ELEC 453/6391 Microwave Engineering

Experiment #4

Network Analyzer Measurements

This experiment has two parts. In the first you will build a single-stub matching circuit for a microstrip line, and then measure the reflection coefficient using an HP8410 network analyzer with a rectangular display (bench 2). In the second part, you will measure the impedance of the four waveguide irises of experiment 3, using an HP8410 network analyzer with a polar display (bench 1). Your lab group has 90 minutes to work on bench 1 and 90 minutes on bench 2.

1. Equipment

Network Analyzers
The lab has two HP8410 Network Analyzers. One operates from 0.11 to 12.4 GHz has a sweeper from 2.0 to 8.2 GHz, and the other operates from 0.11 to 18 GHz, and has a sweeper from 5.9 to 12.4 GHz. You will need to use both NAs in this experiment. You will use the NA with the polar display to find the admittance of the waveguide irises, and the NA with the rectangular display to find the reflection coefficient of a microstrip transmission line with a single-stub tuner.

Bench #1, Polar Display
(Along the back of the room)

- HP 8410C Network analyzer with HP 8411A 0.11 to 12.4 GHz harmonic frequency converter and **HP 8414B polar display**
- HP 8743B 2.0 to 12.4 GHz transmission/reflection test unit
- HP 8350B sweeper with HP 83592A **0.01 to 20.0 GHz** RF plug-in
- APC-7 to N female adapter
- HP X281A waveguide to coaxial transition
- Shorting plate
- X-band waveguide matched load
- Irises A, B, C, D used in Experiment 3
- HP X870A slide screw tuner

Bench #2, Rectangular Display
(near the door)

- HP 8410C Network analyzer with HP 8411A 0.11 to 18 GHz harmonic frequency converter and **HP 8412A rectangular display**
- HP 8743B 2.0 to 18 GHz transmission/reflection test unit
- HP 8350B sweeper with HP 83540B **2 to 8 GHz** RF plug-in
- APC-7 to SMA male adapter, female to female SMA adapter, SMA short circuit with male connector
- Loads: 50 Ω SMA male; short circuit SMA male; female-female SMA adapter.

- 27 Ω, 1/4 W resistor, with SMA connector
- Microstrip line with $Z_0 = 50\,\Omega$ on GML 1000 board, terminated with a load resistor.
- 3M 1183 conducting tape, X-acto knife (for cutting the tape),glass plate, steel ruler, magnifying glass, digital calipers

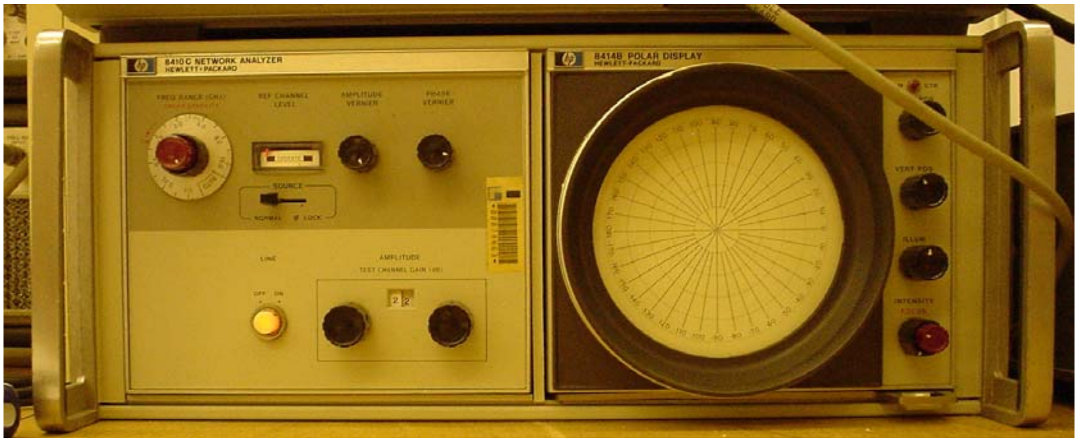


Figure 4.1(a) HP8410 network analyzer with the HP8414B polar display (bench 1).

Figure 4.1(b) The HP8410 network analyzer with the HP8412 rectangular display (bench 2).

2. Introduction

In this experiment you will use an HP8410 network analyzer (NA) to measure the reflection coefficient of the X-band waveguide irises and of a microstrip circuit. The lab has two HP8410C NAs. One has been set up with the polar display, Fig. 4.1(a), which shows the magnitude and angle of the reflection coefficient as a function of frequency on polar axes, in a Smith Chart format. You will use to measure the reflection coefficient of the waveguide irises at X band from 10.3 to 10.7 GHz. The other NA has been set up with the rectangular display, Fig. 4.1(b), which shows the magnitude and angle of the reflection coefficient on rectangular axes, as a function of frequency. You will use it to measure a microstrip circuit from 2 to 4 GHz.

Network Analyzer

A vector network analyzer, such as the HP8410 in Figure 4.1, has two input channels, located on the HP8411A harmonic frequency converter. Like the vector voltmeter of Experiment 2, one input is the "reference" channel and the other is the "test" channel. If the voltage at the reference connector or "port" is $V_{ref} = \left|V_{ref}\right| e^{j\phi_{ref}}$, and the voltage at the test port is $V_{test} = \left|V_{test}\right| e^{j\phi_{test}}$, then the network analyzer measures the ratio of the voltage at the "test" port to the voltage at the "reference" port, $\frac{V_{test}}{V_{ref}} = \frac{\left|V_{test}\right|}{\left|V_{ref}\right|} e^{j(\phi_{test}-\phi_{ref})}$. So the network analyzer measures the ratio of the test-port voltage to the reference-port voltage, $A = \frac{\left|V_{test}\right|}{\left|V_{ref}\right|}$, and is sometimes called a "ratiometer". The NA measures the difference in phase between the test-port voltage and the measurement-port voltage, $\phi = \phi_{test} - \phi_{ref}$. Much less expensive "scalar" network analyzers measure the amplitude ratio only.

Figure 4.2 HP8350 sweeper with HP83592 plug-in unit for 0.1-20 GHz.

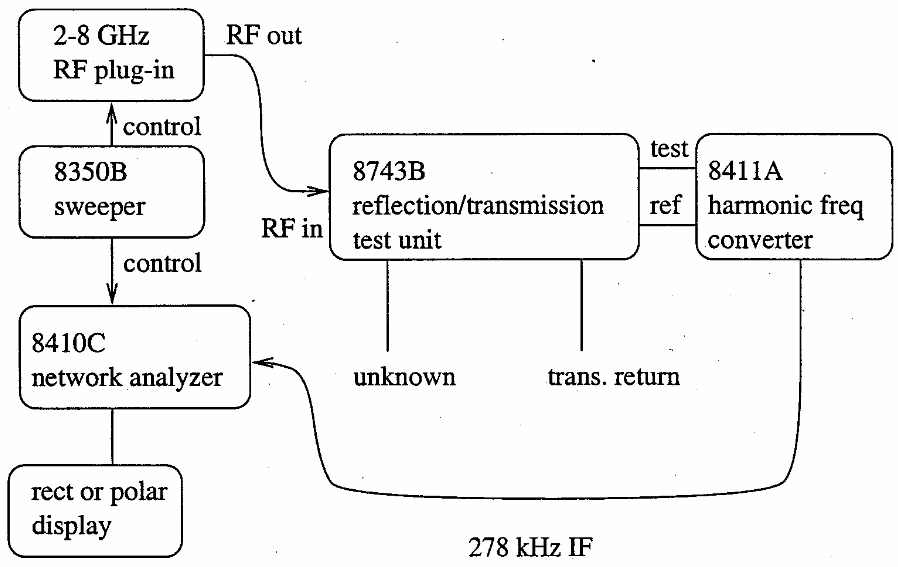
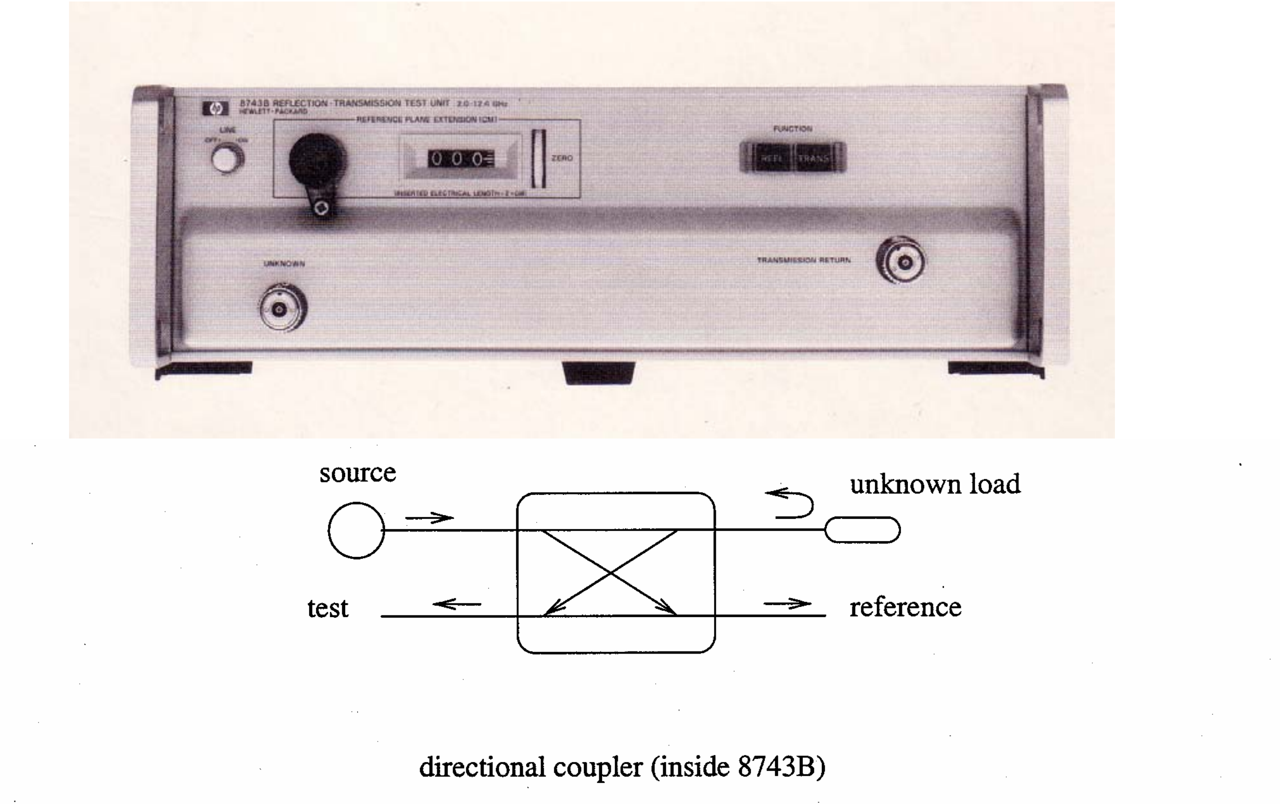


Figure 4.3 HP8410 Vector Network Analyzer and frequency sweeper.

A network analyzer is usually operated in conjunction with a swept-frequency generator or "sweeper", such as the HP8350 in Figure 4.2. To operate the sweeper, set a starting frequency f_1 and a stopping frequency f_2 for the sweeper, and trigger it. Then the sweeper gradually increases the frequency from f_1 to f_2, and the network analyzer records the voltage ratio at each frequency on its display unit. On the rectangular display in Fig. 4.1(b), the horizontal axis is the frequency from f_1 to f_2, and the vertical axis is either the amplitude ratio A in decibels, or the phase difference ϕ in degrees. The amplitude and the phase curves can be displayed at the same time. The "polar" display of Fig. 4.1 (a) shows $A\angle\phi$ on polar axes and is equivalent to a Smith Chart presentation.



directional coupler (inside 8743B)

Figure 4.4 HP8743B "reflection/transmission test set", or "S-parameter test set".

Figure 4.3 is a block diagram of the NA/sweeper measurement system. The HP8350B sweeper provides control information to the network analyzer and to the RF plug-in unit, which generates the actual RF voltage. The RF unit supplies the signal to the "source" or "RF in" port of the reflection/transmission test set. The test set, Figure 4.4, uses a directional coupler to provide a sample of the RF signal from the generator to the "reference" port of the network analyzer, which is located on the HP8411 "harmonic frequency converter". The RF voltage is routed to the "unknown" port of the test set, and the load reflects some voltage back. A directional coupler samples the reflected voltage and then routes the sample to the "test" port of the harmonic frequency converter. The harmonic frequency converter down-converts to an intermediate frequency of 278 kHz, preserving the relative amplitude and phase of the test signal relative to the reference signal. The 278-kHz IF is more easily measured and processed than the RF signal itself. Narrow-band detection at IF brings high sensitivity, wide dynamic range, and immunity from harmonics. The HP8410 network analyzer extracts the amplitude and phase and displays them on either a rectangular display plug-in unit or a polar display plug-in unit. The HP8410 is very similar in operation to the newer HP8510[1] and HP8720 network analyzers. The newer instruments are microprocessor controlled, whereas the HP8410 is manually controlled, and so is easier to learn and less confusing to work with.

A key element in any network analyzer is the directional coupler[2], which separates the incident signal from the reflected signal. The "directivity" of the directional coupler is a figure-of-merit which measures how well the two signals are separated. Pozar discusses the measurement of the directivity[3] and the effect of coupler directivity on the accuracy of reflection coefficient measurements[4].

Measuring an Unknown Impedance

The NA is very similar to the vector voltmeter (VV) of Experiment 2. Recall that the vector voltmeter has two channels, A and B. The VV measures either the voltage at channel A, or by manually changing the position of a switch, the voltage at channel B and the phase difference between channel B and channel A. The VV is oriented towards manually-controlled measurement at one frequency. The NA differs from the vector voltmeter because the NA measures the *ratio* of the channel B or "test" channel voltage to the channel A or "reference" channel voltage, $A = \frac{|V_{test}|}{|V_{ref}|}$. The NA is set up to be controlled by a sweeper, so can measure across a frequency band from f_1 to f_2, rather than at individual frequencies. So measuring the reflection coefficient as a function of frequency with the NA is much easier and faster than taking measuring individual frequencies with a vector voltmeter.

The NA is used to measure the reflection coefficient of a load with directional coupler, as was done with the VV in Experiment 2. Recall that a dual directional coupler[5] was used to sample the "incident" voltage for channel A of the VV, and the voltage reflected from the load for channel B. After calibration with a short circuit load, the ratio of channel B to channel A is the reflection coefficient. Using the NA, the dual directional coupler is packaged inside the "reflection/ transmission test set" of Fig. 4.4, which is also called an "S-parameter test set" because it is used to measure the reflection coefficient $\Gamma = S_{11}$ and the transmission coefficient S_{21}. The block diagram shows that the signal from the sweeper is connected to the "source" port, which is on the back of the HP8743. The source port delivers the signal to a directional coupler, and most of the power is delivered to the "unknown" port on the reflection/transmission test set, where the unknown load impedance is connected. The directional coupler samples the incident wave from the "source" port and routes it to the "test" channel of the NA. The reflected voltage from the unknown load is sampled and delivered to the "reference" channel of the NA. The reflection coefficient is equal to the ratio of the reflected wave to the incident wave, hence the ratio of the voltage at the "test" port

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[1] Pozar, Section 4.3

[2] Pozar, Sec. 7.9, p.414 describes the use of directional couplers for network analyzers.

[3] Pozar page 357.

[4] Pozar page 414.

[5] Pozar page 354 and Figure 7.4.

to the voltage at the "reference" port, which is precisely what the NA measures, with proper calibration.

A short circuit is used to "calibrate" the NA, as was done for the VV in Experiment 2. Calibration compensates for the different transmission-line lengths in the test channel and reference channel. The reflection/transmission test set contains a mechanical "line stretcher" similar to that used in Experiment 2 for stub matching. Turning the crank changes the length of the line stretcher. Connect a short circuit to the "unknown load" port, and adjust the line stretcher in the reflection/transmission test set to cancel out the difference in path length in the test channel and the reference channel. Change the length of the line stretcher until the NA shows a phase of ± 180 degrees. The NA should show that the magnitude of the reflection coefficient is unity. We say that the short-circuit is used to establish the location of the "reference plane" where the unknown load will be connected,

Replace the short circuit with the unknown load, and the "calibrated" network analyzer measures the magnitude and phase of the reflection coefficient Γ of the load. As the sweeper increases the frequency from f_1 to f_2, the network analyzer shows the magnitude and phase of Γ at each frequency, and the result is a graph of the magnitude $|\Gamma|$ and the angle of Γ as a function of frequency. The lab computer can trigger the sweeper and then record the magnitude and phase of the reflection coefficient at each frequency to a data file, as described below.

Figure 4.5 The stub tuner installed on the microstrip line, connected to the reflection port of the HP8743B transmission/reflection test set.

Microstrip Transmission Line and Single-Stub Matching

In Part 2 of this lab, you will design a single-stub matching circuit for a 50-Ω microstrip line terminated with a load resistor. Figure 4.5 is a photo of the microstrip line, which runs from an SMA edge connector at the top of the photo to the chip resistor "load" at the bottom. The microstrip line is mounted on the test port of the reflection/transmission test set of the network analyzer. In Figure 4.5, the load has been "matched" to the line with a "single stub" matching circuit. Fig. 4.6 is a sketch of the stub tuner with a 100-Ω load. The stub consists of a short 50-

Ω transmission line terminated with an *open* circuit. Designing the stub consists of choosing the distance of the stub from the load, and the length of the stub.

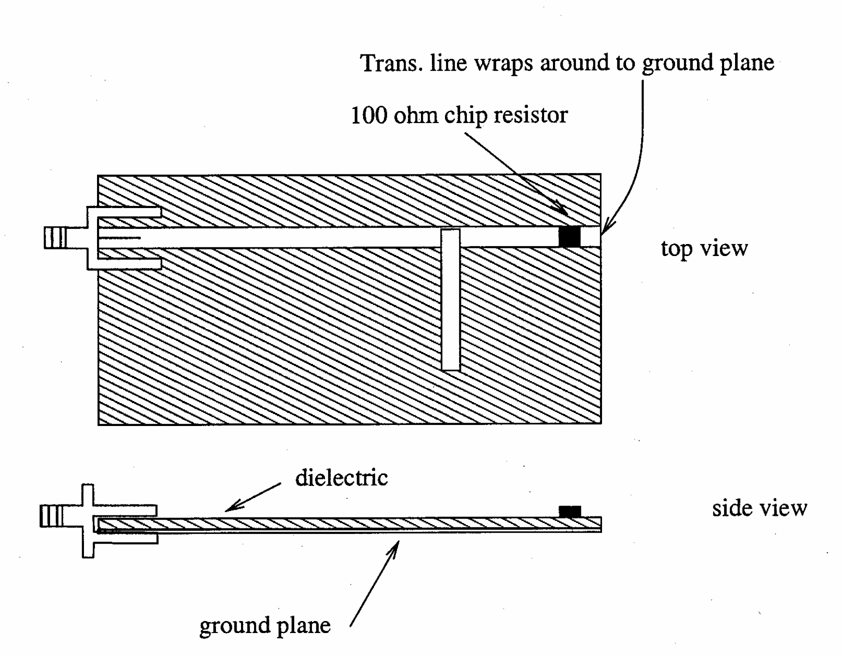

Figure 4.6 Microstrip transmission line.

The material for the circuit board in Figure 4.5 is GIL Technologies GML 1000[6]. The thickness is 0.030 inch, and the relative permittivity is ε_r=3.20. The line is 73 mils wide and has a characteristic impedance of $Z_0 = 50\,\Omega$.

The line in Figures 4.5 and 4.6 is about 2 inches (2000 mils) long. The line is terminated with a resistor R_L, which is a $100\,\Omega$, 10 mW chip resistor in Fig. 4.5. In the lab, there are several circuit boards with lines of various lengths and with various values of R_L. In the lab, the demonstrator will give you a circuit board, and your job is to match the load to the line, using a single stub matcher[7], as shown in Figure 4.6. First, you will measure the value of the load resistor using the network analyzer. Then you will design a single-stub matching circuit, built it, and measure the quality of the match using the network analyzer.

3. Preliminary Exercise

Answer these questions before you come to the lab. The lab demonstrator will check that you have answered these questions before he permits you to do the experiment.

1. Calculate the effective relative permittivity of the GML 1000 substrate material for a microstrip line 73 mils in width. You should get $\varepsilon_e = 2.55$. Calculate the characteristic

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[6] Information about the GIL Technologies GML 1000 board is at www.gilam.com.

[7] Pozar, Section 5.2, page 228.

impedance and verify that it is $Z_0 = 50$. Use the formulas in Pozar[8]. Calculate the phase velocity[9].

2. In the lab you will have to design a single-stub tuner. For practice, design a single-stub matching circuit[10] assuming that the load resistor is 100 ohms. The microstrip transmission line has a characteristic impedance of 50 ohms, the phase velocity calculated in question 1. Your design consists of the distance of the stub from the load, and the length of the stub. Note that there are two possible designs.
3. Model your stub design with the TRLINE program, and find the bandwidth for a return loss better than 20 dB, for both designs. Plot the return loss as a function of frequency. Choose the design which has the larger bandwidth.

4. Procedure in the Laboratory

This experiment has two parts. In Part 1, you measure the admittance of the waveguide irises, and "match" an unknown load with a sliding-screw matching device. Use bench 1, which has the polar display for part 1. In Part 2, you design a stub tuner and install and test it on a microstrip board. Use bench 2, which has the rectangular display. You only need the NA for a few minutes for each measurement, so if needed the two lab groups can share the use of the NA which is set up for the microstrip measurements.

Setting up the Sweeper

The HP8350B sweeper has many controls and settings. To start, press the green button to "reset to defaults" so that the instrument is in a known state. For the iris measurement, set the sweeper with a starting frequency of 10.3 GHz, and a stopping frequency of 10.7 GHz. This includes the three frequencies of 10.4, 10.5 and 10.6 GHz used for the waveguide iris measurements in Experiment 3. For the microstrip measurement, set the sweeper with a starting frequency of 2 GHz, and a stopping frequency of 4 GHz. Keep the output power level on the sweeper low, but high enough that the HP8410 reference-channel level meter is in the "operate" range. *Do not exceed an output power of 6 dBm.*

You can set the sweep rate on the HP8350B sweeper by pressing the "time" key which is at the bottom of the middle of the sweeper in the set of three keys labeled "SWEEP". The "FREQUENCY/TIME" display should read 0.025 sec, which is the fastest sweep time. With this setting the sweeper ramps up the frequency from 2 to 4 GHz in 0.025 seconds. But this may be too fast for the HP8410 to track, and so the display may be unstable or "jumpy". You can slow down the sweep rate by pressing the "time" key and turning the knob under the FREQUENCY/TIME display. A relatively slow rate such as 1 sec makes the 8410 quite stable.

Operating the Network Analyzer

To use the HP8410 network analyzer to measure the reflection coefficient of an unknown load, proceed as follows. Check the settings on the network analyzer. Make sure that the network analyzer's frequency range knob is set to the appropriate frequency range, "8-16 GHz" for the iris measurement and "2-4 GHz" for the microstrip measurement. Set the source switch to "normal". Make sure the sweeper's power output is high enough that the reference-channel level meter is in

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[8] Pozar Section 3.8 and equations 3.195, 3.196 and 3.197.

[9] Pozar equation 3.193.

[10] C.W. Trueman, ELEC453 Lecture Notes, Set 11

the “operate” range. If the NA’s display is jumpy, adjust the red stability knob, or slow down the sweep rate of the sweeper, until the display looks steady. With a slow sweep rate, the CW setting on the red stability knob works well.

Make sure that the HP8743B reflection/transmission test set is set for “reflection”. The reflection/transmission test set has an “advanced precision connector” or “APC” connector. To use the network analyzer with X-band waveguide components, and APC-7 to N male adapter is mounted, followed with an HP X281A coaxial to waveguide transition. To calibrate the network analyzer, establish the location of the “reference plane” with a short circuit on the “unknown” port. For the iris measurement use a coaxial-to-waveguide transition, Fig. 4.7, and the shorting plate. For the microstrip measurement, use a female-to-female adapter plus a male short-circuit load, as shown in Fig. 4.14. Then adjust the test channel gain on the 8410 network analyzer so that $|\Gamma| = 1$. Then adjust the line stretcher on the reflection/ transmission test set by turning the crank until the phase of the reflection coefficient is ± 180 degrees. You are ready to measure an unknown load. Connect it to the measurement port and the network analyzer’s display shows the reflection coefficient as a function of the frequency.

Figure 4.7 Coax to waveguide transition on the NA reflection test port.

Fig. 4.8 The HP8414 polar display.

4.1 Iris Admittance Measurement

Use bench 1, which has the HP83592A X-band RF plug in for the sweeper and the HP8414B polar display installed in the HP8410 network analyzer. Fig. 4.7 shows the unknown port of the reflection/transmission test set, with a coaxial-to-waveguide transition installed. The NA is calibrated by mounting the shorting plate and adjusting the line stretcher to establish the location of the measurement plane. Then an iris is mounted, backed by the matched load, and the reflection coefficient is measured.

The polar display, Fig. 4.8, shows the reflection coefficient $\Gamma = |\Gamma| \angle \theta$ on polar axes. The polar display shows the complex-Γ plane, so the horizontal axis is the real part of Γ, and the vertical axis is the imaginary part of Γ. The center of the display is $|\Gamma|$=0. The distance from the center is the magnitude of the reflection coefficient, $|\Gamma|$, and the outer circle is $|\Gamma| = 1$. Figure 4.8 shows the reflection coefficient for a load as a function of frequency. As the frequency changes, the polar display's trace shows the variation of the reflection coefficient with frequency. In Fig. 4.8, the reflection coefficient lies approximately on the negative real axis, and varies from $\Gamma \approx -0.75$ to $\Gamma \approx -1$.

Calibration

With the sweeper set for 10.3 to 10.7 GHz, mount the shorting plate on the coax-to-waveguide transition. To set up the polar display, press the beam finder, and adjust the "horiz pos" and "vert pos" centering controls to put the beam at the center of the polar display, as nearly as possible. Adjust the 8410 test channel gain control and the amplitude vernier so that the trace is at $|\Gamma| = 1$, that is, on the outer circle of the polar display. You will see an arc on the $|\Gamma| = 1$ circle. Then adjust the line stretcher by turning the crank. As you turn the crank, the arc gets shorter and moves towards the $\Gamma = -1$ point. When you see a spot at $\Gamma = -1$, as shown in Fig. 4.8, the NA is calibrated and ready for reflection coefficient measurement.

Measuring the Reflection Coefficient

Remove the shorting plate, and mount an iris backed by the matched load. The HP8410 automatically measures the reflection coefficient as a function of frequency and shows the result on the polar display. You can get a paper copy of the display, and a data file of your measurement on your diskette by following the instructions in Section 5.

4.1.1 Iris Measurement

Calibrate the NA with the shorting plate. Use the lab computer[11] to to make a *paper copy* of your calibration display, and *save the corresponding "dat" file to your diskette*. Label the paper copy with the name of the "dat" file. You will need the "dat" file for your lab report, so record the name of the "dat" file in Table 4.1.

Mount the waveguide matched load on the measurement port. The NA measures the reflection coefficient and shows it on the polar display. Make a paper copy of the polar display, and label it with the name of copy the corresponding "dat" file on your diskette. Record the name of the "dat" file in Table 4.1.

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[11] Follow the instructions in Section 5, below.

Then mount iris A, backed by the matched load, on the measurement port. Make a paper copy of the polar display, and label it with the name of copy the corresponding “dat” file on your diskette. Record the name of the “dat” file in Table 4.1. Repeat for iris B, iris C and iris D.

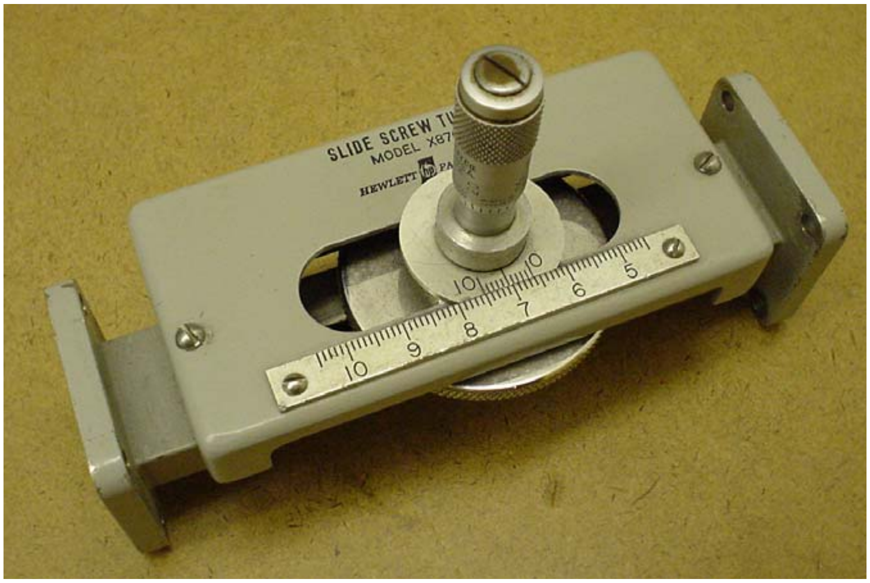

Figure 4.9 The slide screw tuner.

4.1.2 Slide Screw Tuner

The slide screw tuner of Fig. 4.9 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 the micrometer is set to zero, the post is all the way in. When it is 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 a shunt inductance. The slide screw tuner behaves the same way as a single-stub tuner. Let Y_1 be the input admittance of waveguide from the post to the load terminated by the load. Choose the distance of the post from the load to make the real part of Y_1 equal to the wave admittance. The post itself behaves as a susceptance connected across the wave guide, in parallel with Y_1. By adjusting the depth of the post, we can obtain a range of susceptance values and so “tune out” the imaginary part of Y_1. Then the input admittance of the post in parallel with Y_1 is a “match” to the wave admittance of the guide.

In industry, tuning screws are often used to match a load to a waveguide. A tuning screw behaves like the post in the slide screw tuner. To “design” the tuning screw we must determine the distance that the tuning screw must be from the load, and the depth of the screw. The position of the screw is sometimes found with a small cylindrical magnet on the inside of the guide, held in place by a larger magnet on the outside. Slide the magnet along the outside of the guide and it drags the cylindrical magnet inside the guide with it. By observing the return loss on a network analyzer, we can slide the magnet along until the RL shows the best match. Then we drill a hole for a tuning screw, tap the hole, insert a tuning screw and adjust its depth to get the best possible match.

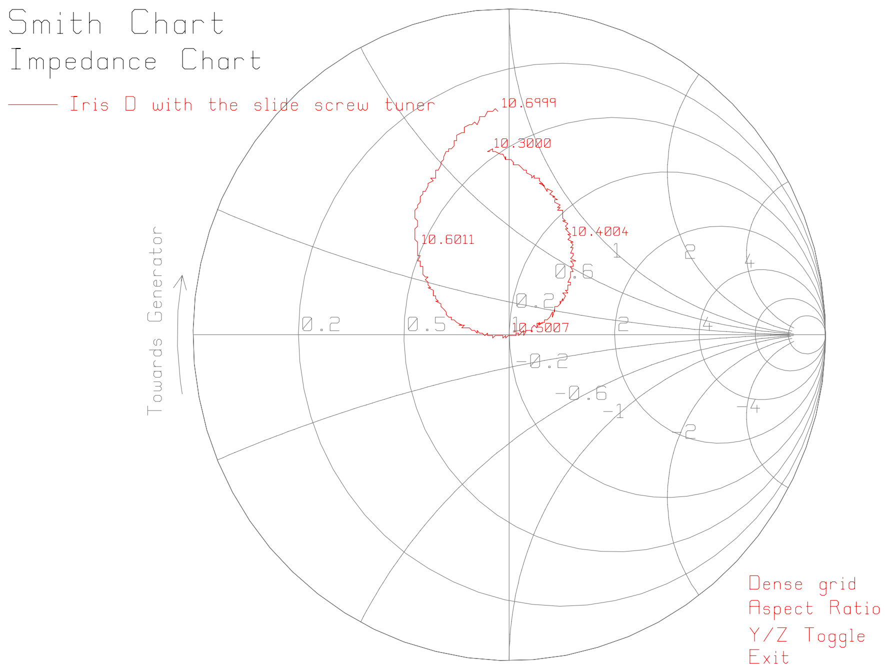

Fig. 4.10 The reflection coefficient of iris D, tuned with the slide-screw tuner.

We can use the slide-screw tuner to gain some experience with tuning in the context of waveguide components. Mount the slide screw tuner on the coax-to-waveguide port of the NA, and then attach iris D backed with the matched load. The reflection coefficient for iris D is large. Adjust the slide screw tuner by trial and error. Move the slide screw nearer and farther from the load, to get the best RL. Then adjust the depth to try to get a perfect match, at 10.5 GHz, as shown in Fig. 4.10. Move the position of the slide screw a little farther from the load, or a little closer to the load, and then adjust the depth of the screw once again. This sounds challenging but is actually quite easy to get an excellent match. Record the distance from the post to the iris and the depth of the post. Use the lab computer to make a "dat" file of the polar display. Make a paper copy of the polar display, save the "dat" file to your diskette, and write the name of the "dat" file in Table 4.2.

4.2 Microstrip Single-Stub Tuner

In this part of the experiment, you will design a single-stub matching circuit for a microstrip line, and use the HP8410 network analyzer to measure the reflection coefficient. Use bench 2, which has the HP83540B RF plug for 2 to 8 GHz in for the sweeper and the HP8412A rectangular display installed in the network analyzer and shown in Fig. 4.1(b). Set the sweeper with a starting frequency of 2 GHz, and a stopping frequency of 4 GHz. You will design the matching circuit for a good impedance match at 3 GHz.

The HP8412A rectangular display, Fig. 4.1(b), shows either the magnitude (in dB) or the phase of the reflection coefficient as a function of frequency, over the frequency range of the sweeper. The magnitude and angle can also be shown together.

Fig. 4.11 The SMA short circuit on the “unknown” port.

Calibration

Set up the sweeper with a start frequency of 2 GHz and a stop frequency of 4 GHz. *Do not exceed an output power of 6 dBm*

An APC to SMA “male” adapter is installed on the APC connector of the HP8743B reflection/transmission test. The APC to SMA adapter has a “male” connector and the SMA short circuit is also “male”, so they must be joined with a “female” to “female” adapter, which is sometimes called a “bullet”. Calibrate the network analyzer to establish the location of the “reference plane”, using a short-circuit load made of a “bullet” and an SMA short circuit, shown in Fig. 4.11, as follows.

SMA connectors should be “finger tight”. Gently turn the nut on the connector until it is barely tight. Never use a wrench! If you over-tighten the connector you will pull the center conductor out of the APC-to-SMA adapter on the instrument, and you will not obtain reliable results.

Set the rectangular display to show “magnitude” with 10 dB per division. Adjust the amplitude offset controls so that 0 dB is at the top of the screen; -40 dB is across the center of the screen, and -80 dB is at the bottom of the screen. The “hp8412” software on the lab computer assumes that the screen is set up this way. Since the short circuit has a reflection coefficient of $\Gamma = -1 \; = 1\angle \pm 180^\circ$, the reflection coefficient is $20\log|\Gamma| = 0$ dB. Adjust the test channel gain and amplitude vernier to obtain a horizontal line across the center of the screen, which is the 0 dB level.

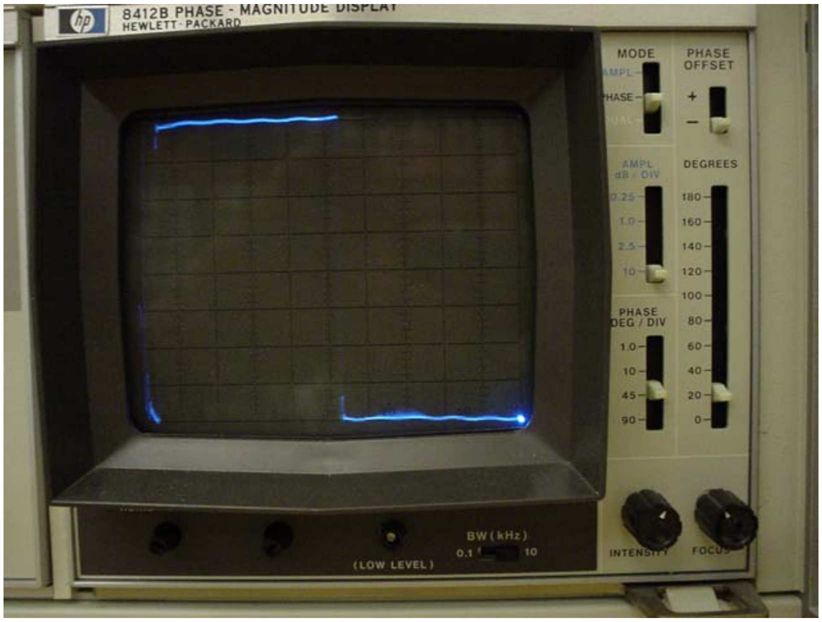

Fig. 4.12 The network analyzer is calibrated by adjusting the line stretcher and the phase offset until the phase of the reflection coefficient for the short circuit switches back and forth between -180 and +180 degrees.

Now switch the display to "phase" with 45 degrees per division. The crank on the reflection/transmission test set adjusts the length of the "line stretcher" and is used to compensate for the path length difference between the test channel and the reference channel. Since the load is a short circuit, the phase should be $+180°$ or $-180°$. Adjust the line stretcher (use the crank on the reflection/transmission test set) and adjust the phase offset slider switch to the right of the screen until the phase curve is flat as shown in Fig. 4.12. Make minor adjustments to the crank and to the phase vernier knob to the left of the screen so that the display jumps back and forth between $+180°$ and $-180°$ and looks a bit like a square wave. If you have problems with the calibration, call the instructor to help you. Re-check the amplitude and re-set it to zero dB if needed.

To measure the reflection coefficient of the microstrip circuit, remove the bullet and the SMA short, and mount the circuit on the "unknown" port. The sweeper continuously sweeps from 2 to 4 GHz, so the display automatically shows the reflection coefficient across this frequency range.

4.2.1 Confidence Checks

Calibrate the NA with the bullet and short-circuit load as described above. Use the lab computer[12] to make a paper copy of your calibration display, and save the corresponding "dat" file to your diskette. Label the paper copy with the name of the "dat" file. You will need the "dat" file for your lab report, so record the name of the "dat" file in Table 4.3.

Testing some loads with known reflection coefficients gives you confidence that your measurement setup is working correctly. An open circuit with the same electrical length as the short circuit is obtained by using the bullet alone. An SMA 50 Ω matched load is also available. It looks almost the same as the SMA short circuit, but looking inside, the short circuit is gold plated, whereas the 50 Ω load is Teflon.

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[12] Follow the instructions in Section 5, below.

Remove the short circuit load from the end of the "bullet" or female-to-female adapter. Leave the bullet itself connected to the network analyzer so that the "open circuit" at the end if the bullet is at the same location as the "short circuit". Since $|\Gamma| = +1$, the reflection coefficient should read 0 dB and the phase should be zero degrees. Use the lab computer to make a "dat" file and a paper copy of the display, and record the name of the "dat" file in Table 4.3.

A matched load provides a second confidence check. Replace the open circuit with a 50 Ω load. Since $\Gamma \approx 0$, the return loss should be 40 dB or better, i.e., the reflection coefficient should be less than -40 dB. The phase can be any value and is not important. Note that the reflection coefficient will not be exactly zero because the connectors themselves are imperfect. Make a "dat" file and a paper copy, and record the name of the "dat" file in Table 4.3.

4.2.2 Microstrip Transmission Line with an Unknown Load Resistor

The lab demonstrator will give you a circuit board with an SMA edge connector and a 50-Ω microstrip line terminated with an unknown resistor. You have calibrated the NA using the SMA "bullet" and short-circuit termination and this puts the reference plane at the input to the microstrip line. Figure 4.5 shows the microstrip line installed on the "unknown" port of the HP8743B S-parameter test set.

SMA connectors should be "finger tight". Gently turn the nut on the connector until it is barely tight. Hold the circuit board in your left hand and turn the nut gently with the fingers of your right hand. *Never turn the circuit board.*

Measure the reflection coefficient of the microstrip line and chip resistor termination from 2.000 to 4.000 GHz. Use the computer to make a paper copy and a "dat" file, and record the name of the "dat" file in Table 4.4.

Now change the location of the reference plane to the position of the load. Use a small piece of copper tape to short out the load resistor, and then re-adjust the line stretcher until the phase is flat and alternates between +180 and -180 degrees, as described above. Make a paper copy and a "dat" file, and record the name in Table 4.4. Then peel back the copper tape so that it does not short out the resistor, and measure the reflection coefficient. Again, make a paper copy and a "dat" file and record the file name in Table 4.4.

Use your measurement of the reflection coefficient "at the load" to find the value of the load impedance terminating your microstrip line. Use the electronic calipers to measure the length of the microstrip line.

4.2.3 Single-Stub Matching Circuit

Using your measured value for the load impedance on your board at 3 GHz, design a single-stub matching circuit, with a center frequency of 3 GHz. Determine the distance from the load to the centerline of the matching stub and the length of the matching stub. Use a Smith Chart for your design. Note that there are two possible designs, and the one with the wider bandwidth is preferred. You can use the TRLINE[13] program on the lab computer to verify that your design works and to determine the bandwidth associated with each design. Think about the geometrical layout and make a drawing of the microstrip line and stub showing all the dimensions. The length of the stub is measured from the open circuit end to the centerline of the main transmission line.

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[13] TRLINE defines "return loss" as $20\log|\Gamma|$, which is not the customary definition!

You will make an open-circuit shunt stub by cutting a piece of 3M 1183 copper tape[14]. Cut the width to 0.030 inch using an X-acto knife. The tape has a conducting adhesive, so sticking it on the main transmission line ensures a proper connection. To make a good connection between the microstrip line and the stub, the tape needs to completely overlap with the main microstrip line. Make the stub a bit longer than the length you found in your design. This allows you to adjust the length by cutting the stub back, to improve the "match". Install your stub in the correct position on the microstrip line. Use the electronic caliper to measure the position and make sure that the stub is the correct distance from the load.

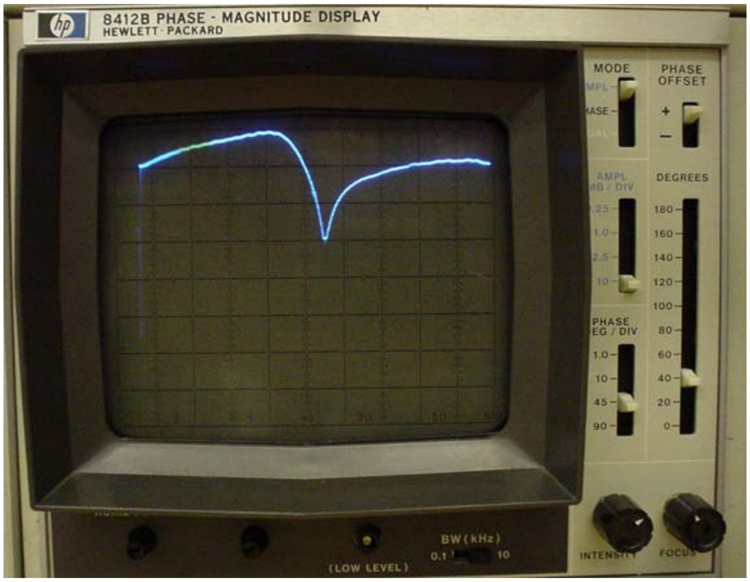

Fig. 4.13 The HP8412A rectangular display.

Re-calibrate the network analyzer by connecting the "bullet" and short-circuit load to the measurement port, and adjust the line stretcher as you did previously. Make a paper copy of the display and a "dat" file, and record the name of the "dat" file in Table 4.5. Then replace the short circuit with the microstrip line with the matching stub installed. Your stub should be too long for the best-possible match. Adjust the length of the stub by shortening it slightly with the X-acto knife (you must remove the stub to cut it or you will damage the circuit board!). For each length, make a "dat" file with the lab computer. Measure each length with the electronic calipers. Record the stub lengths and the names of the "dat" files in Table 4.4. Fig. 4.13 shows the magnitude of the reflection coefficient after the stub length has been adjusts. The vertical axis runs from -80 dB at the bottom of the CRT to 0 dB at the top. The single-stub matching circuit provides a match with a maximum return loss of about 30 dB, but not well centered on 3 GHz.

If you make the stub too short, the match is spoiled! Try several different lengths and record the lengths and the "dat" file names in Table 4.4. Table 4.5 has space for up to five different lengths, but you may not need to try this many.

You will need to re-install the stub on the microstrip in experiment 5 so carefully save the small piece of copper tape that you used to make the stub.

5. Using the Linux Computer

The lab's Linux computer controls the frequency sweepers using a GPIB card in the computer and a GPIB cable to the sweepers. The HP8410 network analyzers provide analog

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[14] For more information on the 3M tape, go to www.3m.com

outputs on BNC connectors on the rear panel of the instrument. One analog output is proportional to magnitude of the response, another to the phase of the response. The analog outputs are connected with BNC cables to a voltage-divider card, and the card's output to an ICS Advent ML16-P analog-to-digital conversion card in the lab's Linux computer. With this setup the computer can record the magnitude and phase of the reflection coefficient measured by the network analyzer, as a function of frequency. Then the data can be written to a diskette for display with the SMTHCHT program.

You can get a "dat" file corresponding to the HP8410 network analyzer's display using the lab's Linux computer. You can also make a paper copy of the NA's display. Follow these instructions:

1. Log in to the computer with user name "Maxwell" and no password.
2. Type "startx".
3. Then type "hp8414 1" to get data from "bench 1", which has the HP8414 polar display, or "hp8412 2" to get data from "bench 2", which uses the HP8412 rectangular display.
4. Type "mcopy –t hp8412.dat a:/filename.dat" to copy the data to your diskette. Don't forget the "-t" switch, which fixes the ends of the lines in the data file so that they can be read on a Windows computer.
5. Record the file name for the data file in one of the tables in Section 6.

The computer obtains the data as follows. The magnitude data and phase data is available as analog voltages on BNC connectors on the back of the HP8412 rectangular display plug-in unit or the HP8414 polar display. Coaxial cables bring these voltages to an eight-channel analog-to-digital (A/D) converter in the computer. A voltage-divider circuit is used to change the voltage levels to be compatible with the ± 128-mV range used by the computer's A/D conversion card. The computer controls the sweeper via the GPIB bus. The computer triggers the sweeper, and then records the magnitude and phase at each frequency.

6. Simulation with ADS

The TRLINE program simulates a microstrip circuits assuming that the microstrip behaves as an "ideal" transmission line of know characteristic impedance and phase velocity. A more sophisticated is available from the computer-aided design (CAD) package called the HP Advanced Design System (ADS), with the "Momentum" utility, which simulates planar structures such as the microstrip transmission line. ADS uses the "method of moments" to rigorously solve for the surfaces currents that flow on the microstrip line, the branch, and on the ground plane. ADS can accurately calculate the behavior of bends and branches in microstrip transmission line structures. ADS calculates the current at the input of the circuit, and from the current finds the input impedance and reflection coefficient. The simulation is done at many frequencies to find the reflection coefficient as a function of frequency.

For your lab report, use ADS to predict the performance of your stub matcher, and compare the return loss[15] with your measured results. You can find instructions for running ADS in the file ADS_Instructions.pdf on the course web site.

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[15] The HP8410 measures $20\log|\Gamma|$, the magnitude of the reflection coefficient in dB, which is a negative number. "Return loss" is usually defined as $\mathrm{RL} = -20\log|\Gamma|$, which is a positive number.

7. Tables of Data

Student name:	
Student I.D.:	
Lab Section:	
Lab Instructor's Signature:	

Table 4.1
File Names for the Iris Measurements

Case	File Name
Calibration with the Shorting Plate	
Waveguide Matched Load	
Iris A	
Iris B	
Iris C	
Iris D	

Table 4.2
File Name for the Slide Screw Tuner Experiment with Iris D

Distance from the post to the iris=___________cm

Depth of the post=_____________cm

Case	File Name
Slide Screw Tuner	

Table 4.3
File Names for the Calibration and Confidence Checks

Case	File Name
Calibration with the Short Circuit Load	
Open Circuit	
Matched Load	

Table 4.4
File Names for the Microstrip Line Measurements

Length of the microstrip line = ________ mm

Case	File Name
Reflection Coefficient at the Input	
Calibration with a short circuit at the load	
Reflection Coefficient at the Load	

Table 4.5
File Names for the Microstrip Line Stub Matching Measurements
Spacing of the tuning stub from the load = __________ mm

Case	File Name
Calibration with a Short Circuit	
Stub length = mm	
Stub length = mm	
Stub length = mm	
Stub length = mm	
Stub length = mm	

8. Questions to Answer in your Lab Report

Your lab report must include a signed “Expectations of Originality” form.

Your lab report must include the tables from Section 7, filled in with your data, and “signed off” by your lab demonstrator at the end of the lab session.

Your lab report will consist of the answers to the following questions:

1) Plot your calibration curve with the shorting plate on a Smith Chart[16]. Comment on the accuracy of the calibration. We expect the reflection coefficient to be $\Gamma = -1$ across the whole frequency range. What is the minimum and maximum $|\Gamma|$ in your calibration? The angle of Γ should be 180 degrees. What is range over which the angle of Γ varies in your calibration?
2) Plot the admittance of each of the four irises, backed by a matched load, as a function of frequency on a Smith Chart (4 separate graphs). In Lab #3, you measured the admittance of each iris-plus-matched-load at 10.4, 10.5 and 10.6 GHz. Include these three points on your Smith Chart plot for each iris. Does the reflectometer measurement from Lab #3 agree with your network analyzer measurement?
3) Plot the reflection coefficient for iris-D-plus-matched-load and for iris D “matched” with the slide screw tuner on a Smith Chart. What is the “return loss” at 10.5 GHz? What is the bandwidth over which the return loss is better than 20 dB?
4) Consider the calibration of the network analyzer with the SMA bullet and short-circuit load. Plot the calibration curve on a Smith Chart. Consider the accuracy of the calibration as you did in question 1 above. What is the range of $|\Gamma|$? What is the range of the angle of Γ?
5) Plot the reflection coefficient from the open circuit load and from the matched load on a Smith Chart. For the open circuit, we expect $|\Gamma| = 1$ and $\angle\Gamma = 0$ degrees. For the matched load we expect $|\Gamma| = 0$. For each, what is the range of $|\Gamma|$? What is the range of the angle of Γ? For the matched load, plot the load impedance as a function of frequency on

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[16] Use the SMTHCHT program with the data file you made in the lab.

rectangular axes[17]. How much does the impedance of the matched load differ from $Z = 50 + j0$ ohms?

6) In part 4.2.2, you calibrated the network analyzer with the “reference plane” at the load resistor. Plot a Smith Chart showing the reflection coefficient of the load resistor from 2 to 4 GHz. What is the value of the load impedance that you measured, at 3 GHz? How did you obtain it from the graph?
7) In part 4.2.2, you calibrated the network analyzer with the “reference plane” at the input of the transmission line, and you measured the reflection coefficient of the microstrip line plus the load. Use the TRLINE program to simulate the microstrip line and load resistor, using your measured value for the length of the transmission line and the load resistor. Make a Smith Chart comparing the measured reflection coefficient from 2 to 4 GHz with the reflection coefficient calculated with TRLINE.
8) Make a drawing of the microstrip line and your design for the stub matcher, giving all the dimensions. Use the length of the stub that gave the best return loss in Part 4.2.3. Simulate the microstrip line and the single-stub matcher with TRLINE. Make a Smith Chart comparing the TRLINE simulation with your measured reflection coefficient.
9) Use the ADS/Momentum program to model the microstrip line and the stub matching circuit. Section 6 above gives some information about ADS and Momentum. Use Momentum to make a “gam” file by following the “Conversion Procedure” at the end of the instructions found at ADS_Instructions.pdf on the course web site. Then you can plot the ADS simulation with the SMTHCHT program, and plot your measured data on the same axes. The ADS simulation and the TRLINE simulation should agree well with each other, and both should agree with the measured reflection coefficient!
10) What is the bandwidth of your stub matcher for a return loss of better than 20 dB? Use your measured data to answer this question.
11) In Experiment 2, we used the measured reflection coefficient for the short circuit load as a correction for the vector voltmeter measurement. The “calibration” graphs of question 1 and question 4 above show that the short circuit load does NOT have a reflection coefficient of $\Gamma = 1\angle 0^\circ$ over the whole frequency range for each measurement. How can the measured reflection coefficient for the short circuit be used to “correct” the measured reflection coefficient for an unknown load? Modern, microprocessor-controlled network analyzers save the “calibration curve” for the short circuit and then “subtract” it from the measured curve for the unknown load. This is called “Response Calibration” and is the *least* accurate calibration procedure for an NA. In experiment 5, you will see “S_{11}” calibration using three standards: a broadband matched load, a short circuit and an open circuit. The procedure is related to that described in Pozar. For expert users: write a short program in C++ or matlab, which reads the data file for the short-circuit calibration, reads the data file for the unknown load, corrects the reflection coefficient data, and then writes a new data file of the corrected load reflection coefficient at each frequency. Then make a Smith Chart comparing the “uncorrected” impedance with the corrected data.

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[17] Note that SMTHCHT makes this easy: the F9 function key creates an impedance vs. frequency file with can be graphed with RPLOT.