

ELEC 456/6341 Antenna Experiments

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Background

During 2009-2017 I created the following five experiments for the course Antennas ELEC 456/6341 at Concordia University.

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Contents

1	Antenna Impedance	1
1.1	Equipment	1
1.2	Impedance Measurement	1
1.3	Printing	2
1.4	Transmission Line	2
1.5	Antenna	3
1.6	Questions	3
2	Monopole Antennas	5
2.1	Equipment	5
2.2	Theory	5
2.3	Calibration	6
2.4	Antenna Impedance	6
2.5	Friis Experiment	6
2.6	Questions	7
2.7	Feko Hints	8
3	Antenna Resonance	9
3.1	Equipment	9
3.2	Objectives	9
3.3	Monopoles	9
3.4	Loop	10
3.5	Questions	10
4	Aperture Antennas	12
4.1	Equipment	12
4.2	Objectives	12
4.3	Theory	12
4.4	Gain Measurement	13
4.5	Waveguide Beamwidth	14

4.6	Horns, Beamwidth	14
4.7	Probe Feed	14
4.8	Questions	14
5	Microstrip Antenna	16
5.1	Equipment	16
5.2	Objectives	16
5.3	Design Equations	17
5.4	Impedance	18
5.5	Gain Testing	18
5.6	Simulation	18
5.7	Questions	19
A	Impedance Measurement	22
A.1	Background	22
A.2	Equipment	22
A.3	The Need for Calibration	23
A.4	Calibration Procedure	23
A.5	The Display	24
A.6	Measurement	25
A.7	Reference Plane	25
A.8	Reporting	26
A.9	2-Port Measurements	26

Lab #1 Antenna Impedance

1.1 Equipment

- Anritsu MS46122A vector network analyzer
- PC and Anritsu driver software
- Two bullets (SMA female-female), one SMA female-female cable
- Female SMA bulkhead connector, calipers, wire, solder
- Numerical Modelling: Feko Code, Version 6.1 or later.
- You bring: ruler, wire cutters, pliers, two Smith charts, camera, memory stick.

1.2 Impedance Measurement

An important part of this course is knowing how to measure impedance. Before doing anything with an antenna, study Appendix A. Learn how to measure the impedance of a short circuit, using the Anritsu network analyzer. This knowledge is an essential prerequisite for this and other labs during the term. You must learn the precise purpose of its settings. Try each one out and see its effect.

- Freq
- Calibration
- Trace
- Display
- Reference Plane: Distance, Phase Offset

Set the sweep for 2.5-3.5 GHz. Make a short-circuited SMA bulkhead jack, using a small piece of wire; use a small amount of solder. Adjust the VNA to get the proper display of $\Gamma = 1/180^\circ$. The reference plane distance is to be adjusted, not the phase.

1.3 Printing

When printing out results, use the required format, which is at (1) *File; Print Setup; 4-Trace Graphical*. Then press *Print*. Your printout should show the date, time, instrument settings, and a plot of Γ . The lab demonstrator should sign your printouts before you leave. Each group member needs to make their own printout for their report.

1.4 Transmission Line

Having performed the calibration, proceed with the following.

Desolder your short circuit. Using the same SMA jack and some wire, make a two-wire transmission line that is about $\lambda/4$ long at 3.1 GHz. Measure the wire diameter, length, and wire spacing.

Measure the reflection coefficient. Print the result.

The curves on the printout are not always so legible. Before leaving the lab, use a pen to highlight the data on the printouts, and annotate any key points on the curves. Use a marker to identify and write down a few values of Γ at specific frequencies in between 2.5-3.5 GHz.

Later, you will calculate Γ . This is an open-circuit stub, with an impedance of

$$Z = -jZ_0 \cot(\beta\ell)$$

where $\beta = 2\pi/\lambda$. It is handy to note that if the wavelength is in centimeters and the frequency is in GHz, then in free space,

$$30 = \lambda \times f.$$

The characteristic impedance of a two-wire line is¹

$$Z_0 = \sqrt{\frac{\mu}{\epsilon}} \frac{1}{\pi} \cosh^{-1} \frac{D}{2a}$$

where D is the wire spacing and $2a$ is the wire diameter.

¹See for example K. Demarest, *Engineering Electromagnetics*. Prentice Hall, 1997.

The network analyzer is a 50Ω system so the relation between measured Γ and impedance is

$$Z = 50 \frac{1 + \Gamma}{1 - \Gamma}.$$

1.5 Antenna

Take your transmission line, and bend the wires out so that it looks like a dipole. Measure the physical dimensions.

As before, measure the reflection coefficient. Print the result. Using a marker, write down a few values of Γ at specific frequencies in between 2.5-3.5 GHz.

1.6 Questions

Your group is required to collect the experimental data. Individually, you write up and submit answers to these questions, and provide your own lab printouts. This is not a lab report. Hand in your work at the beginning of your next lab, in two weeks. It will be marked like homework.

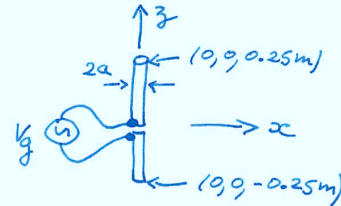
1. Use the Feko code to calculate the transmission-line impedance as a function of frequency, $Z(f)$. Also show the polar version $\Gamma(f)$, on a Smith chart.
2. Based on the above data, what is Z_0 for the transmission line? What value is expected from the simple analytic formula?
3. Use the Feko code to calculate the antenna impedance as a function of frequency, $Z(f)$. Also show the polar version $\Gamma(f)$, on a Smith chart.
4. You and your group are to write your ID numbers and sign the work, with the pledge: "We certify that this submission is the original work of the group and meets the Faculty's Expectations of Originality."

Appendix

Documentation for Feko can be found at
<http://users.encs.concordia.ca/~paknys/elec456.html>

Feko Model of Dipole

$f = 300 \text{ MHz}$
length = 0.5 m
diameter $2a = 1 \text{ mm}$
conductivity = ∞
 $V_g = 1 \text{ V}$



Cad feko:

Construct \rightarrow Line

Click on Model Tree \rightarrow Model \rightarrow Line 1

Click on Details Tree; Right click Wire 1 \rightarrow create port
Wire port

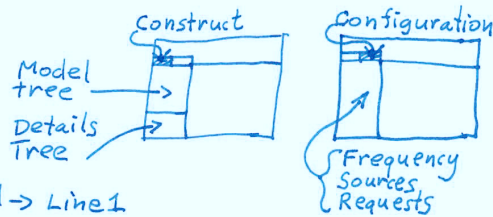
Model Tree \rightarrow Freq. 300 MHz

Source/Load \rightarrow Voltage Source 1 V

Request \rightarrow Far fields, currents

Mesh \rightarrow create Mesh \rightarrow Wire radius $a = 0.0005$
(global)

Solve/Run \rightarrow Feko Solver



Post feko:

Home \rightarrow cartesian \rightarrow Far field, currents

Home \rightarrow out file to see .out data

To get a frequency plot, set the frequencies in cad feko. Delete the Far Field and Current requests.

In post feko, ask for Home \rightarrow Smith.

Use Measure \rightarrow Cursors to see the freq. and Γ values.

Lab #2 Monopole Antennas

2.1 Equipment

- Anritsu MS46122A vector network analyzer
- PC and Anritsu driver software
- SMA female-female bullet, male short circuit, male 50Ω
- Two SMA cables, approx. 12", two antenna supports
- Two monopoles: 3"x3" ground planes with SMA connectors
- 1" copper tape, calipers, wire, solder
- You bring: ruler, wire cutters, pliers, Smith charts, camera

2.2 Theory

In this experiment we will measure the impedance and gain of a $\lambda/4$ monopole antenna. Monopoles have an advantage over dipoles because they are easy to feed with a coaxial cable.

A half-wave dipole has $Z \approx 73 + j42\Omega$. It's a common trick to make a dipole slightly shorter than $\lambda/4$. This makes its impedance drop to $Z \approx 70 + j0\Omega$. Since $X = 0$ it is now said to be "resonant." Getting rid of the reactive part is good because it simplifies impedance matching to 50Ω .

Image theory states that a $\lambda/4$ monopole has an impedance that is half of the $\lambda/2$ dipole's impedance, so $Z \approx \frac{1}{2}(73 + j42)\Omega$.

The gain of a $\lambda/4$ monopole is double that of the dipole, so $G = 2 \times 1.64$ or 5.15 dB.

The doubling of gain only happens in the ideal case, with an infinite ground plane. In practice we have a finite ground plane. As a result, the gain is much smaller.

2.3 Calibration

First, read the notes “Impedance Measurement” with a focus on the 2-port procedure.

Set the sweep for 3-4 GHz. Calibrate the network analyzer for 2-port reflection measurement. Use two cables. Use short/open/load on port 1, short/open/load on port 2, then a “thru” between ports 1 and 2 with a female-female bullet connecting the two cables. We can now measure the forward-power transmission coefficient which is

$$\frac{P_2^-}{P_1^+} = |S_{21}|^2 = |T|^2$$

where P_2^- comes out of port 2 and P_1^+ goes into port 1 of the 2-port device under test.

2.4 Antenna Impedance

Make a short circuit with an SMA connector and conducting tape. Connect it to the port. Add corrections for the reference plane. The result should show $\angle \Gamma = \pm 180^\circ$.

Make a monopole that is $\lambda/4$ at 3.6 GHz. Write down the wire diameter and length. Measure the impedance for 3-4 GHz and print the result in the Smith chart format.

Use markers to identify the resonant frequency. It should be near 3.6 GHz. Resonance occurs when the antenna reactance is zero. This happens when $\angle \Gamma = \pm 180^\circ$ or $\angle \Gamma = 0^\circ$.

2.5 Friis Experiment

For the transmission $T = |S_{21}|$ make a note where the 0 dB level is. In this experiment we do not care about the phase, so reference plane compensation for the phase of S_{21} is unnecessary.

Make a second monopole with the same size as the first one. Put the two antennas on the supports, remove the bullet, and connect the antennas to the cables. Calculate the minimum distance such that the three far-field criteria $r > 1.6\lambda$, $r > 5D$, $r > 2D^2/\lambda$ are satisfied. Make sure that your antennas are not too close together. Record T at 3.6 GHz for several values of antenna spacing. You will have to plot it later on.

From the Friis formula we know that conjugate-matched antennas obey

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

Since the antennas are not matched to the 50Ω network analyzer,

$$|S_{21}|^2 = \left(\frac{\lambda}{4\pi r} \right)^2 \underbrace{G_t(1 - |\Gamma_a|^2)}_{G_t^r} \underbrace{G_r(1 - |\Gamma_a|^2)}_{G_r^r}$$

where G_t^r and G_r^r are called the “realized gain” and account for the mismatch. The antenna impedance Z_a can be used to obtain $\Gamma_a = (Z_a - 50)/(Z_a + 50)$. Since $G_t = G_r$ you can use S_{21} to find the gain of the monopole antenna. (S_{21} is always the same and does not depend on the matching situation.)

You’ll notice that at larger distances, T varies with frequency. This is because of multipath propagation. Make a note of these variations for a small and a large distance. Also record the height of the ground plane above the table. By moving around your hand or other reflecting obstacle, try to identify “sensitive areas” that are associated with dips in the received power. Report their locations.

2.6 Questions

Your group is required to collect the experimental data. Individually, you write up and submit answers to these questions. It is not a lab report. Hand in your work at the beginning of your next lab, in two weeks. It will be marked like homework.

1. Plot your impedance data for the monopole on a Smith chart. Identify a few frequency points, and the resonant frequency. At resonance, how does this compare with the simple theory that $Z = (70 + j0)/2$ Ohms? Use Feko to calculate the input impedance vs. frequency, for the monopole on a finite ground plane. Compare with your measurement.
2. In a two-antenna link at 3.6 GHz, how much loss does the mismatch contribute?
3. For the 3.6 GHz monopole and 3x3 inch ground plane, use Feko to calculate G . Then use the Friis formula to plot the theoretical P_r/P_t in dB, vs. antenna spacing. The distance should be plotted on a

logarithmic scale. This will give a straight line with a drop of 6 dB per double distance.

4. Plot the measured P_r/P_t in dB, vs. antenna spacing. The distance should be plotted on a logarithmic scale. Compare with the above computed result. Using the measured P_r/P_t , obtain the gain.
5. Comment on the impact of multipath on your results (1/2 page or less). Can you identify any regions in space that contribute to multipath?
6. You and your group are to write your ID numbers and sign the work, with the pledge: “We certify that this submission is the original work of the group and meets the Faculty’s Expectations of Originality.”

2.7 Feko Hints

Make the plate with *Construct* \rightarrow *Rectangle*, and make the monopole with *Construct* \rightarrow *Line*. Then in the Menu Tree, select both the *Rectangle* and *Line* with Ctrl-left-click (they will turn blue). Then press *Construct* \rightarrow *Union*. This way the mesher will treat the wire and plate as one connected structure.

If you want to break a union, in the Model Tree, ctrl-left-click on the line and plate, listed below the Union, to select both. Then, right-click Copy gives a new line and plate. Then delete the old unioned line and plate.

Generally, you can right-click on items in the Model Tree and deactivate them with Include/Exclude. This is sometimes better than deleting them; you can re-use the items later on.

An infinite ground plane can be found under *Construct* \rightarrow *Planes/arrays*. The monopole should *not* be unioned to an infinite ground.

Lab #3 Antenna Resonance

3.1 Equipment

- Anritsu MS46122A vector network analyzer
- PC and Anritsu driver software
- Two 3x3" ground planes with SMA connectors
- Two SMA cables, approx. 12", two antenna supports
- SMA female-female adapter, a "bullet"
- 1" copper tape, calipers, wire, solder
- You bring: ruler, wire cutters, pliers, Smith charts, camera

3.2 Objectives

In this experiment we will measure the impedance of a top loaded monopole, a long monopole, folded monopole, and a resonant loop. The loop's radiation pattern will be considered.

3.3 Monopoles

Make a monopole that is $\lambda/4$ at 3.0 GHz. Then measure the impedance, for 2-4 GHz and print the result in the Smith chart format. Use markers to identify the resonant frequency, which occurs when the antenna reactance is zero.

Our goal now is to make the antenna less tall. Snip off a bit of the antenna and put a piece of conducting tape to make it top loaded. In general, top loading makes the resonant frequency go down. Adjust the top loading so that you get a resonance at about 3 GHz. Measure the dimensions of the

antenna structure. (It's a success if your antenna is less tall than the original $\lambda/4$ monopole.) Take a picture of the antenna and record the impedance.

Now, make a 10 cm long monopole. Measure the impedance from 2-4 GHz. Record the impedance and identify the resonant frequencies with markers. The impedance magnitude will be highest when the feedpoint current is lowest.

The folded monopole has four times the impedance of an ordinary monopole. The bandwidth is expected to be a bit more broad. Make a folded monopole that is $\lambda/4$ at 3 GHz. Make a note of the physical dimensions and record the impedance for 2-4 GHz. The foldover spacing is usually $O(\lambda/100)$ but the exact amount is not critical. Ground the end of the fold with copper tape and solder. You will know that your result is good if 4X impedance is achieved.

3.4 Loop

We want to make a 1λ resonant circular loop for 3 GHz. At resonance, $Z \approx 100 \Omega$ and $D \approx 3.5$ dB.

Construction is simplified by making a semicircular loop above a ground plane. Do this by putting a piece of copper tape on the ground plane, and soldering the free end of the wire to the tape. This will keep the ground plane clean for future users.

Record the impedance over 2-4 GHz; mark the resonant frequency.

Now make a monopole for 3 GHz. Narrow down the sweeper to a range of about 0.2 GHz. Using your monopole and loop, set up a Friis-type experiment. Rotate the loop in azimuth, and measure the effect on the received power. It will be a minor effect.

Assuming a vertical monopole transmitter, you are sending a vertical E field. The loop can receive a vertical E field, and by reorienting it, a horizontal E field.

3.5 Questions

Your group is required to collect the experimental data. Individually, you write up and submit answers to these questions. It is not a lab report. Hand in your work at the beginning of your next lab, in two weeks. It will be marked like homework.

1. What is the measured resonant frequency and impedance of your top-loaded monopole? What is the height? How does this compare to the

unloaded monopole?

2. What are the measured resonant frequencies of the long monopole? This is where the reflection coefficient has a phase of 0° or 180° .
3. What is the measured resonant frequency and impedance of your folded monopole?
4. What is the measured resonant frequency and impedance of your loop?
5. For the long monopole, folded monopole, and loop, use Feko to compute the resonant frequencies and input impedances. Compare with the experiment.

For impedance calculations you can use an infinite ground plane. This can be found under *Construct* \rightarrow *Planes/arrays*. The wire should *not* be unioned to an infinite ground.

For a loop, use *Construct* \rightarrow *Create arc* \rightarrow *Elliptic arc* to create the geometry.

6. What antenna orientations were needed in the experiment to obtain maximum power transfer between the monopole and the resonant loop? Make an annotated sketch of the azimuth pattern, highlighting the maximum and minimum points.
7. Use Feko to calculate and plot the directivity pattern of the 3 GHz resonant loop, in the horizontal plane.
8. You and your group are to write your ID numbers and sign the work, with the pledge: "We certify that this submission is the original work of the group and meets the Faculty's Expectations of Originality."

Lab #4 Aperture Antennas

4.1 Equipment

- Anritsu MS46122A vector network analyzer
- PC and Anritsu driver software
- Two different horn antennas
- SMA cables 2x, waveguide transitions 2x, waveguide stands 2x
- Waveguide elbows or short straight sections 2x
- SMA female-female adapter
- LabVolt antenna pattern measurement setup
- You bring: ruler, protractor, camera, memory stick

4.2 Objectives

In this experiment we will measure the characteristics of some aperture antennas at X band: an open ended waveguide, and two sizes of pyramidal horns. Take all of your measurements at a frequency of 10.5 GHz.

4.3 Theory

For a rectangular aperture in the xy plane, the radiation pattern in the xz plane only depends on the aperture characteristics along the x direction. The radiation pattern in the yz plane only depends on the aperture characteristics along the y direction.

For a rectangular aperture with linear dimensions L_x , L_y the directivity is

$$D = \frac{4\pi}{\lambda^2} \epsilon_{ap} L_x L_y. \quad (4.1)$$

Taper	HP(rad)	SLL(dB)	ϵ_t
constant	$0.866\lambda/L$	-13.3	1
cosine	$1.19\lambda/L$	-23.0	$8/\pi^2$

Table 4.1: Line source properties.

The aperture efficiency for an open-ended waveguide is $\epsilon_{ap} = 8/\pi^2$. For an optimum-gain horn antenna, $\epsilon_{ap} = 0.51$.

For an open-ended waveguide, the E and H plane patterns follow from the line source data, in Table 4.1.

Some simple yet useful formulas can be used to find D from the E-plane and H-plane half-power beamwidths θ_1 , θ_2 . Some common approximations are

$$D \approx \frac{4\pi}{\theta_1\theta_2} = \frac{41,253}{\theta_1^\circ \theta_2^\circ}; \quad \text{low gain, no sidelobes} \quad (4.2)$$

$$D \approx \frac{35,230}{\theta_1^\circ \theta_2^\circ}; \quad \text{open-ended waveguide} \quad (4.3)$$

$$D \approx \frac{26,000}{\theta_1^\circ \theta_2^\circ}; \quad \text{horn} \quad (4.4)$$

4.4 Gain Measurement

From the Friis formula we know that

$$|S_{21}|^2 = \frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r} \right)^2 G_t G_r. \quad (4.5)$$

Since $G_r = G_t$ you can use the measured transmission loss to obtain the gain of the open-ended waveguide. Use the VNA to measure the transmission loss S_{21} between two open-ended waveguides, and determine the gain. (Make sure that the distance is big enough to satisfy far-field conditions.)

Take your setup with the pair of open-ended waveguides and note the distance between the apertures and the coupling reading. Now attach a horn to one of the waveguides, while maintaining the same aperture spacing as before. You should see the coupling go up. This rise in coupling will let you figure out the horn's gain. In dB this means

$$\text{Horn gain} = \text{Waveguide gain} + \text{measured increase in the coupling.}$$

Measure the physical dimensions of the open waveguide a, b and the flange A, B . The flange thickness can be neglected.

Measure the physical dimensions of the horns

$$A, a, R_H \Rightarrow \ell_H \Rightarrow R_1$$

$$B, b, R_E \Rightarrow \ell_E \Rightarrow R_2$$

4.5 Waveguide Beamwidth

Measure the 3-dB beamwidth for the open-ended waveguide. Do this by rotating the waveguide in azimuth. Do it for both the E-plane and H-plane. Note that when the waveguide's broad wall is horizontal you get the H-plane pattern, and when the narrow wall is horizontal you get the E-plane pattern.

4.6 Horns, Beamwidth

Using the LabVolt setup, measure the E-plane and H-plane radiation pattern for the smaller horn. Identify the the 3-dB beamwidth in each plane. Save the measured pattern data on a memory stick.

Repeat, for another larger horn.

4.7 Probe Feed

A probe feed in a waveguide is usually placed $\lambda_g/4$ from the short-circuit end. The guide wavelength can be found from $\beta = 2\pi/\lambda_g$ where

$$(m\pi/a)^2 + (n\pi/b)^2 + \beta^2 = \omega^2\mu\epsilon$$

and $m, n = 1, 0$ for the dominant mode.

4.8 Questions

Your group is required to collect the experimental data. Individually, you write up and submit answers to these questions. It is not a lab report. Hand in your work at the beginning of your next lab, in two weeks. It will be marked like homework.

In all aspects of your analysis, you can neglect the antenna ohmic losses, so that $G = D$.

1. For the open-ended waveguide measurements, provide HP_E , HP_H . Compare these with Table 4.1 theory. Compare the measured G with D in Eq. (4.1).
2. Make a Feko model of the open-ended waveguide plus flange. Assume that the flange is thin, and use a probe feed. Show the E-plane and H-plane patterns. Find G , HP_E , HP_H . Compare with measurements.
3. For the small horn measurements, show HP_E , HP_H on the LabVolt patterns. Compare these with Table 4.1. theory. Compare the measured G with D in Eq. (4.1). Assume an optimum design. Is this a good assumption? Use the antenna dimensions to figure out if this is an optimum horn.
4. Make a Feko model of the small horn. Show the E-plane and H-plane patterns. Find G , HP_E , HP_H . Compare with measurements.
5. Repeat Questions (3), (4) for the larger horn.
6. How good are Eq. (4.3) and Eq. (4.4) for finding D ? Try them out for the open-ended waveguide and two horns. Evaluate by comparing with the measured G .
7. You and your group are to write your ID numbers and sign the work, with the pledge: "We certify that this submission is the original work of the group and meets the Faculty's Expectations of Originality."

Lab #5 Microstrip Antenna

5.1 Equipment

- Anritsu MS46122A vector network analyzer
- PC and Anritsu driver software
- SMA cables 2x, waveguide transitions 2x
- SMA female-female adapter
- Rogers 2002 31 mil one-sided copper board
- 3M copper tape, X-acto knife, glass plate
- SMA female bulkhead connector
- You bring: ruler, protractor, camera

5.2 Objectives

The objective in this lab is to design, fabricate, and test a microstrip, or “patch” antenna. A computer model for the antenna will also be developed, using Feko. A microstrip antenna is shown in Figure 5.1.

Microstrip antennas have several advantages: they are inexpensive, easy to make, physically robust, and have a low profile. Some disadvantages include reduced efficiency due to dielectric loss, and a limitation to low-power applications.

The antenna is fed by a microstrip line. If the antenna reflection coefficient is Γ_{ant} and the feedline plus antenna reflection coefficient is Γ_{in} then they are related by

$$\Gamma_{in} = \Gamma_{ant} e^{-j2\beta\ell} \quad (5.1)$$

where

$$\beta = \frac{2\pi}{\lambda_0/\sqrt{\epsilon_e}} = \frac{2\pi f}{c/\sqrt{\epsilon_e}} \quad (5.2)$$

is the phase constant for the transmission line, ℓ is its length, and ϵ_e is the effective relative permittivity of the substrate. Conversely, the antenna impedance follows from

$$\Gamma_{ant} = \Gamma_{in} e^{j2\beta\ell} \quad (5.3)$$

and

$$Z_{ant} = 50 \frac{1 + \Gamma_{ant}}{1 - \Gamma_{ant}}. \quad (5.4)$$

5.3 Design Equations

To design a microstrip transmission line, the equations for the characteristic impedance Z_0 and effective permittivity ϵ_e are plotted in Figure 5.2. and Figure 5.3. From these graphs it can be seen that a 50Ω line should be about 100 mils wide. The effective permittivity ϵ_e is also shown. This is a corrected permittivity that accounts for the fringing field effects of the microstrip line.

For the antenna, L is the patch length, measured from the feed point to the open circuit end, and W is the width. The substrate has a permittivity ϵ_r and a thickness t . At resonance the patch length should be slightly less than a half wavelength, so that

$$L = 0.49 \frac{\lambda_0}{\sqrt{\epsilon_r}}.$$

Here, λ_0 is the free-space wavelength and $\lambda_0/\sqrt{\epsilon_r}$ is the wavelength inside the dielectric.

The antenna impedance Z_{ant} can be controlled by choosing W . At resonance Z_{ant} is real and is approximately given by

$$Z_{ant} = 90 \frac{\epsilon_r^2}{\epsilon_r - 1} \left(\frac{L}{W} \right)^2 \Omega.$$

The impedance bandwidth (in percent) is approximately

$$B = 377 \frac{\epsilon_r - 1}{\epsilon_r^2} \frac{W}{L} \frac{t}{\lambda_0}.$$

The directivity is approximately

$$D = \begin{cases} 3.3 \text{ (5.2 dB)}; & W \ll \lambda_0 \\ 4W/\lambda_0; & W \gg \lambda_0. \end{cases}$$

The circuit board to be used in this lab is Rogers 5880 which has $\epsilon_r = 2.20$ and $\tan \delta = 0.0009$ at 10 GHz. The thickness is 1/32 inch, or 31 mils. (1000 mils = 1 inch.)

Before coming to the lab, design a 50Ω patch antenna for operation at $f_0 = 9.8$ GHz.

5.4 Impedance

Make a 50Ω transmission line that extends from the edge of the board to roughly the center. Use an X-acto knife, ruler, and glass plate to cut it. Connect it to the SMA connector at the edge.

Set the sweep for 9.0-11.0 GHz and calibrate the VNA. Then adjust the reference plane so that the SMA connector plus feedline reads $\Gamma = 1/\underline{0}^\circ$. Therefore, the reference plane is at the tip of the open-circuit line.

Make the patch antenna out of copper tape and place it at the very tip of the line. The patch should be just touching the tip of the feedline, but not overlapping it. Then put another small piece of tape on top, to join the feedline to the patch.

Measure Γ for the feedline plus patch over 9.0-11.0 GHz. Mark the value at f_0 . Also mark the observed resonant frequency (i.e. where Γ is real).

5.5 Gain Testing

Use the Friis method to measure the gain of the patch antenna at the frequency f_0 . Do this by measuring the P_r/P_t for a pair of waveguide transitions. Then replace one of the waveguides with the patch. Since the waveguide gain is known from Lab #4, you can find the patch gain.

5.6 Simulation

We will use Feko to model the feedline, and the feedline plus patch antenna. Follow the posted file `patch-10ghz.cfx`. The main steps are:

1. Make up the dielectric material using *Construct* \rightarrow *Media* \rightarrow *Dielectric* and give it a name, e.g. *substrate1*.
2. Make the infinite (*xy*) substrate and ground plane with *Construct* \rightarrow *Planes/arrays* \rightarrow *Plane/ground* \rightarrow *Planar multilayer substrate* \rightarrow *Layer 1* \rightarrow *thickness t* and set *medium=substrate1*. For the dielectric layer give it a ground plane by selecting *Bottom* from the ground-plane dropdown list; the ground will show up in orange.

3. Make the metal patch and feedline; union them.
4. In the Details Tree, find the feed line's edge for the source. Then, right-click *Create Port* \rightarrow *Microstrip Port*
5. Set the frequency and put a voltage source at the port.

It is important to have a 50Ω line in between the port and the patch. This makes the meshing at the feed point more realistic. Note that the line will have a big effect on the phase of Γ . At 10 GHz, just 1 cm of line will change the phase of Γ by $2\beta\ell = 329^\circ$.

5.7 Questions

Your group is required to collect the experimental data. Individually, you write up and submit answers to these questions. It is not a lab report. It will be marked like homework.

This is the last experiment. Submit your report at my mailbox at EV5.175.

1. Provide the antenna dimensions for your design and show a photo of the antenna.
2. Use Feko to model the feedline plus antenna. Plot Γ_{in} for 9.0-11.0 GHz in the Smith chart format.
Use Equations (5.2) and (5.3) to obtain Γ_{ant} from Γ_{in} . Do this for at least five frequencies, and sketch the locus for Γ_{ant} on a Smith chart. What is the resonant frequency?
3. Compare the Feko computed Γ_{ant} and measured results, on one Smith chart.
4. Plot the Feko E-plane and H-plane gain patterns at f_0 .
5. Compare the maximum gain from Feko and the measured gain.
6. The Feko patch model refers to a "Green's function." What is its purpose? Is its usage mandatory? Explain in one page or less.
7. You and your group are to write your ID numbers and sign the work, with the pledge: "We certify that this submission is the original work of the group and meets the Faculty's Expectations of Originality."

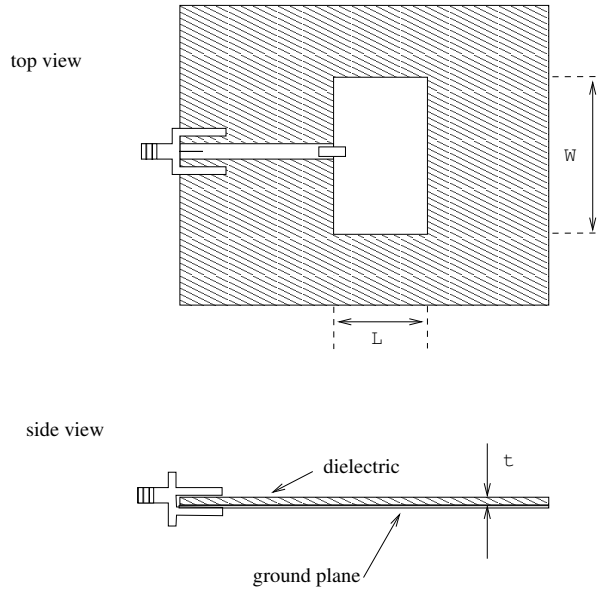


Figure 5.1: Microstrip antenna.

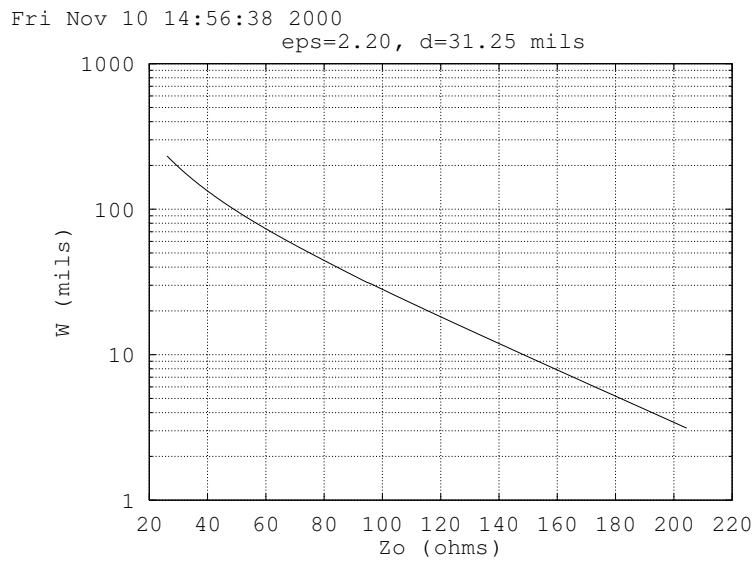


Figure 5.2: Line width vs. impedance.

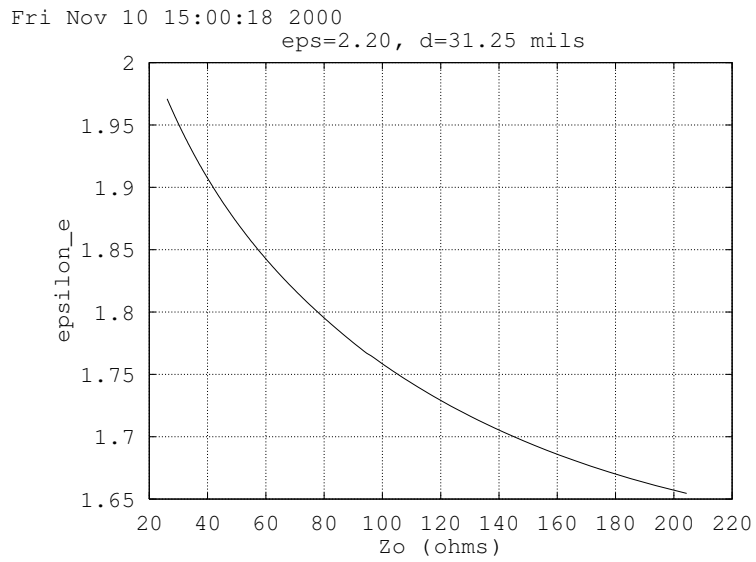


Figure 5.3: ϵ_e vs. impedance.

Appendix A Impedance Measurement

A.1 Background

The Anritsu ShockLine MS46122A is a vector network analyzer (VNA) which permits us to measure the S parameters of a 1-port or 2-port network. The term ShockLine refers to the transmission-line technology used in its internal workings. It is controlled by a PC through a USB interface. The VNA is shown in Figure A.1 and the user interface is in Figure A.2. The manuals and driver software can be downloaded from the company website (Anritsu Company, 2016).

For a 1 port, the parameter S_{11} is identical to the reflection coefficient, so $S_{11} = \Gamma$. There is a 1:1 relation between Γ and the impedance Z via the relations

$$\bar{Z} = \frac{Z}{Z_0} = \frac{1 + \Gamma}{1 - \Gamma}$$

and the admittance obeys

$$\bar{Y} = \frac{Y}{Y_0} = \frac{1 - \Gamma}{1 + \Gamma} = \frac{1}{\bar{Z}}.$$

In the above, $Z_0 = 50 \Omega$ and $Y_0 = 1/Z_0 = 0.02 \text{ U}$. The VNA measures Γ , but can also display Z and Y .

A.2 Equipment

To get familiarized with the VNA we will use

1. Anritsu VNA and PC with driver software
2. Anritsu calibration kit, with SMA male connectors
3. One cable, SMA male to SMA male
4. Two SMA female-female adapters (“bullets”)

5. One SMA male short-circuit
6. One SMA male 50 Ω load

A.3 The Need for Calibration

When using a VNA to measure an unknown load impedance Z , a cable is almost always used to connect the VNA to the load. As an example, suppose that our “unknown” load is a short circuit and that it is connected by a polyethylene coax cable. The cable is assumed to be 1 cm long, and has a characteristic impedance of $Z_0 = 50 \Omega$. The frequency is 3 GHz.

In this measurement we would hope to see $Z = 0$. But this is not what happens. Here, $\beta = \omega\sqrt{\mu_0\epsilon_0\epsilon_r} = 0.942 \text{ rad/cm}$, and $\beta\ell = 54 \text{ deg}$. The impedance of the cable+load seen by the network analyzer will be

$$Z = jZ_0 \tan \beta\ell = j69 \Omega.$$

Therefore, when measuring Z of the terminating load, it is important to remove the impedance-transforming effect of the cable.

A.4 Calibration Procedure

The Anritsu’s calibration procedure allows us to mathematically remove the effect of the connecting transmission line, so that the VNA measures the terminating impedance. It also allows the VNA to perform sophisticated error corrections that compensate for imperfections (reflections and losses) in the connectors and cables. The procedure makes use of three different terminations: short, open, and matched. These are provided by the “calibration kit” shown in Figure A.3(a). The SMA components in case (b) provide the same function as the cal kit and can be used instead.

Here is an example of how to calibrate the VNA, over 2 – 4 GHz for a 1-port measurement. The terms in a box appear at the top of the VNA menu bar. Menu *subitems* appear in italics. The steps are:

1. **CAUTION:** Always touch ground before a cable’s center pin, to avoid possible damage by electrostatic discharge
2. **CAUTION:** The connectors should be made finger-tight and never forced
3. Power up the VNA and let it warm up for 30 minutes

4. Right-click on the PC to start the ShockLine driver software (run it with administrator privileges)
5. resets the VNA to its “standard” state
6. *Start 2 GHz; Stop 4 GHz; # of Points 201*
7. *Calibrate; Manual Cal; 1-Port Cal; Port 1; Reflective Devices; Port 1 Connector; K-Conn (male)*
8. We will now use the calibration kit. Connect an SMA cable to VNA Port 1. Connect the other end of the cable to the OPEN terminal on the cal kit. Click on *Open*.
9. Repeat, with the cable connected to the SHORT terminal on the cal kit. Click on *Short*.
10. Repeat, with the cable connected to the LOAD terminal on the cal kit; this is a $50\ \Omega$ load. Click on *Load*.
11. An information panel asks “Please Click Done.” Press “OK” and then click *Done* on the menu at the right side.
12. Disconnect the cal kit, and leave the bullet at the end of the cable. This concludes the calibration.

A.5 The Display

To see Γ on a Smith chart:

1. *# of Traces 1; Trace Layout* (can pick the top one).
2. *Trace Format; Smith (R+jX) Impedance*
3. Ask for *S11* if it’s not there already.

We will always use one “channel.” However we might want multiple traces. You will see names like (Tr 1), (Tr 2) and so forth above each graph. To modify a particular trace you need to click on its name near the graph, to make it “active.” The parameters of the active one can then be altered. Their orientation can be adjusted with *Trace Layout*.

It is nice to see both a Smith display of Γ as well as a log magnitude/phase display. To get both, ask for *# of Traces 3; Trace Layout*

and choose a layout. Above the second trace, click on (Tr 2) and choose *Trace Format; Log Mag.* Above the third trace, click on (Tr 3) and choose *Trace Format; Phase.* As before, ask for *S11* on each trace, if it's not there already.

A.6 Measurement

For your first measurements, use a cable terminated by an open female-female bullet. This gives an open circuit. You should measure $\Gamma = 1/\underline{0^\circ}$, a dot at the right end of the Smith chart. Then connect a male SMA short circuit; you should measure $\Gamma = 1/\underline{180^\circ}$, a dot at the left end of the Smith chart. Finally, connect a male SMA $50\ \Omega$ load. You should see $\Gamma = 0$, a dot at the center of the Smith chart.

A.7 Reference Plane

From the above experiments, the cal kit established a “reference plane” which defines the position on the transmission line at which Z is being measured. In this case the reference plane is slightly past the end of the line, inside the short-circuit termination. However, the reference plane could be positioned elsewhere, if desired.

Suppose that we wanted to use some other “home made” structure as a short circuit reference, such as an SMA connector with a wire jumper soldered to it. These have $\Gamma \neq 1/\underline{180^\circ}$, due to the connector's electrical length, and possibly some inductance or capacitance at the end. We can tune out those effects and obtain a displayed reflection coefficient of $\Gamma = 1/\underline{180^\circ}$.

1. *Measurement; Reference Plane; Distance.* This introduces a fictitious piece of transmission line. It can have a positive or negative length. This moves the impedance on the Smith chart toward the generator, or toward the load.
2. *Measurement; Reference Plane; Phase Offset.* This changes the phase of Γ by a fixed amount, for all frequencies.

As the frequency sweeps, Γ for the home-made short will appear as some sort of a locus along the outer edge of the Smith chart. You should be able to adjust the reference plane distance until the locus almost collapses down to a dot. Then, the phase offset should be adjusted to move the dot to the right place, i.e. the left side of the chart where $\Gamma = 1/\underline{\pm 180^\circ}$.

A.8 Reporting

Colors: In the lab, it is sometimes hard to view the default colors, e.g. a yellow trace on a white graticule. If needed, you can modify the color scheme for better visibility. Go to (8) *Utilities; System; Setup; Colors Setup* and choose something like Graticule Main = Gray; Graticule Sub = Gray.

Printouts: Provide a hardcopy of your measured results in any report. To get the required format, go to (1) *File; Print Setup; 4-Trace Graphical*. Then press *Print*. Your printout should show the date, time, instrument settings, and a plot of Γ .

The curves on the printout are not always so legible. Before leaving the lab, use a pen to highlight the data on the printouts, and annotate any key points on the curves.

Data Files: You can save your measured data as an s1p (1-port) or s2p (2-port) file, with Home *File; Save Data*. Then you can use the ShockLine program at home on your PC at home to further examine the data. When viewing a data file, you need the “hold” mode which is at Sweep *Hold Functions; Hold*

A.9 2-Port Measurements

This is very similar to the 1-port case.

1. Calibration *Calibrate; Manual Cal; 2-Port Cal; Port 1; Reflective Devices; Port 1 Connector; K-Conn (male)*
2. On port 1, do the OPEN, SHORT, and LOAD calibration
3. Press *Back*
4. On port 2, do the OPEN, SHORT, and LOAD calibration
5. Press *Back*
6. Connect port 1 to port 2, using the THRU connection on the calibration kit, or a bullet.
7. On the menu, press *Thru; Thru 1-2*
8. An information panel asks “Please Click Done.” Press “OK” and then click *Done* on the menu at the right side.

9. Click on the desired trace (Tr 1), (Tr 2), or whatever case you need.
Press and ask for S_{21} .
10. You are now ready to measure S_{21} between the two ports.

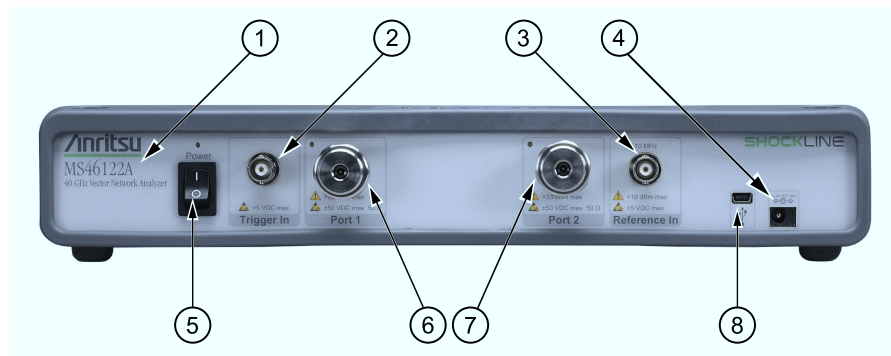
Chapter 3 — Front and Rear Panels

3-1 Chapter Overview

The chapter provides an overview of the MS46122A Series VNA hardware user interface including front panel buttons and front panel connectors. Included are photographs of the front and rear panels. Each port and connector is described with its connector type, its function, input/output limits, and a cross-reference to a detailed connector pin-out diagram.

3-2 Front Panel Components

The MS46122A Series VNA front panel and port connectors are identified below in [Figure 3-1](#).



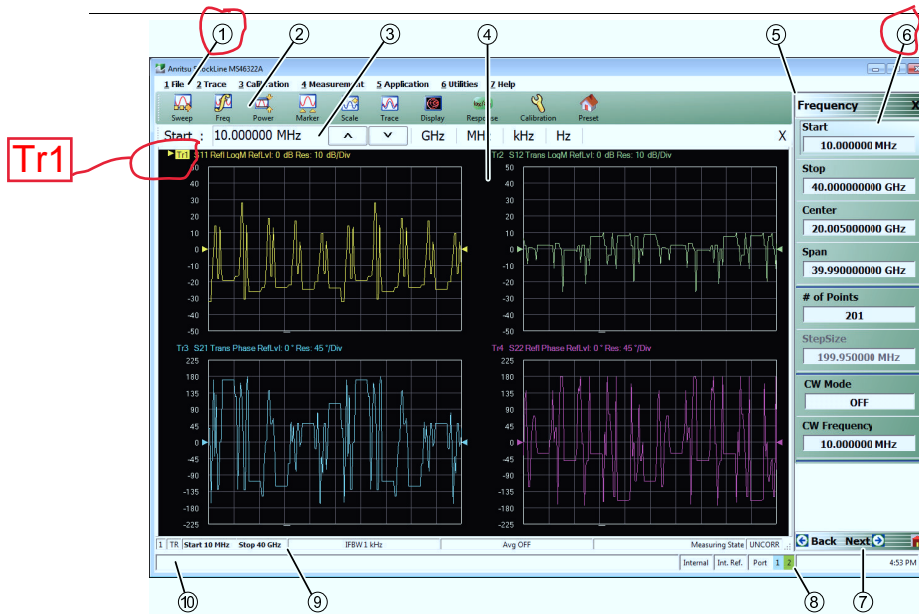
1. ID Plate – Instrument model number identification	5. Operate / Standby Power Switch
2. Trigger In	6. Test Port 1 – K(m) or N(f)
3. 10 MHz External Reference Input	7. Test Port 2 – K(m) or N(f)
4. DC Power Supply Connector	8. USB Port

Figure 3-1. MS46122A VNA Front Panel

Figure A.1: Anritsu 2-port VNA. Taken from Anritsu Company (2016).

User Interface Control and Display Areas

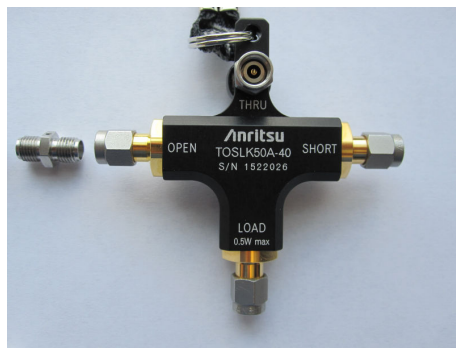
The instrument main display can be manipulated by clicking with an attached USB mouse. The figure below shows the general display areas for a single channel displaying four graphical traces.



1. **Menu Bar** – Displays nine (9) drop down menus: File, Main, Channels, Trace, Calibration, Measurement, Application, Utilities, and Help.
2. **Icon Toolbar** – User-configured with up to 10 user-selected quick access icons.
3. **Field Toolbar** – Appears only when field button is clicked for input. Display field for value, with one or more units (such as dB, dBm, or Hz), an Enter button, and an X close button.
4. **Display Area** – Displays from one to 16 trace display graphs. Each trace display can optionally have from one to 12 markers, a reference marker, and an upper and lower limit line.
5. **Menu Title** – Displays the name of the displayed right-side menu. Menu titles are unique to each menu.
6. **Menu Buttons** – The menu buttons allow the user to set parameters, make configuration selections, read result values, start processes, toggle between two or more values, display sub-menus, and display dialog boxes.
7. **Menu Navigation Buttons** – The navigation buttons always appear at the bottom of the right-side menu and allow browser-like forward and backward navigation through the user's history. Back returns to previous selected higher-level menu, Next returns to a previously selected lower-level menu, and Home returns to the Main Menu.
8. **System Status Bar** – Displays status messages, and configuration status that affects the entire instrument.
9. **Trace Status Bar** – Provides status for active trace near the bottom of the screen.
10. **Tableau Data Display/Input Area** – The tableau area only appears when the appropriate menu button is selected. When selected, the display shrinks upwards and the tabular data area expands.

Figure 4-2. User Interface Display Areas

Figure A.2: VNA control screen. Taken from Anritsu Company (2016).



(a)



(b)

Figure A.3: (a) Calibration kit. (b) Equivalent SMA components.

Bibliography

Anritsu Company. *Operation Manual, ShockLine MS46122A Series Compact Vector Network Analyzer*. Morgan Hill CA, Mar 2016. <http://www.anritsu.com>.