?

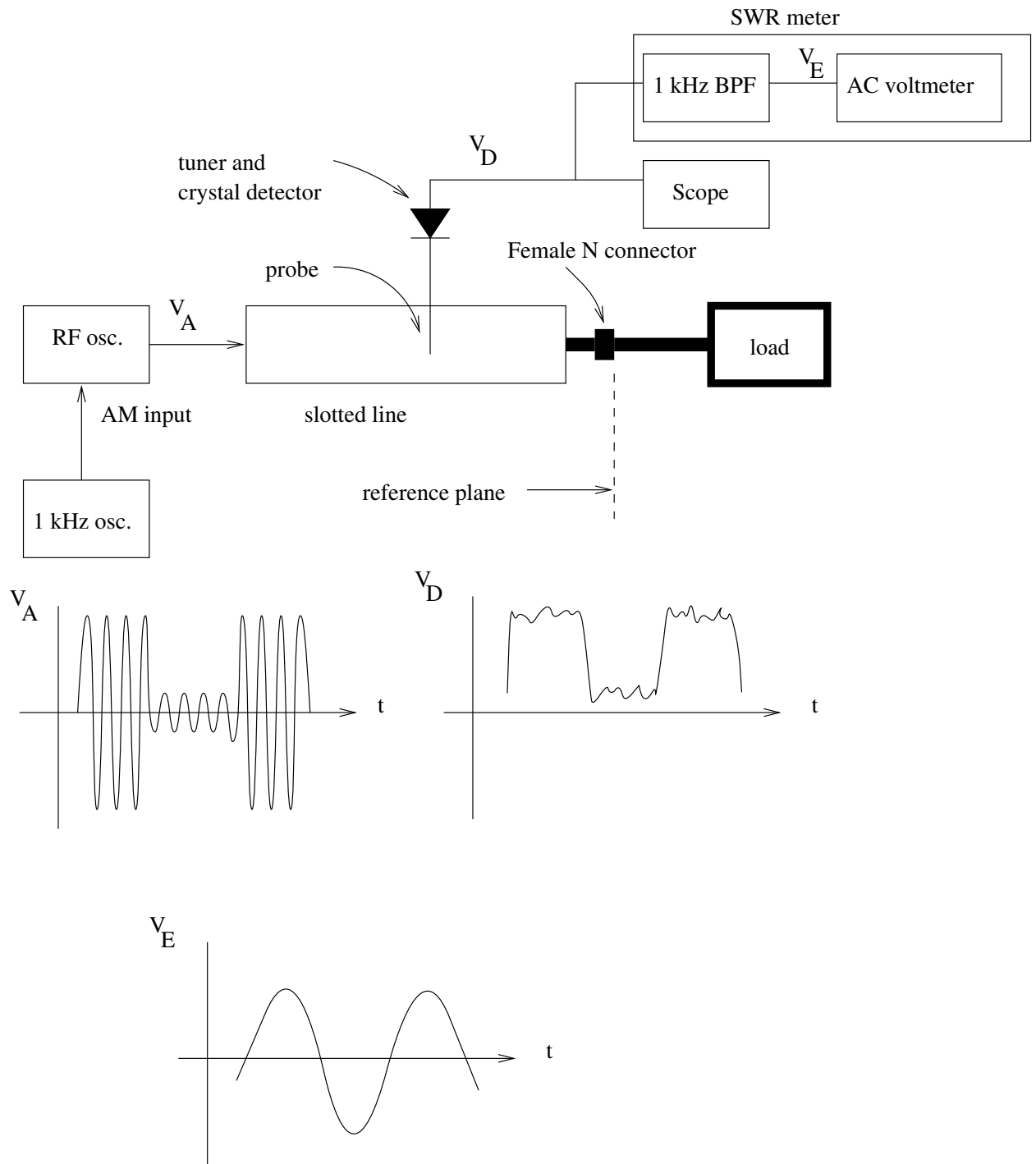


Figure 1.1: Block diagram of setup, and voltage waveforms.

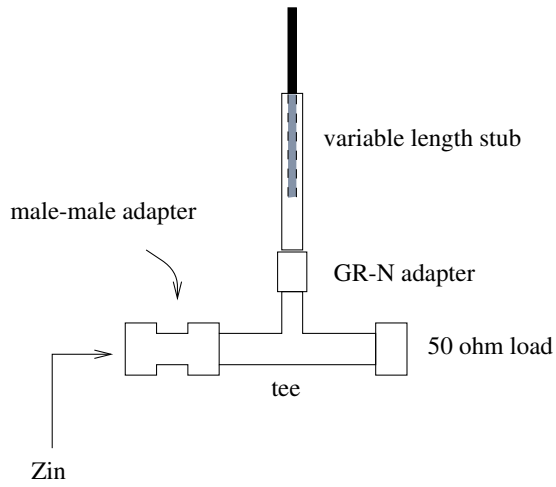


Figure 1.2: Variable length SC stub in parallel with  $50\Omega$  load.

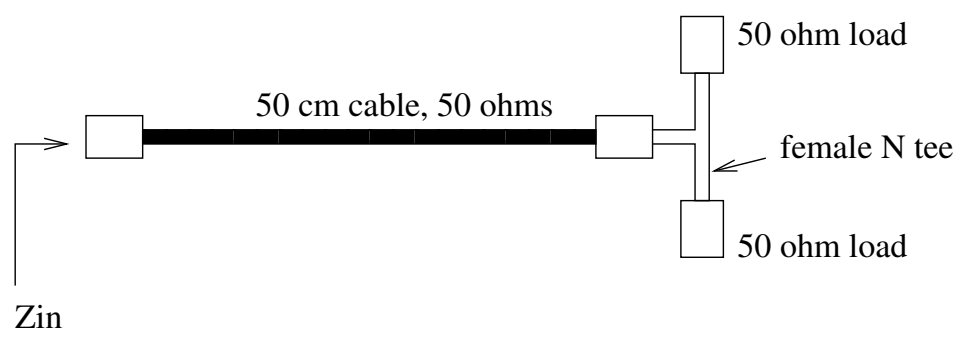


Figure 1.3: 50 cm coaxial cable with two  $50\Omega$  loads.

## Lab #2 Impedance Measurements Using a Slotted Waveguide

### 2.1 Equipment

- Gunn diode source: Macom voltage controlled oscillator transceiver MA87728-M01
- 0-10 volt DC power supply
- HP 8735B PIN modulator
- Wavetek 182 oscillator: 0-2 MHz, with  $50\Omega$  2V output
- Waveguide variable attenuator, e.g. Waveline 612DR 0-40 dB
- Wavetek 182 oscillator: 0-2 MHz, with 2V p-p output and  $50\Omega$  output.
- Caswell X-101 ferrite isolator or Airtron 337312 circulator + Waveline 654 matched load.
- HP X532B or Sivers cavity type absorption wavemeter
- HP 809B or FXR X115A slotted waveguide
- FXR B200-A waveguide probe with 1N23 crystal detector
- Oscilloscope, HP415 SWR meter, BNC-BNC cable
- Loads: Waveline 654 matched load, shorting plate, four waveguide irises (labelled A,B,C,D), and measurement calipers
- HP X370C 10 dB waveguide attenuator

## 2.2 Introduction

This lab makes use of X-band waveguide components. The internal waveguide dimensions are 0.9 by 0.4 inches. A block diagram of the setup is shown in Figure 1.

The microwaves are generated by a *Gunn diode*<sup>1</sup>, named after the British physicist J. Gunn. It is a GaAs or InP device which exhibits a negative resistance characteristic. The bias voltage is in the range  $6 \leq V_G \leq 10$  volts DC. The Gunn is mounted in a resonant cavity, and it oscillates at the resonant frequency of the cavity. It generates  $10mW$ , in the range 10.0–10.6 GHz.

To obtain AM, we use a *PIN diode* (p-intrinsic-n). It is mounted as a post across the waveguide. When it is reverse biased, nothing happens. When it is forward biased in the range  $0 \leq V_P \leq 0.8$  volts, it looks like a conducting post, causing the waves to be reflected back to the source. Hence, the PIN diode can be used as a switch, to produce an AM signal. We can modulate the signal with a sine or square wave; the distortion will be small if the modulation signal is small.

The HP 8735B PIN diode modulator has a BNC connector. The center pin is connected to the cathode, so a negative bias voltage blocks the RF signal. About  $-8mA$  on the center pin will cause complete cutoff.

The RF source is connected to a ferrite isolator<sup>2</sup>, which permits propagation only in one direction. This suppresses reflections from the source, and also reduces “frequency pulling”.

The slotted waveguide has a slot cut in the side, so that the E field can be measured with a probe. The probe assembly is connected to a 1N23 crystal detector, and the demodulated output is viewed on the scope and SWR meter. A screw on the top adjusts the probe depth. There is also a probe-to-diode matching network. Depending on the model, it might have a knob and sliding stub, or two collars. It needs to be adjusted for maximum output.

The exit end of the slotted waveguide defines the reference plane, where the unknown load is connected.

## 2.3 Setup

Connect the Gunn source, isolator, modulator, wavemeter, attenuator, and slotted waveguide. For the Gunn source, apply  $+8V$  with respect to ground.

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<sup>1</sup>Pozar, Sec. 10.5

<sup>2</sup>Pozar, Sec. 9.4.

Be careful not to exceed this voltage or reverse the polarity, as you will blow the diode. **Let the equipment warm up for 20 minutes.** Otherwise the frequency will drift.

Connect the crystal detector output to the scope and SWR meter. Connect a 1 kHz square wave generator to the PIN modulator. Set the DC offset=0, and use the  $50\Omega$   $2V_p - p$  output. Adjust the frequency until you get maximum deflection on the SWR meter.

Check the operation of the system by measuring a “standard load.” Use a 10 dB fixed attenuator with a shorting plate. If everything is working properly, you should measure an SWR of 1.22. You might have to adjust the RF power level and/or the probe depth to get a good reading. If the crystal voltage is in the range 10-100 mV, you’re probably not overloading it.

The SWR is 1.22 because the wave incident on the plate is attenuated by 10 dB, and its reflection is attenuated by another 10 dB, so the reflection, or “return loss” is 20 dB.

Now measure and record the SWR of a matched load. This number is useful; it represents the threshold where useful measurements can be made.

## 2.4 Measurement of Standing Waves

Now replace the matched load with the shorting plate. Slide the probe carriage back and forth, observing the high SWR. Record the locations of two or three null positions. Determine the guide wavelength.

Find the frequency of operation, using  $f = c/\lambda$ . Note that the standing wave pattern does *not* give  $\lambda$ . Rather, we must use the dispersion relation  $(1/2a)^2 + (1/\lambda_z)^2 = (1/\lambda)^2$ .

Now find the frequency by using the wavemeter. Carefully tune it until you see a drop in power, then read off the frequency. At resonance, the wavemeter absorbs a small amount of power, causing about a 1 dB drop on the SWR meter.

## 2.5 Impedance Measurement

We will use the Smith chart to find the impedance of the load. This involves 3 steps: (1) Record the null positions with a short circuit load. (2) Now replace the short with the unknown impedance and measure the SWR. Draw the corresponding constant SWR circle. (3) (a) If the unknown’s minima are shifted towards the load by X wavelengths, relative to the short circuit nulls, then on the chart, move X wavelengths towards the generator, measured

from  $Z=0+j0$  (b) if the unknown's minima are shifted towards the generator by  $X$  wavelengths, relative to the short circuit nulls, then on the chart, move  $X$  wavelengths towards the load, measured from  $Z=0+j0$ .

If  $\bar{Y}$  is needed, it can be obtained from  $\bar{Z}$  by rotating  $\bar{Z}$  by  $180^\circ$  around the Smith chart.

In this lab, when we say "impedance" we mean the normalized impedance  $\bar{Z}$ , which has a 1:1 correspondence with the reflection coefficient. In the context of waveguides, an unnormalized impedance  $Z$  cannot be measured.

### 2.5.1 Open Ended Waveguide

The open ended waveguide is an antenna. Measure the reflection coefficient and find the corresponding  $\bar{Z}$ . Avoid obstructing the open end, as this will affect the measurement.

### 2.5.2 Irises

Measure the impedance of the four irises A,B,C,D in parallel with a matched load termination. Note that two of the irises are narrow in the E-plane, and two are narrow in the H-plane. Use the calipers to measure the physical dimensions of the irises, for later use.

## 2.6 Questions

Your group is required to write up and submit answers to these questions. Hand in the work at class time. It will be marked like homework.

1. What are your measured values of SWR for (a) the matched load, and (b) 10 dB attenuator with shorting plate?
2. What is the measured guide wavelength? What is the frequency from (a) the guide wavelength and (b) the wavemeter?
3. Open ended waveguide: What % of the incident power gets reflected? What % gets transmitted? What does this say about trying to have an "open circuit" at the end of a waveguide?
4. For the four irises, show your measured impedances on a Smith chart. On the chart, convert them to admittances.
5. On the same chart, plot the theoretical admittances,  $\bar{Y} = 1 + j\bar{B}$ , using the formulas of Section 7.

6. Suppose you made a 1 mm error in measuring a null position. How much of an error would there be in the phase of the reflection coefficient?

## 2.7 Iris Formulas

Some waveguide irises are described in Pozar Sec. 4.6. We will consider the symmetrical inductive and capacitive irises. These formulas are taken from Collin.<sup>3</sup>

For the symmetrical inductive iris of width  $d$

$$\bar{B} = \frac{-2\pi}{\beta a} \cot^2 \frac{\pi d}{2a} \left( 1 + \frac{a\gamma_3 - 3\pi}{4\pi} \sin^2 \frac{\pi d}{a} \right)$$

where  $\gamma_3^2 = (3\pi/a)^2 - k^2$ , and  $\beta^2 = k^2 - (\pi/a)^2$ . The waveguide dimensions are  $a, b$  with  $b \leq a$ . The iris width  $d$  is measured in the H-plane, with  $0 \leq d \leq a$ .

For the symmetrical capacitive iris of height  $d$

$$\bar{B} = \frac{2\beta b}{\pi} \left( \ln \csc \frac{\pi d}{2b} + \left( \frac{2\pi}{b\gamma_2} - 1 \right) \cos^4 \frac{\pi d}{2b} \right)$$

where  $\gamma_2^2 = (2\pi/b)^2 - k^2$ , and  $\beta^2 = k^2 - (\pi/a)^2$ . The waveguide dimensions are  $a, b$  with  $b \leq a$ . The iris width  $d$  is measured in the E-plane, with  $0 \leq d \leq b$ .

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<sup>3</sup>“Foundations for Microwave Engineering,” R.E. Collin, McGraw-Hill, 1966. We note that the original work first appeared in “Waveguide Handbook” by N. Marcuvitz, McGraw-Hill 1951.



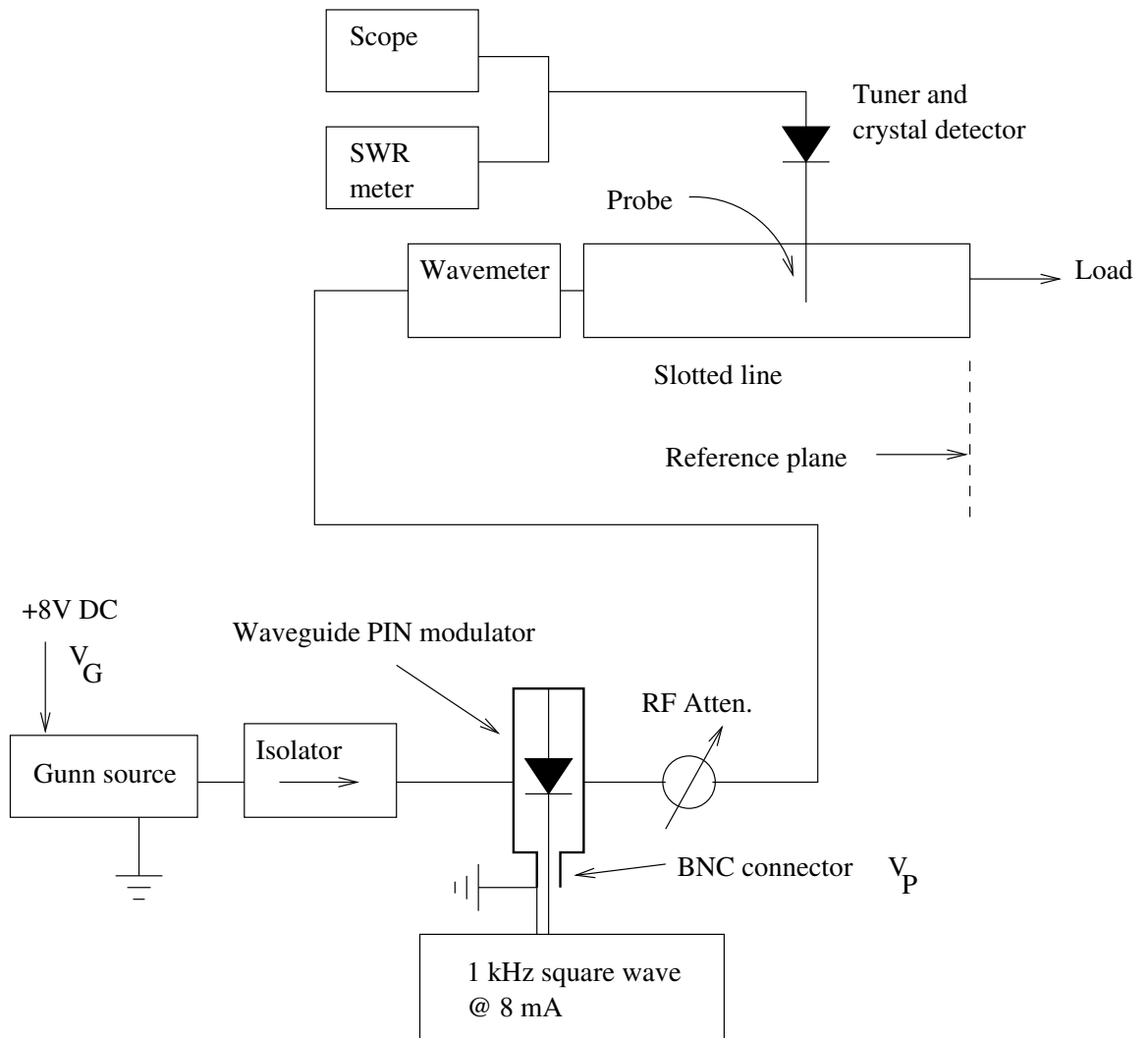


Figure 2.1: Block diagram of the setup.

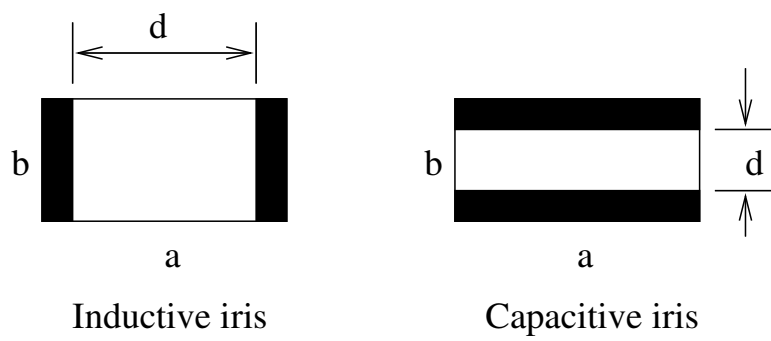


Figure 2.2: Symmetric waveguide irises.

## Lab #3 Diodes: Gunn, Varactor, and PIN

### 3.1 Equipment

FM setup for Gunn diode:

- Macom voltage controlled oscillator transceiver MA87728-M01
- 0-10 volt DC power supply, 1-20 volt DC power supply, digital voltmeter
- HP X752A 3 dB directional coupler
- Waveline 654 matched load
- Coax-waveguide transition, 50 cm coax, 10 dB coax attenuator
- HP 5347A power meter/frequency counter + HP 8481A thermocouple sensor head (300 mW max for power meter, 7 dBm for frequency counter)

AM setup for Gunn diode:

- Macom voltage controlled oscillator transceiver MA87728-M01
- 8 volt DC power supply
- Caswell X-101 ferrite isolator or Airtron 337312 circulator + Waveline 654 matched load
- Waveline 612DR 0-40 dB variable attenuator
- HP 8735B PIN modulator
- Wavetek 182 oscillator: 0-2 MHz, with 2V p-p output and adjustable DC offset
- HP X752C 10 dB directional coupler, two waveguide stands

- Waveline 654 matched load
- 3 dB E-plane tee
- HP X485B tunable detector mount with 1N23 crystal, BNC cable, scope
- HP 8569B spectrum analyzer, coax-waveguide transition, 50 cm coax
- PC with GPIB card and Linux/GPIB software
- HP 432A power meter + HP 478A thermistor head (30 mW max)

### 3.2 Introduction

In this lab we want to measure the characteristics of a Gunn diode, varactor diode, and PIN diode, at X-band. We will use a power meter and a spectrum analyzer.

The *Gunn diode* is a GaAs or InP device which exhibits a negative resistance characteristic. The bias voltage is in the range  $6 \leq V_G \leq 10$  volts DC. The Gunn is mounted in a resonant cavity, and it oscillates at the resonant frequency of the cavity. Compared to a klystron, the Gunn is inexpensive (\$30), reliable, and easy to operate. However, the operating frequency drifts with temperature, and its AM and FM noise performance is inferior. Also, compared to tubes, the power output of semiconductor devices is low.

We can change the resonant frequency of the Gunn/cavity by putting in a small post. A *varactor diode* can be used for the post. By applying a reverse bias or “tuning voltage” of  $1 \leq V_T \leq 20$  volts DC on the varactor, we are able to tune the operating frequency of the Gunn oscillator. By modulating  $V_T$  we can produce an FM signal.

A *PIN diode* (p-intrinsic-n) can be mounted as a post across a waveguide. When it is reverse biased, nothing happens. When it is forward biased in the range  $0 \leq V_P \leq 0.8$  volts, it looks like a conducting post, causing the waves to be reflected back to the source. Hence, the PIN diode can be used as a switch, to produce an AM signal. We can modulate the signal with a sine or square wave; the distortion will be small if the modulation signal is small.

### 3.3 Bias Voltages

Be careful, you can blow the Gunn diode if you apply more than +10 V, or get the polarity backwards. Also be careful to stay in the range +1 to +20

V for the varactor bias. For the PIN modulator, a bias of -0.8 V, 20 mA is sufficient to achieve full attenuation. Using the 2V output on the signal generator is safe for the PIN.

### **3.4 Power Meters**

Be careful to never exceed the limits of a power meter, as a blown sensor head is costly, about \$1000. The 478A can operate at 10 mW but will blow at 30 mW.

In general, a power meter measures small changes in the characteristics of a thermistor or thermocouple element that is heated up by RF signal power. Since this is based on the heating effect, we have a true RMS response. It is also broadband, so it gives the total power in the signal plus all harmonics or sidebands that might be present.

#### **The HP432A**

This meter has a range of 10 MHz-10 GHz and -20 dBm to +10 dBm. Incoming RF power causes heating of the 478A thermistor sensor; this changes its DC resistance. The power meter measures this small change in resistance.

To use it, set the mount resistance to  $200\Omega$  and set the cal. factor knob by using the graph printed on the sensor head. We need to follow a special nulling procedure because the meter uses a 10 kHz impedance bridge, and the 478A head needs to see the 10 kHz impedance of the RF source under test. (1) Connect the sensor head to the RF source under test. (2) Turn the source off. (If it is inconvenient to turn it off, then turn it down.) (3) Select the desired power range on the meter. (4) Press and hold the “fine zero” switch until the meter zeros. (5) Now apply power and take the reading.

#### **The HP5347A**

This instrument uses a semiconductor thermocouple sensor head, which produces a small DC voltage in response to RF heating. Its range is 10 MHz-18 GHz and -30 dBm to +20 dBm. For accurate readings, a calibration and zeroing procedure needs to be followed. (1) Use the 5347A to measure and store the frequency of the CW signal; it then uses a lookup table for the sensor calibration data. (2) Follow the power calibration and zeroing procedure, as described on top of the instrument. (3) You are now ready to measure power.

Note that this instrument is unable to take a frequency reading if any modulation is present. The frequency counter can only work with CW signals, though we can measure the power of any signal.

### 3.5 Spectrum Analyzer

We have an HP 8569B spectrum analyzer for 0.01-22 GHz. The quick way to start using it is to set all the controls to the green settings.

The spectrum analyzer is connected to a General Purpose Interface Bus (GPIB.) Data can be transferred back and forth between the spectrum analyzer, and a PC that has a GPIB card. A small c program

```
/usr/local/src/hp8569.c
```

is used to communicate with the spectrum analyzer. The PC runs the Linux operating system.

#### 3.5.1 Hardcopy of Spectrum

You can make a paper copy of a spectrum plot by following these instructions: (1) turn on the printer, monitor, and computer (2) login as `maxwell` (no password) (3) type `startx` to start the X-windows (4) type `hp8569 1` or `hp8569 2` to obtain a plot for lab bench 1 or 2.

When you are finished, (1) type `ctrl-alt-backspace` to exit X-windows, then (2) `exit` to logout from the console. (3) Use `ctrl-alt-del` to begin the shutdown. (4) When you see the message *Rebooting*, you should turn off the computer. Press and hold the power switch for 5 seconds.

### 3.6 FM setup

Assemble the setup in Fig. 1. Connect +8V to the Gunn diode. To avoid frequency drift, **let the Gunn warm up for 20 minutes**. The source signal passes straight through a 3 dB directional coupler, and part of the signal is sampled, travelling up the side arm.<sup>1</sup> The sampled part goes to a waveguide-coax transition. We can connect either the power sensor head, or a piece of coax + frequency counter. Use a 10 dB coax attenuator with the frequency counter; the input needs to be less than 7 dBm.

Note that because of the properties of the directional coupler, signals can travel from the load back to the source, but cannot travel from the side arm back to the source. So, minor mismatches in the side arm will not affect the source.

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<sup>1</sup>Pozar, Sec. 7.4.

Being careful about the polarity and voltage levels, make the following tests. (1) With the varactor open circuited, plot the output power vs Gunn voltage. (2) Plot the frequency vs Gunn voltage. (3) With 8V Gunn bias, plot the frequency vs varactor voltage.

Take a power reading with and without the 50 cm coax, to determine its loss.

Remove the matched load, and put your finger over the aperture. What is the effect on the frequency?

### 3.7 AM setup

Assemble the setup in Fig. 2. Connect +8V to the Gunn diode. For now, leave the PIN modulator disconnected. Use two waveguide stands so that the 50 cm coax can reach the spectrum analyzer.

A 10 dB directional coupler samples the signal. It is then split in half (3 dB) by an E-plane tee.<sup>2</sup> One arm of the tee goes to a waveguide-coax transition, to feed a spectrum analyzer or power meter. The other arm of the tee feeds a tunable crystal mount, and we observe its signal on a scope.

With CW modulation, record the power (in dBm) as seen on the spectrum analyzer. Now disconnect the spectrum analyzer and connect the power meter. Turn the RF down, and zero the power meter. Then turn it back up and take the power reading. Take readings with and without the 50 cm coax, to determine the cable loss.

Note that the spectrum analyzer input impedance is not exactly 50Ω. The input reflection coefficient can change slightly as the spectrum analyzer sweeps. If the input attenuator is set to 0 dB, you might see a jiggling on the oscilloscope connected to the crystal mount. Set the input attenuator to  $\geq 10dB$  to improve the match.

Now we will use the PIN modulator. On the HP 8735B PIN modulator, applying a negative voltage to the center pin of the BNC connector will forward bias the PIN diode, and block the incident wave. A positive voltage has no effect.

Apply a 1 kHz sine wave to the PIN modulator. Use the 2 V output. Adjust the amplitude and DC offset of the sine wave to get low distortion of the sine wave, as seen at the crystal detector. Now switch the modulation to 1 MHz. Use the spectrum analyzer to record the amplitude (in dBm) of the spectral components. Also measure the power, using the power meter.

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<sup>2</sup>Pozar, Sec. 7.2.

To compare the powers, we need to add up the powers in all the sidebands of the modulated signal.

Tune the modulating frequency from 1 kHz to 2 MHz, and observe the voltage at the crystal. Find the 3 dB bandwidth. (Note that 3 dB means 1/2 diode voltage.)

### 3.8 Questions

Your group is required to write up and submit answers to these questions. Hand in the work at class time. It will be marked like homework.

FM questions:

1. Plot the Gunn power in milliwatts, vs. Gunn bias voltage. Do not exceed 10 V. Account for the directional coupler.
2. Plot the Gunn frequency vs. Gunn bias voltage. Do not exceed 10 V.
3. Plot the Gunn frequency vs. varactor tuning voltage,  $+1 \leq V_T \leq 20$  Volts. Use a Gunn bias of 8.0 V.
4. From the “finger experiment,” how much does the load affect the frequency?

AM questions:

1. What is the CW power of the Gunn, using (a) the spectrum analyzer, and (b) the power meter? Be sure to take out the losses due to the directional coupler, tee, and coax cable. From the spectrum analyzer, what is the frequency?
2. For 1 kHz modulation, sketch the waveform present at (a) the PIN input (show the DC part) and (b) the crystal output.
3. For the 1 MHz AM signal, plot the spectrum analyzer display. The power in the spectrum is

$$P(mW) = \sum 10^{dBm/10}.$$

Find the power in the carrier + sidebands. Compare with the power meter.

4. What is the 3 dB bandwidth of the PIN modulator + crystal demodulator?



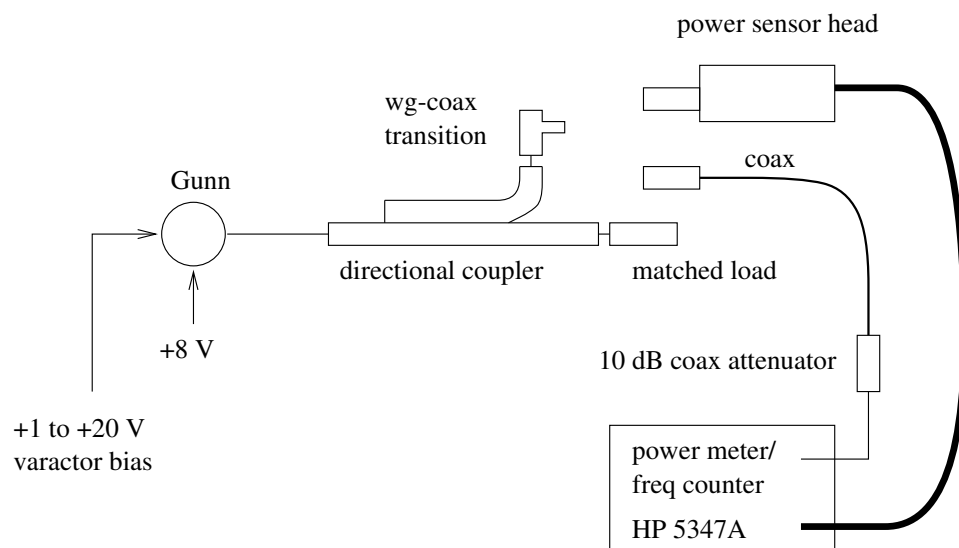


Figure 3.1: FM test of Gunn and varactor diodes.

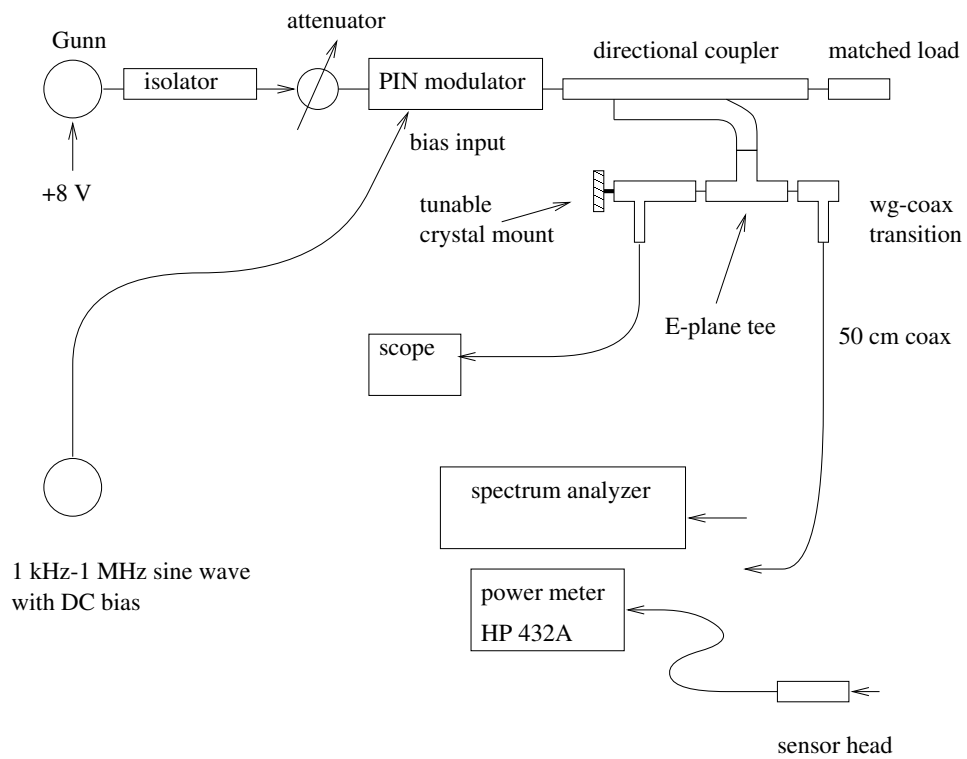


Figure 3.2: AM test of Gunn and PIN diodes.

## Lab #4 Doppler Radar and Friis Transmission

### 4.1 Doppler Radar

#### 4.1.1 Equipment

- Macom voltage controlled oscillator transceiver MA87728-M01
- 8 volt DC power supply
- Sivers or HP wavemeter
- 20 dB directional coupler, 15 inch flexible waveguide, FXR X621A H-plane tee, HP X485B tunable detector mount with 1N23 crystal.
- E & M Labs X234LT circulator, 10.7–11.7 GHz
- Omega 438 X band pyramidal horn, approx. 13.5 by 11.2 cm
- Tektronix TDS 340 storage scope
- tennis ball, foil, string, ruler, masking tape, wood block

#### 4.1.2 Introduction

In this lab we try out a doppler radar by using a swinging ball on a string as a target. An electromagnetic wave will have a doppler shift in frequency, when viewed from a moving reference frame. The amount of shift is  $f_c v_d / c$ , where  $f_c$  is the carrier frequency and  $v_d$  is the velocity of the observer. For a radar system, both the incident and scattered waves get doppler shifted by the moving target, so the total shift is

$$f_d = 2f_c v_d / c$$

Section 12.3 in Pozar contains a discussion of radar systems.

From mechanics, if the pendulum swings with a horizontal displacement

$$x(t) = A \sin \sqrt{\frac{g}{l}} t,$$

then the velocity is

$$v(t) = A \sqrt{\frac{g}{l}} \cos \sqrt{\frac{g}{l}} t$$

### 4.1.3 Setup

It is possible to use the Macom transceiver as a self-contained radar system. However, in this lab, we will only use it as an RF source. We will “build” the radar with waveguide components.

The setup is shown in Fig. 1. The signal is transmitted at frequency  $f_c$ . The received signal is at  $f_c \pm f_d$ , depending on whether the target is approaching or receding. The received signal passes to the mixer, which has  $f_d$  at the output.

In general, a mixer is a device that multiplies two signals, producing components at the sum and difference frequencies of the two signals. In this lab, a “single ended mixer” is implemented by using a detector diode and an H-plane tee.<sup>1</sup>

If the received signal is  $\cos \omega_c t$  and the local oscillator is  $\cos \omega_0 t$  then the output current of the single ended mixer is proportional to  $\cos(\omega_c - \omega_0)t +$  other high frequency components.

The ferrite circulator<sup>2</sup> allows us to use the same antenna for both transmit and receive. The signal can pass from port 1 to 2, 2 to 3, and 3 to 1— but not in the opposite sense, e.g. 2 to 1. Hence, the signal passes from 1 to 2 on transmit, from 2 to 3 on receive, and the receiver is isolated from the transmitter. Circulators and other ferrite devices tend to be narrow band.

Assemble the setup shown in Fig. 1. For mechanical reasons, a flexible waveguide is used to connect the output of the directional coupler to the mixer.

Turn on the Gunn diode. On the scope, press “autoset” to get a reasonable setting based on the input. Set it for DC coupling. Tune the detector mount to obtain maximum output. Use the wavemeter to find the frequency.

Switch the scope to AC coupling. Hang the target from the ceiling. Keep a distance of 1 meter or so in between the antenna and target, to be in the

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<sup>1</sup>The single ended mixer is described in Pozar Sec. 10.2, p.565. The H-plane tee is in Sec. 7.2.

<sup>2</sup>Pozar, Sec. 9.6

far field. Swing the pendulum for several different amplitudes. You can use the wood block like a T-square to help position the ball above the position scale on the benchtop. Now, record the maximum doppler frequency for each case. This is most easily accomplished with the storage scope. The scope is discussed in more detail, in the next section.

#### 4.1.4 Storage Scope

The Tektronix TDS340 digital real time scope helps us observe the doppler signal, which is FM. Proper use of this instrument requires at least 2 hours to study the manual. What follows here are only a few tips to help with our particular lab.

By using a time base of about 100 ms/div, most of the interesting doppler waveform features will be captured. An even better approach is to use the scope's built in FFT to see what the highest frequency component is. This is done as follows. The scope always digitally stores a time record of 1000 points, and uses this to obtain a 1000 point frequency spectrum.

By choosing the horizontal sweep menu `fit to screen` off/on, the user can choose to show either 500 or 1000 of the data points on the screen. Either setting is ok, though choosing "off" with 500 points might be preferred, because it hides the aliased part of the spectrum. Note that this choice affects both the time and frequency displays.

The FFT is invoked by choosing the menu `math FFT Ch.1`. Next, adjust the horizontal position so that you can see the first point of the FFT sequence, which always corresponds to DC. You can also use the `cursor` menu's v-bars to read off the frequencies; they are displayed beside the `@` symbol on the screen.

Press the `start/stop` button to freeze the time signal. With the slow sweep rate of 100 ms/div, you have to wait for *at least two* screens of data to go by, before the 1000 point memory gets filled with data. (Remember that the screen is showing only 500 points). After pressing `stop`, the FFT will appear.

Don't forget to measure the length of the string.

#### 4.1.5 Questions

1. Compare your radar measured velocities with velocities predicted from mechanics.
2. Assuming a source output of  $40mW$ , frequency  $f = 10GHz$ , a metal sphere target with radius  $a = 4.8cm$ , an antenna gain of  $15dB$ , and a

target distance of  $2m$ , use the radar range equation (Pozar 12.27) to estimate the received power. The radar cross section of the sphere can be estimated from Pozar Fig. 12.13.

## 4.2 Friis Transmission

### 4.2.1 Equipment

- Macom voltage controlled oscillator transceiver MA87728-M01
- 8 volt DC power supply
- Waveline 612DR 0-40 dB variable attenuator
- Sivers or HP wavemeter
- RG 214 U coaxial cable, HP X281 coax-waveguide transition
- Two Waveline 6 inch straight waveguide sections, 4 stands
- Two LRL 531 horns 4.5 by 3.2 cm
- One Narda 640 standard gain horn 7.3 by 5.4 cm (16 dB @ 10.000 GHz)
- HP 432A analog power meter with HP 478A thermistor head, HP X281A coax-waveguide transition.
- ruler, masking tape, wood block

### 4.2.2 Introduction

In this experiment we wish to measure the power received by horn antennas. The Friis Transmission Formula<sup>3</sup> states that

$$P_r = P_t \left( \frac{\lambda}{4\pi r} \right)^2 G_t G_r$$

where  $P_t$  = transmitter power,  $P_r$  = received power,  $G_t$  =transmitter antenna gain, and  $G_r$  =receiver antenna gain. In dB's the Friis formula becomes

$$P_r(dBm) = P_t(dBm) + 20 \log(\lambda/4\pi r) + G_t(dB) + G_r(dB).$$

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<sup>3</sup>Pozar Sec. 12.2

If a horn antenna is of “optimum design” then a good approximation of the gain turns out to be

$$G = \frac{4\pi}{\lambda^2} \times 0.5 \times A_p$$

where  $A_p$  is the physical area of the horn aperture. The 0.5 factor comes about because the aperture efficiency of a horn is about 50 %. The Narda 640 standard gain horn is described in the antenna book by Balanis.<sup>4</sup> At 10 GHz the gain is 16 dB.

The Friis formula assumes that the antennas are in the far field. This occurs for distances

$$r \geq 2D^2/\lambda$$

where  $D$  =largest dimension of the antenna aperture.

We also note from the Friis formula that the received power falls off as  $1/r^2$ , so we lose 6 dB each time the distance is doubled.

### 4.2.3 Setup

Assemble the setup of Fig. 2. Screw the waveguides together at point “A.” Measure the source frequency and power. Turn the the RF output “off” with the attenuator, and press the “fine zero” switch on the HP432A power meter. Note that the power meter drifts, so you should do this frequently during the experiment. Now turn on the RF output and record the transmitter power  $P_t$  in dBm.

Disconnect the waveguides at point “A” in Fig. 2 and install the small LRL 531 horns. Use two stands on each 6 inch waveguide. Set the stands for maximum height, with the support posts resting on top of the set screws.

At 10 GHz the far field for these antennas is about 15 cm, so put the horns at a distance of 15-20 cm. You need to optimize the receiver’s transverse position and the antenna angle. Do this by alternately sliding each support stand back and forth, in an iterative way, until you get maximum power. Now record the received power  $P_r$  in dBm. Since  $G_t = G_r$  you can use the Friis formula to deduce the antenna gain.

We now will try another way to measure the antenna gain. With a distance of 35 cm or more, measure  $P_r$  for the pair of LRL 531 horns. Now remove the receiver horn and replace it with the Narda 640 standard gain horn. From the change in power reading, you can now deduce the gain of the LRL 531 horn.

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<sup>4</sup>“Antenna Theory and Design,” C.A. Balanis, Fig. 13.24, Wiley 1997.

Put back the LRL 531 horns. Measure the received power as a function of distance, for 20 to 100 cm spacing. (In theory, you should see a 6dB drop for every doubling of distance.) For each measurement, carefully align and rotate the receiver to obtain maximum power. Remember to frequently zero the power meter. Use the wood block as a T-square to help position the receiver horn above the scale on the benchtop. Also, measure the uncertainty by performing a “multipath check” for each case; this is described below.

Multipath propagation exists because we can have reflected rays from the benchtop and other parts of the room. To obtain an estimate of these uncertainties, put your hand **flat** on the benchtop and slide it back and forth along the range between the antennas. Record the fluctuation in dB, of  $P_r$ .

When done, you should have a table of data with distance,  $P_r(dBm)$  and the uncertainty in dB.

#### 4.2.4 Questions

1. What is the measured gain of the LRL 531 horn, as obtained from having two identical horns?
2. What is the measured gain of the LRL 531 horn, when using the standard gain horn as a reference?
3. What is the theoretical gain of the LRL 531 horn, based on the aperture area?
4. Plot the measured  $P_r/P_t$  in dB vs. distance, for the LRL horns. Use a log scale for the distance. On the same graph, use the Friis formula to plot the theoretical result. Use the gain from Question 1.
5. Comment (1/2 page or less) on the effect of the surrounding environment, with respect to multipath effects. Is it a serious problem in this experiment?



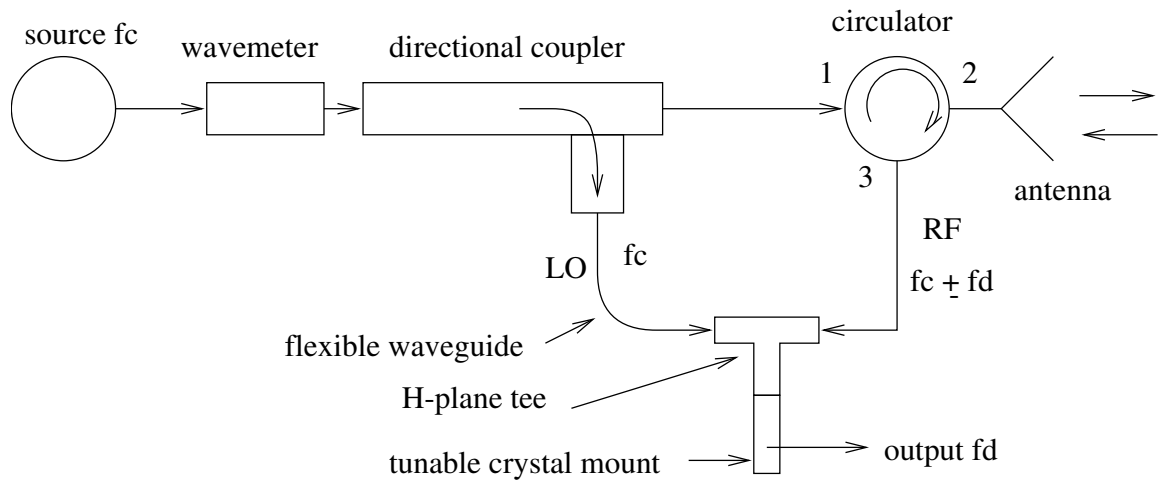


Figure 4.1: Doppler radar block diagram.

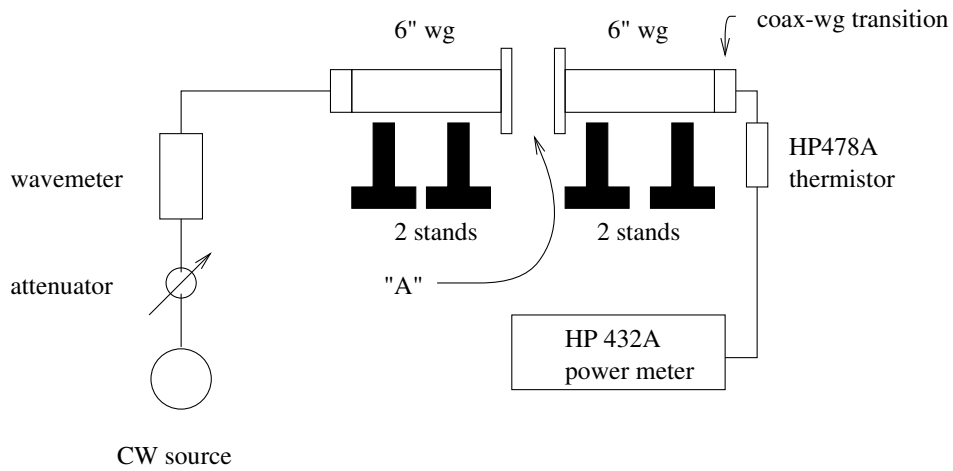


Figure 4.2: Friis transmission experiment. Connect the waveguide flanges together at “A” to measure  $P_t$ . Insert the antennas at “A” to test them.

## Lab #5 Network Analyzer I

### 5.1 Equipment

- Network analyzer, HP 8410C, with HP8412 rectangular display
- HP 8743B 2.0-12.4 GHz transmission/reflection test unit
- HP 8411A 0.11-12.4 GHz harmonic frequency converter
- Sweeper, HP 8350B + HP 83540B 2-8 GHz RF plug-in
- Adapters: one APC-7 to SMA male
- Loads:  $50\Omega$  SMA male, short circuit SMA male, female-female SMA adapter
- GML 1000  $50\Omega$  microstrip line with SMA connector and  $100\Omega$  10 mW chip resistor
- 3M 1183 conducting tape, X-acto knife (for cutting the tape), glass plate, steel ruler, magnifying glass, digital calipers
- Linux PC with ICS Advent ML16-P A/D card and GPIB card; voltage divider interface for A/D card

### 5.2 Introduction

In this lab, we will design a single stub microstrip matcher for a  $50\Omega$  microstrip line and  $100\Omega$  load, as in Fig. 1.

The return loss and bandwidth will be measured with a network analyzer. The theoretical performance will be predicted with a sophisticated CAD package.

A vector network analyzer allows us to measure the transmission and reflection coefficients of an unknown, both magnitude and phase. We will use the HP 8410 network analyzer, which operates from 2-12 GHz.

CAD is now a standard tool for microwave engineering. We will use the HP Advanced Design System (ADS). It has many functions; we will focus on the “Momentum” utility, which allows us to simulate planar structures such as microstrip and stripline. It uses the method of moments to rigorously solve for the unknown currents on the conductors, at all positions on the circuit. From the currents, it then finds the S parameters, vs. frequency.

### 5.3 Microstrip Line

The circuit board to be used is GIL Technologies GML 1000. The thickness= 0.030 inch,  $\epsilon = 3.20$ . The line is 73 mils wide and has an impedance of  $50\Omega$ . This is in agreement with the microstrip equations (3.195)-(3.197) in Pozar. In addition,  $\epsilon_e = 2.55$ .

The line is about 2 inches (2000 mils) long. Measure it, to be sure. At one end there is an SMA connector. At the other end there is a  $100\Omega$  10 mW chip resistor. Your job will be to match the load to the line, using a single stub matcher. An open circuit shunt stub is realized with a piece of 3M 1183 copper tape. The tape has a conducting adhesive, so sticking it on the main transmission line ensures a proper connection.

For more information on the 3M tape, go to [www.3m.com](http://www.3m.com). The GIL Technologies GML 1000 board is at [www.gilam.com](http://www.gilam.com).

When measuring impedances, we need to establish the location of the reference plane terminals. For a reference short, we can use an SMA connector with conducting tape, as in Fig. 1. By coincidence, it turns out that it has the same electrical length as an SMA male SC + SMA female-female adapter. We prefer the latter, as it is more reliable and produces repeatable results.

An open circuit with the proper electrical length is obtained by using the SMA female-female adapter, alone.

A  $50\Omega$  SMA matched load is also available. It looks almost the same as an SMA SC. Looking inside, the SC is gold plated, whereas the  $50\Omega$  load is teflon.

SMA connectors should be finger tight. Never use wrenches or pliers!

### 5.4 Stub Matcher

Before going to the lab, design a single stub matcher for the  $100\Omega$  load, at  $f=3.000$  GHz. Use a Smith chart. Calculate the physical length and position of the stub. Think about the layout and make a drawing. To make a good connection, the tape needs to completely overlap with the main line. The

length is measured from the open circuit end to the centerline of the main transmission line. Note that the wavelength on the line at 3.000 GHz is  $\lambda = 6.26\text{cm}$ .

## 5.5 Network Analyzer

The network analyzer (NA) allows us to measure the magnitude and phase of the reflection coefficient for an unknown load. In principle, all NA's use a dual directional coupler to sample the incident (reference) and reflected (test) waves. Taking the ratio of test wave and reference wave gives us  $\Gamma$ . Sometimes an NA is called a ratiometer.

To find the ratio, the NA mixes the RF signals down to a lower intermediate frequency, 278 kHz, where they can be more easily measured and processed for display. The IF signals preserve the magnitude and phase of the original reference and test signals. Narrow band detection at IF brings high sensitivity, wide dynamic range, and immunity from harmonics that might exist in the source.<sup>1</sup>

We will use the NA to measure the return loss of an unknown load. The setup is outlined in Fig. 2. The unknown is connected to the reflection port.

Set the sweeper for 2.5–4.0 GHz, and 5 dBm output power. Check the settings on the NA.<sup>2</sup> To calibrate and check it, by using a short circuit, open circuit, and matched load. We begin with the short circuit, which has  $\Gamma = 1\angle 180^\circ$ . ( $RL = 20 \log |\Gamma| = 0\text{dB}$ .)

Set the NA display for “magnitude.” Adjust the test channel gain and amplitude vernier and note the level; this will be your reference level for a return loss of 0 dB. You should have a horizontal line at the middle of the screen. Now switch the display to “phase.” On the 8743B reflection/transmission test unit, adjust the crank for reference plane until the phase plot has no slope. Now make minor adjustments to the reference plane and phase vernier so that the display reads  $\pm 180^\circ$ . Some parts of the trace might be at  $+180^\circ$ , other parts  $-180^\circ$ , so the phase display will look

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<sup>1</sup>The HP 8410 is very similar in operation to the newer HP 8510, described in Pozar, Sec. 4.3, p.205.

<sup>2</sup>The NA should be set for source=normal, freq range=2-4 GHz, The display might look jumpy. You need to adjust the red stability knob and/or slow down the sweep rate, until the display looks steady. If you are using a slow sweep rate, the CW setting for stability works well.

Adjust the sweeper RF output so that the 8410 ref. channel level meter is in the “operate” range. If you're using the 8350B sweeper you will notice it has many settings. Note that you can start over by pressing the green button for “reset to defaults”

a bit like a square wave. If you have problems with the calibration, call the instructor to help you.

Remove the short and put an open circuit. Since  $\Gamma = 1\angle 0^\circ$ , the RL should read 0 dB and the phase should be zero.

Remove the open circuit and put the  $50\Omega$  load. Since  $\Gamma \approx 0$ , the RL should be 40 dB or better. The phase can be any value and it is not important.

Now we are ready to measure return loss  $20 \log |\Gamma|$  and the phase of  $\Gamma$  for an unknown load.

## 5.6 Impedance Measurement

For 2.5-4.0 GHz, measure  $\Gamma$  magnitude and phase, for the line +  $100\Omega$  load. Make a plot, using the PC. Login as maxwell with no password, and type `startx`. Then type `hp8412 1` or `hp8412 2` for bench 1 or 2.<sup>3</sup>

Now we want to make the matching stub. Find a 1.5 inch piece of conducting tape. Do your cutting with the X-acto knife, steel ruler, and glass plate. Use the calipers and magnifying glass to determine the 73 mil line width.

Attach the stub to the main line. It should completely overlap the main line. Plot the RL for 2.5-4.0 GHz. (I do not require the match frequency to be exactly 3.000 GHz.) Write down the physical dimensions used.

Try making the stub a bit longer or a bit shorter, and obtain a second result. Record the length, plot the result.

Turn off the calipers when you are done.

## 5.7 Simulation

To learn how to use Momentum, follow the instructions in the manuals, distributed in class. Modify your `.cshrc` file. Then do the exercise in Ch. 4, “Designing a Microstrip Line.”

Now use Momentum to simulate your theoretical design of the  $50\Omega$  to  $100\Omega$  single stub matcher, Obtain  $|S_{11}|$  for 2–4 GHz.

You need to create a *Project*, a *Schematic*, and a *Layout*. In the *Layout* window you then access the functions

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<sup>3</sup>The mag/phase data is available as analog voltages at the back of the HP8412 display plugin. For mag/phase, bench 1 uses A/D Ch. 1 and Ch. 2; bench 2 uses A/D Ch. 5 and Ch. 4. A voltage divider is used to make the 8412 voltages compatible with the  $\pm 128mV$  required by the A/D card. The sweeper is controlled by GPIB.

- *Momentum* → *Substrate Create*
- *Momentum* → *Substrate Precompute*
- *Momentum* → *Port Editor*
- *Momentum* → *Simulation*

The input port is  $50\Omega$ . To make the output port  $100\Omega$  go to: *Layout Window* → *Momentum* → *Port Editor*.

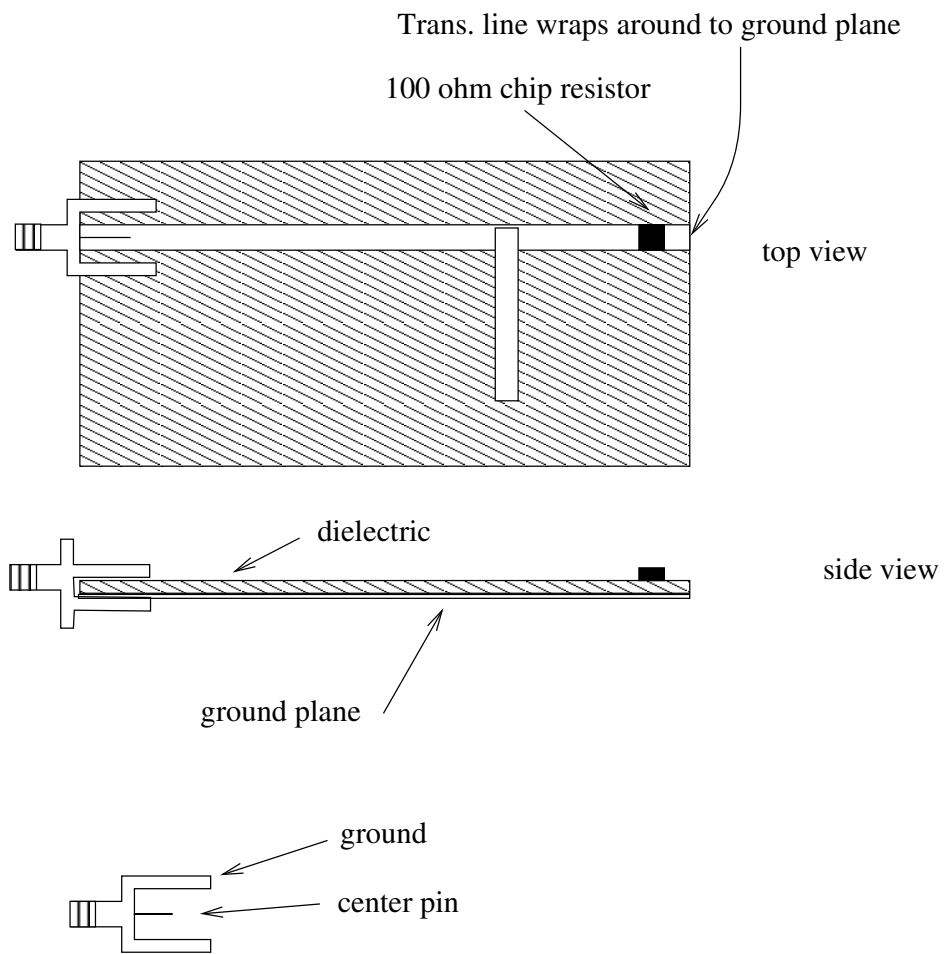
In the schematic window, you will need the components *Port*, *MLIN*, *MTEE*, and *MLOC*. Presence of red dots in the schematic indicate a problem, unconnected components.

Each time you modify the circuit and generate a layout, you should also recompute the mesh. Otherwise the layout will not look right. In addition, presence of cyan dots in the layout indicate a problem, unconnected components.

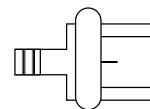
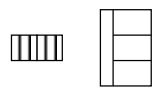
You can change the text size for components. First, *Select* → *All* then *Edit* → *Component* → *Component Text Attributes*.

## 5.8 Questions

1. Draw your theoretical design for a  $50\Omega$  to  $100\Omega$  single stub microstrip transformer. (Do this before going to the lab.)
2. Plot the measured RL and phase, for your microstrip line with  $100\Omega$  load, for 2.5-4.0 GHz.
3. Plot the measured RL for your microstrip line with  $100\Omega$  load with single stub matcher, for 2.5-4.0 GHz.
4. Draw your actual design for the  $50\Omega$  to  $100\Omega$  single stub microstrip transformer, as used in the lab.
5. Use Momentum to model your theoretical design from Problem 1. Find the bandwidth for 20 dB return loss. Show the plot of  $|S_{11}|$  for 2.5-4.0 GHz.
6. Return the Momentum manual to Dr. Paknys.

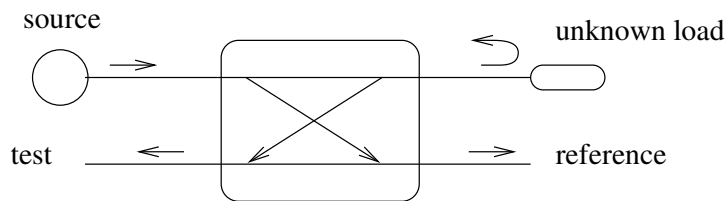
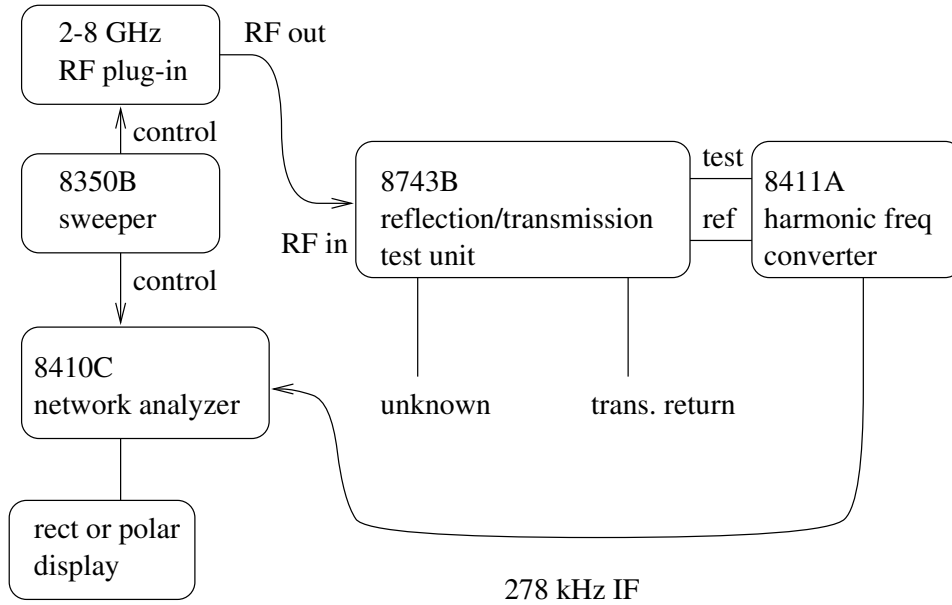


SMA edge connector



SMA female-female + SMA SC male = SMA + tape short ckt

Figure 5.1: Microstrip lines and SMA components.



directional coupler (inside 8743B)

Figure 5.2: HP 8410 Vector Network Analyzer. The 8743B test unit uses a directional coupler to measure the incident and reflected waves. The reference signal is a sample of the source, and the test signal is a sample of the reflection. The 8411A measures the ratio test/reference, of the two signals. The signal gets down-converted to 278 kHz, to facilitate signal processing. The result,  $\Gamma$ , appears on the display.



## Lab #6 Vector Network Analyzer II

### 6.1 Equipment

#### 6.1.1 X Band Reflectometer

- HP 8672A 2-18 GHz synthesized signal generator, 1 kHz 2V p-p audio oscillator, HP X281 coax to waveguide transition, RG 214U coax cable
- HP X750D 20 dB crossed guide “Moreno” directional coupler, HP X370C 10 db fixed waveguide attenuator
- Narda 950 180° hybrid (magic T), Waveline 654 matched load, Aircom tunable crystal mount, HP 415E SWR meter
- HP X382A rotary vane variable attenuator, HP X885A phase shifter, three 90° H-plane elbows, long 90° elbow- FXR X64A, 10 inch flexible waveguide
- Shorting plate, matched load, irises A, B, C, D.

#### 6.1.2 Network Analyzer, Bench #2 for 5.9-12.4 GHz

- Network analyzer, HP 8410C, with HP 8412A rectangular display
- HP 8743B 2.0-18 GHz transmission/reflection test unit
- HP 8411A 0.11-18 GHz harmonic frequency converter
- HP 8350B sweeper with HP 83545A 5.9-12.4 GHz RF plug-in
- APC-7 to N male adapter, coax-waveguide transition
- Shorting plate, matched load, irises A, B, C, D
- HP X870A slide screw tuner

### 6.1.3 Network Analyzer, Bench #1 for 2.0-8.2 GHz

- Network analyzer, HP 8410C, with HP 8414B polar display
- HP 8743B 2.0-12.4 GHz transmission/reflection test unit
- HP 8411A 0.11-12.4 GHz harmonic frequency converter
- HP 8350B sweeper with HP 83540B 2-8 GHz RF plug-in
- 27  $\Omega$  1/4 W resistor, with SMA connector
- SMA type: APC-7 to SMA male adapter, female-female, SC male
- 50 $\Omega$  2 inch GML 1000 line with 100 $\Omega$  load
- 50 $\Omega$  2 inch GML 1000 line with SC load
- Microstrip 90° hybrid, three 50 $\Omega$  SMA male loads

## 6.2 Introduction

A vector network analyzer allows us to measure the transmission and reflection coefficients of an unknown, both magnitude and phase. This is more sophisticated than a scalar network analyzer, which measures only the magnitude. We will use the HP8410's to measure the impedance of waveguide, and microstrip components. We will also measure impedance by using a directional coupler.

A key element in any network analyzer is the directional coupler, which allows us to sample the reflected or transmitted fields for a device under test.<sup>1</sup> By comparing with a reference signal (a sample of the incident field) we can then obtain the magnitude and phase of the reflection and transmission coefficients of the device under test.

The hard part is how to compare the reference and unknown signals, in both magnitude and phase. The easiest way is to subtract them. They will cancel, if and only if their magnitudes and phases are equal. We will use a "home made" network analyzer at X band, to illustrate the principles of amplitude and phase comparison. In this case, a directional coupler is used to sample the reference and reflected signals. They are subtracted in an E plane waveguide tee. When they are equal, cancellation occurs. The difference signal is easily monitored with a crystal detector.

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<sup>1</sup>Pozar, Sec. 7.9, p.414 describes the use of directional couplers for network analyzers.

### 6.3 X Band Reflectometer

The HP 8672A synthesized signal generator operates from 2-18 GHz, with an output range of  $-120$  to  $+3$  dBm. It uses a Yttrium iron garnet (YIG) tuned oscillator<sup>2</sup> that is phase locked to an internal 10 MHz crystal (also called time base.) The frequency stability is dependent on the time base. An external audio oscillator is used to provide AM.

Assemble the setup in Fig. 1. Note that a flexible waveguide is required to “make ends meet.” The magic tee has two inputs: one is the “reference signal” and the other is the “test signal.” The crystal is on the  $\Delta$  port and a matched load is on the  $\Sigma$  port. When the two inputs are equal, we get a null at the  $\Delta$  port, and all the power goes into the  $\Sigma$  port where we have the matched load. Hence, when the SWR meter shows a null, we know the reference and test signals are equal.

Set the carrier frequency to 10.600 GHz. Using the meter on the 8672, set the audio oscillator for 100 % modulation. Adjust the audio oscillator frequency to match the narrow bandpass of the HP 415E SWR meter. Tune the crystal detector mount for maximum output. (The switches in the 415 E are dirty, you sometimes need to wiggle them.)

#### 6.3.1 Measuring $\Gamma$

Put a shorting plate as the unknown. Adjust the phase shifter and attenuator until a null is observed. Record the attenuator and phase shifter setting, let's call it  $A_1\angle\phi_1$ . Now put the unknown load, and measure  $A_2\angle\phi_2$ . The reflection coefficient follows from

$$\frac{A_2}{A_1} = |\Gamma|$$
$$\phi_2 - \phi_1 + 180^\circ = \angle\Gamma$$

You can test this out by using a sliding short circuit as a load. As the line is lengthened, you should observe a decrease in phase. Note: you should be using the **top** scale on the phase shifter.

Use the reflectometer to measure the impedance of iris A,B,C,D terminated with a matched load.

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<sup>2</sup>Pozar Sec. 10.5, p. 591

## 6.4 Network Analyzer, 5.9-12.4 GHz

Connect a coax-waveguide transition at the reflection port. Set the sweeper for 10.500-10.700 GHz. Using a waveguide shorting plate, calibrate the NA so that  $RL = 0dB$  and the phase is  $\pm 180^\circ$ .

### 6.4.1 Irises A, B, C, D

Measure  $\Gamma$ , magnitude and phase, for irises A, B, C, D terminated with a matched load. Plot your data by using the PC. Login as `maxwell`, no password. Type `startx` and `hp8412 2` to get a plot.

### 6.4.2 Slide Screw Tuner

The slide screw tuner is a length of waveguide with a slot cut in the wall, similar to the slotted line. The tuner is 14 cm long. A thin metal post sticks into the slot, parallel to the E field, and can move along the slot. The post's depth of penetration is adjustable, with a micrometer. When set to zero, the post is all the way in. When set to 400, it is fully retracted, by 0.400 inch. A short post acts like a shunt capacitance and a very long post becomes an inductive post. So the post acts like a series L-C. At the right length it can resonate and look like a short.

The  $\Gamma$  for iris D is large. Use the slide screw tuner with iris D + matched load, and adjust it for a good match at 10.600 GHz. Record the distance from the post to the iris. Plot the RL for 10.500-10.700 GHz.

### 6.4.3 Waveguide Cutoff

To observe waveguide cutoff, measure the RL for the coax-wg transition + matched load. Use a frequency range that goes below 6.5 GHz, and plot the result.

## 6.5 Network Analyzer, 2-8 GHz

We will measure  $\Gamma$  for microstrip circuits, using the HP8414 polar display. The SMA SC with female-female adapter is used for a SC reference.

To use the polar display: Press the beam finder, adjust the x and y centering. Adjust the sweeper RF output so that the 8410 ref. channel level meter is in the "operate" range. With a SC load, adjust the 8410 test channel gain and amplitude vernier so that the trace is at  $|\Gamma| = 1$ . Adjust the reference plane so that the SC impedance appears as a point, and not as

a locus on the display. This way, the SC reference is frequency independent. Adjust the phase vernier so that the SC appears at  $Z=0+j0$  on the Smith chart.<sup>3</sup>

To make plots, on the PC, type `hp8414 1`.

### 6.5.1 27 $\Omega$ Resistor

Connect the 27  $\Omega$  resistor at the NA unknown port. Plot the reflection coefficient for 2.000-4.000 GHz. Use the sweeper's marker to identify the frequencies at a few data points.

### 6.5.2 Microstrip Line I

We have two versions of the GML 1000 2 inch microstrip line. One has a 100 $\Omega$  load, and the other one has the load shorted out by using a small piece of conducting tape. Use the shorted line to calibrate the NA. Adjust the reference plane and phase vernier to get a spot at  $Z = 0 + j0$ . Then plot  $\Gamma$  for the line with chip resistor, on 2.000-4.000 GHz.

### 6.5.3 Microstrip Line II

Recalibrate the NA. This time, use the SMA SC. Plot  $\Gamma$  for the line with the resistor, on 2.000-4.000 GHz.

### 6.5.4 Quadrature Hybrid

The quadrature hybrid is described in Pozar Sec. 7.5. Typical behavior for the device is shown in Fig. 7.25. The substrate is Hitachi LX67, having  $\epsilon_r = 3.38$ , loss tangent = 0.005 at 3 GHz, and a thickness of 30 mils.

Plot  $S_{11}$  for the quadrature hybrid, on 2.000-4.000 GHz. Put 50 $\Omega$  SMA loads at the three unused ports.

Get the calipers and measure the dimensions of the hybrid. You will need this later on, for simulation purposes.

## 6.6 Questions

Please make the plots easy to read. Label everything.

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<sup>3</sup>A useful tip: Sometimes the polar display can vanish unexpectedly. To get it back, try to unplug and plug the polar display by slightly moving its locking lever.

1. For the reflectometer, give a table of values for your attenuator and phase shifter settings. Convert the data to impedance by using a Smith chart. Finally, find the iris admittances.
2. Compare the above data to what you measured with the HP network analyzer. For 10.600 GHz, plot the NA data on the same Smith chart as in Question 1.
3. Comment on the slide screw tuner. In your measurement, was the post inductive or capacitive? Use the iris susceptance and slide screw position to calculate the susceptance of the slide screw.
4. What is the measured cutoff frequency of the waveguide?
5. Show the measured  $\Gamma$  on Smith charts, for the  $27\Omega$  resistor, microstrip lines I and II, and the hybrid. Comment on your results.
6. Derive an expression for  $\Gamma(f)$  for the microstrip line with  $100\Omega$  load. Use ordinary transmission line theory and the appropriate  $\epsilon_e$ .
7. Make an ADS simulation of the hybrid and compare with measured results for  $|S_{11}|$ .

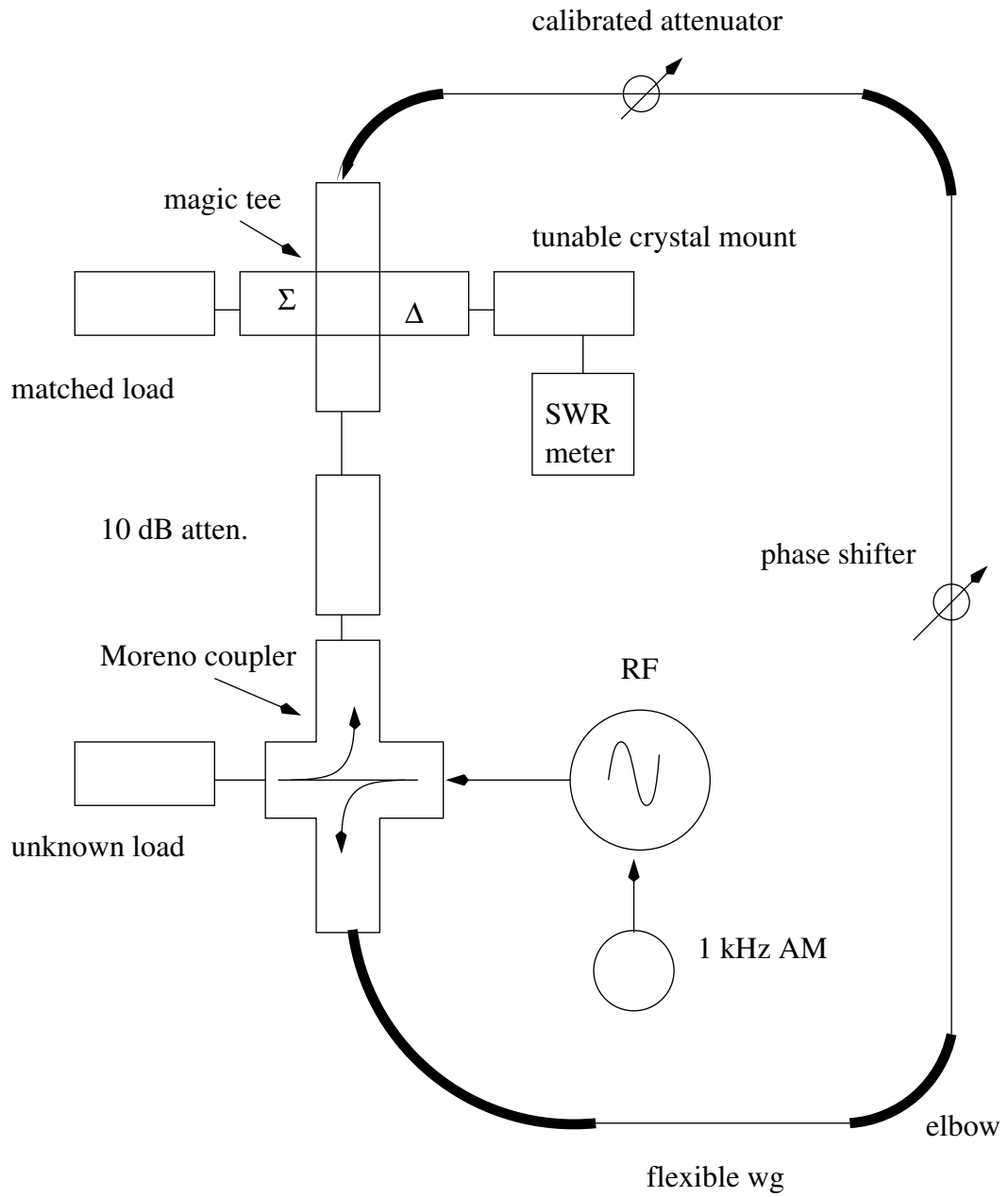


Figure 6.1: Setup for X band “network analyzer”.

## Appendix A GPIB Instrument Control

Programs were written to control a National Instruments PCIIa GPIB card and an ICS Advent ML16-P 8 bit A/D card. Drivers for the PCIIa and ML16-P were found at the *Linux Lab Project* <http://www.llp.fu-berlin.de/>.

The GPIB card controls the HP8569 spectrum analyzer and HP8350 sweeper. The ML16-P A/D card is used to collect data from the BNC jacks on the HP8412 and HP8414 network analyzer displays.

Here is an example of controlling the HP8350B sweeper. The program writes the FA command to the bus. The sweeper returns the start frequency, as set on the instrument knob.

```
#include <stdio.h>
#include <math.h>
#include <stdlib.h> /* need for atof */

#include <ib.h>      /* GPIB */

main(){

char cmd[80] ;
float startfreq ;
int dev;

/* 8350 sweeper gpib init */
if((dev=ibfind("hp8350-1")) & ERR ){
printf("Can't find the device hp8350-1 !\n");
exit(1);
}

/* get the 8350 start freq */

strcpy(cmd,"OP FA\n");
if(ibwrt(dev,cmd,strlen(cmd)) & ERR){ printf("Write Error!\n"); exit(1); }
```



```
if(ibrd(dev,cmd,79) & ERR){printf("Read Error!\n");exit(1); }
startfreq = atof(cmd) * 1.e-6 ;
printf("Start Frequency (MHz) = %f\n" ,startfreq);

/* Reset sweeper: untalk unlisten un-remote*/

cmd[0] = UNL;
cmd[1] = UNT;
if( ibcmd(dev,cmd,2L) & ERR ){
printf("Error sending UNL,UNT\n");
exit(1);
}

if( ibsre(dev,0) & ERR ){
printf("Error unset\n");
exit(1);
}

/* End of pgm */ }
```