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FACULTY OF APPLIED SCIENCE AND ENGINEERING
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ECE422H1S: RADIO AND MICROWAVE WIRELESS SYSTEMS

EXPERIMENT 1: ANTENNA MEASUREMENTS

1 Introduction

The purpose of this laboratory is to introduce you to several different types of antennas and their characteristics. Specifically, you will study characterize common antennas used in practise: a half-wavelength dipole, and a microstrip patch antenna. You will learn how to characterize the following characteristics of antennas:

- Input impedance / input reflection coefficient
- Radiation patterns, and the principal planes in which the patterns are measured (E-plane and H-plane)
- Polarization

You will need the following pieces of equipment to complete this experiment:

- Agilent network analyzer
- SMA calibration kit (short, open, load, thru)
- Planar half-wavelength dipole antenna
- Planar Yagi antenna array
- Microstrip patch antenna
- Wilkinson power divider (3-port board with oval-shaped trace on it)
- Quadrature hybrid (3-port board with square-shaped trace on it)
- 2 mounting tripods and associated hardware
- 2 SMA cables

- 2 UFL cables and SMA-to-UFL adaptors
- UFL removal key
- Ruler / measuring tape
- Computer running MATLAB or Microsoft Excel, for recording data

2 Half-Wave Dipole Antenna

This dipole is basically the half-wavelength dipole that we have learnt about in class. It consists of a length of conductor that is approximately one half-wavelength long at the design frequency. The conductor is realized using a printed circuit board trace in this case. The entire dipole is fabricated on a low-loss microwave laminate. The laminate has negligible loss and, for the purposes of this design, does not appreciably change the electrical characteristics of the dipole.

Examining the dipole antenna, you will notice that it is fed from the centre by a miniature type of coaxial connector known as a UFL connector, which is a low-cost easy-to-use connector used in wireless devices such as LAN cards and cellular phones. Between the UFL connector and the two arms of a dipole is a small integrated circuit known as a *balun* which is used to convert the unbalanced coaxial feed to feed a balanced antenna. If the balun was absent, connecting the dipole to the coaxial cable would cause a current imbalance, resulting in currents flowing along the coaxial cable shield, leading to spurious radiation that would degrade the radiation characteristics of the antenna.

2.1 Input Impedance Measurement

1. Measure the length of the antenna and determine the approximate operating frequency of the antenna.
2. Calibrate the network analyzer from 800 MHz to 1 GHz according to the instructions at the end of this document.
3. Connect the dipole to the reflection port of the network analyzer with a UFL cable. You will need to use SMA-to-UFL adaptors to connect the coaxial cable on the network analyzer to the antenna. **Do not force the cable into the UFL connector!** Align the cable and the connector and gently push the cable into the connector. When removing the cable, please use the UFL cable removal key.
4. Press [FORMAT] and select Log Mag.
5. Press [MARKER] and set the marker to where the reflection coefficient of the antenna is lowest. Determine the -10 dB bandwidth.

6. Press [FORMAT] and select Smith to display the Smith Chart. Determine the frequency where the antenna is resonant; i.e., where the input reactance of the antenna is zero. Record the impedance and compare it to the expected value for a half-wave dipole.

7. Press [FORMAT] and select Log Mag. Measure the input reflection measurement of the Yagi antenna as well. Determine the -10 dB bandwidth. Does it have a wider or narrower bandwidth than the dipole. Move the marker to the point where the Yagi is matched the best. This will be the frequency at which you conduct pattern measurements. It should be reasonably close to the dipole frequency.

2.2 Pattern Measurement

Now, we will measure the pattern of the dipole antenna. It is most meaningful to do this in two *principal planes* of the antenna, known as the E-plane and H-plane. The E-plane is the plane that fully contains the radiated E-field polarization of the antenna. Similarly, the H-plane fully contains the radiated H-field polarization of the antenna. For a dipole antenna, the E-plane is a plane containing the dipole axis at any arbitrary azimuth angle (i.e. $\phi =$ constant). The H-plane is the plane normal to the axis of the antenna ($\theta = 90°$).

2.2.1 E-Plane

Set the tripods a fixed distance apart, and leave this distance fixed for the remainder of the experiment. On one tripod, you will mount the dipole under test. On the other tripod, you will mount a reference antenna, which for this experiment is a Yagi antenna. The Yagi antenna is a type of antenna array with high directivity along the broadside axis of the elements. It is a good reference antenna because it allows us to "focus" our measurements over a small spatial area, due to the high directivity of the antenna.

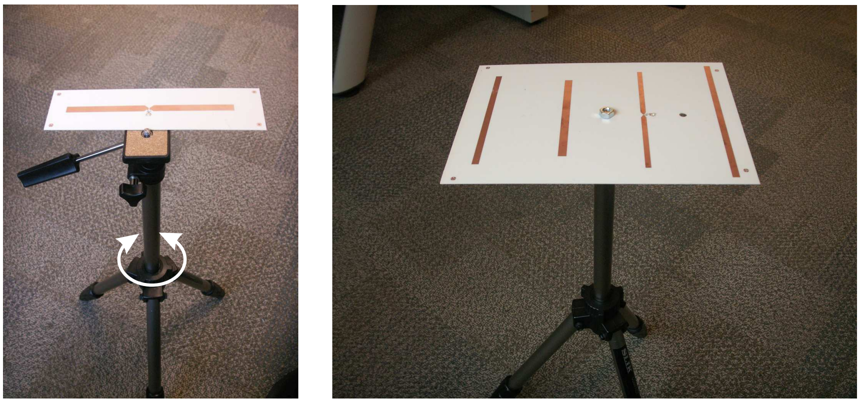
1. Press [MEAS] and select S21. Make sure a marker is placed at the resonant frequency of the Yagi antenna. The transmission coefficient (s_{21}) can now be easily read.

2. Record the distance between the two tripods.

3. Attach the dipole on the tripod horizontally as shown in Figure 1(a).

4. Attach the Yagi antenna to the other tripod as shown in Fig 1(b). Notice that the Yagi, which is composed of dipole-like elements, is *co-polarized* with the dipole so that it can properly receive transmissions from the dipole antenna. By rotating the dipole tripod head your can change the angle between the dipole axis and the imaginary axis between the transmitter and the receiver. Hence, you are effectively changing the angle θ by rotating the tripod head.

5. Align the dipole such that the arms are in parallel with the arms of the Yagi when the tripod pedestal is at $0°$. Refer to Figure 1.



(a) Dipole (b) Yagi

Figure 1: E-Plane measurement setup

6. Connect the dipole to the reflection port of the network analyzer.
7. Record the s_{21} values measured by the network analyzer.
8. Rotate the pedestal by $15°$.
9. Repeat 7 and 8 until you have completed $360°$ of measurement.

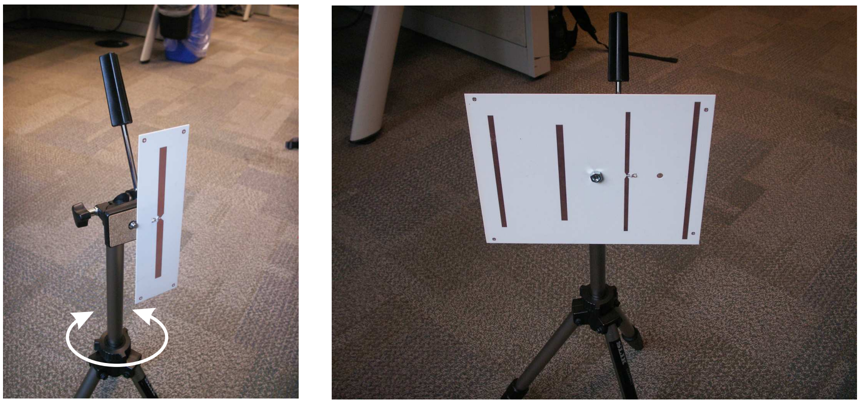
When measuring the pattern, keep the Yagi antenna fixed. Only the dipole needs to be rotated during the experiment.

When measuring the pattern, it may be helpful to turn on averaging. If you turn on averaging, make sure that you restart averaging whenever you change the angle of the dipole. To turn on averaging, press [AVG] and select Averaging On. To restart averaging, press [AVG] and then select restart.

In your report, compare the measured E-plane pattern with the predicted pattern by plotting the theoretical pattern with a normalized version of your measurement. How do they compare?

2.2.2 H-Plane

1. Place the dipole on the tripod vertically using a piece of tape. In other words, the arms of the dipole should be perpendicular to the lab bench.
2. Turn the tripod head holding the Yagi antenna so that the polarization is matched with the dipole (i.e., the arms of the dipole and Yagi elements are parallel and vertical). Refer to Figure 2.
3. Connect the dipole to the reflection port of the network analyzer.
4. Record the s_{21} values measured by the network analyzer.



(a) Dipole (b) Yagi

Figure 2: H-Plane measurement setup

5. Rotate the pedestal by $15°$.
6. Repeat 4 and 5 until you have completed $360°$ of measurement.

In your report, comment on the variation of the H-plane field pattern and compare that to what is expected.

2.2.3 Cross-Polarization

The previous two experiments measure the co-polarization (co-pol) pattern on the E-Plane and the H-Plane; thus, the electric field of the transmitting antenna and the receiving antenna are in parallel. In this section, you will measured the cross-polarization (x-pol); the electric field of the transmitting antenna and the receiving antenna are orthogonal to each other. This is useful for measuring the *polarization purity* of the antenna under test; if we pick up cross-pol, it means that the transmitting antenna is creating radiation components that are cross-polarized with what is expected. As a dipole is expected to be highly discriminatory with respect to polarization, this is a measure of the quality of the antenna.

1. Place the dipole on the tripod vertically as shown in Figure 2.
2. Adjust the Yagi antenna such that it is mounted horizontally.
3. Align the dipole such that the arms are ORTHOGONAL to the arms on the reference antenna when the tripod pedestal is at $0°$.
4. Connect the dipole to the reflection port of the network analyzer.
5. Record the s_{21} values measured by the network analyzer.
6. Rotate the pedestal by $15°$.

7. Repeat 5 and 6 until you have completed $360°$.

Compare the values in this experiment with those from the co-polarization experiments. They should be at least an order of magnitude (10 dB) lower than those measured in the co-polarized experiment. Comment on what factors could have led to higher than expected cross-pol levels in your report.

2.3 Additional Questions

1. Estimate the free space loss between the two antennas in your experiment, knowing the distance between the antennas (which you have recorded) and the gains of the antennas. The gain of the Yagi is approximately 7.3 dBi.

2. What is the ratio between the co-pol to the x-pol at $0°$?

3. When measuring the input impedance, you will notice that it changes when an object is placed in close proximity to the antenna. Discuss how the impedance is affected by nearby objects and the underlying assumptions used in the impedance formula of the dipole.

   If you are an antenna designer for a cellphone company, discuss ways on how you would mitigate the problem of changing impedance. Also discuss any potential issues that may occur in the transceiver electronics when the impedance varies greatly.

3 Microstrip Patch Antenna

The microstrip patch antenna is a very popular antenna used in a variety of devices. It is popular because it is easy to construct, using standard printed circuit board techniques, and it has a low profile (it doesn't stick up like a wire antenna). It is hence very easy to integrate with electronics. It also has decent amount of gain for a small antenna.

A diagram of a basic half-wave patch antenna is shown in Figure 3. It consists of a large patch of metal into which we couple energy from a microstrip feed. The physical patch dimensions are width W and length L. It is fed by a microstrip feed line with width which is usually chosen so that the characteristic impedance of the feed is 50 ohms. Like any other device, an antenna has an input impedance. If the feed line shown in the diagram were connected directly to the edge of the antenna, the input impedance at that point would be in the hundreds of ohms, which would be a poor match to the 50 ohm line being connected there. To match the input line (which is 50 ohms) to the high impedance of the patch, a simple quarter-wave transformer is used. Such a transformer is visible on the microstrip patch board.

A single-feed patch antenna like the one shown in Figure 3 resonates at a frequency determined by the length of the antenna L, which is approximately half a wavelength (taking into effect wave-length shortening by the substrate). The radiated polarization is parallel to edges of the patch in the

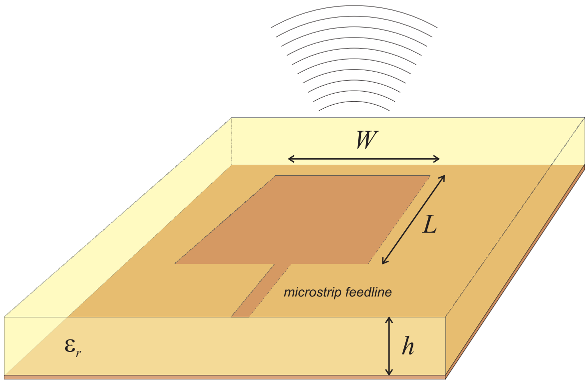


Figure 3: Diagram of a half-wave microstrip patch

resonant direction. Because the patch is backed by a ground plane, we expect most of the radiation to be on the patch side of the substrate, and very little radiation behind the ground plane.

The patch you are using in the experiment is equipped with two feeds. As the patch itself is square, the resonant frequencies associated with each polarization are the same. Hence, we can use the two feeds to superpose two signals, in order to study concepts we know from lectures on polarization.

3.1 Input Impedance Measurement

1. Remove the SMA to UFL adaptor.
2. Calibrate the network analyzer if it is not calibrated.
3. Attach the SMA cable to one of the inputs (it doesn't matter which one) of the patch antenna.
4. Attach a $50\ \Omega$ load to the other input of the patch antenna.
5. Press [MEAS] and select S11.
6. Press [FORMAT] and select Log Mag.
7. Press [MARKER] and set the marker to the point where the antenna is best matched to 50 ohms. You might also display reflection coefficient on a magnitude scale to determine the optimal match point. Record the resonant frequency of the patch and the corresponding input impedance / input reflection coefficient.
8. You will now measure the impedance of the other input port. Swap the load and the cable and repeat 7. Verify that two ports have resonant frequencies that are close to each other.

3.2 E-Plane Pattern Measurement

1. Terminate one of the input of the patch antenna with a 50Ω load.

2. Connect the patch to the reflection port of the network analyzer.
3. Attach the patch onto the tripod and adjust the arms of the reference antenna such that it is aligned to the E-plane of the patch. Refer to Figure 4.
4. Ensure that the face of the patch is perpendicular to the direction of the reference antenna and that the pedestal is at $0°$.
5. Press [MEASURE] and select S21.
6. Press [FORMAT] and select Log Mag.
7. Press [MARKER] and place marker at the center frequency.
8. Record the value read out by the network analyzer.
9. Rotate the pedestal by $15°$.
10. Repeat 8 and 9 until you have reached $360°$.

3.3 H-Plane

1. Continuing from the previous section, align the patch such that one of the edges of the square patch that is excited is in parallel with the arms of the reference antenna.
2. Ensure that the face of the patch is perpendicular to the direction of the reference antenna and that the pedestal is at $0°$.
3. Make sure the network analyzer is measuring s_{21} and place a marker at the center frequency.
4. Record the value read out by the network analyzer.
5. Rotate the pedestal by $15°$.
6. Repeat 4 and 5 until you have reached $360°$.

In your report:

1. Comment on the radiation pattern of the antenna, based on your observations of the principal plane patterns of the patch. Compare the measured and theoretical radiation on the E- and H-planes. The theoretical E- and H-plane E-field patterns for a patch antenna in the yz-plane are as described in the standard spherical coordinate system. The E-field pattern in the E-plane, $\theta = 90°, 0° \leq \phi \leq 90°$ and $270° \leq \phi \leq 360°$ is (up to a constant):

$$E_\phi = \frac{\sin\left(\frac{k_o h}{2}\cos\phi\right)}{\frac{k_o h}{2}\cos\phi}\cos\left(\frac{k_o L_e}{2}\sin\phi\right). \tag{1}$$

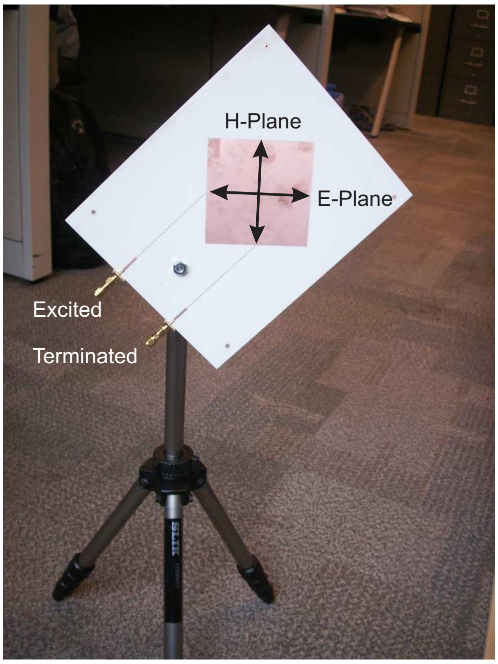


Figure 4: The E-Plane and H-Plane orientation of a circularly polarized patch antenna when one of the ports is excited while the other is terminated.

The E-field pattern in the H-plane, $\phi = 0°, 0° \leq \theta \leq 180°$ is (up to a constant):

$$E_\phi = \sin\theta \frac{\sin\left(\frac{k_o h}{2}\sin\theta\right)}{\frac{k_o h}{2}\sin\theta} \frac{\sin\left(\frac{k_o W}{2}\cos\theta\right)}{\frac{k_o W}{2}\cos\theta}, \tag{2}$$

where k_o is the free space wave number at the frequency of interest, $L_e = 89.568$ mm is the effective length of the patch, $h = 0.8$ mm is the thickness of the substrate, $W = 87.63$ mm is the width of the patch. You will need to normalize the measured and the theoretical E-field patterns to a common maximum value, i.e. 0 dB.

2. Using a free-space loss calculation, determine the approximate peak gain of the microstrip patch.

3.4 Linear Polarization

Now we will excite the antenna in such a way that it produces linear polarization from two in-phase excitations. In-phase excitation can be achieved by splitting a signal using a Wilkinson power divider, which evenly divides power between the two output ports while keeping the two signals in phase with each other.

1. Attach the Wilkinson power divider to the patch.

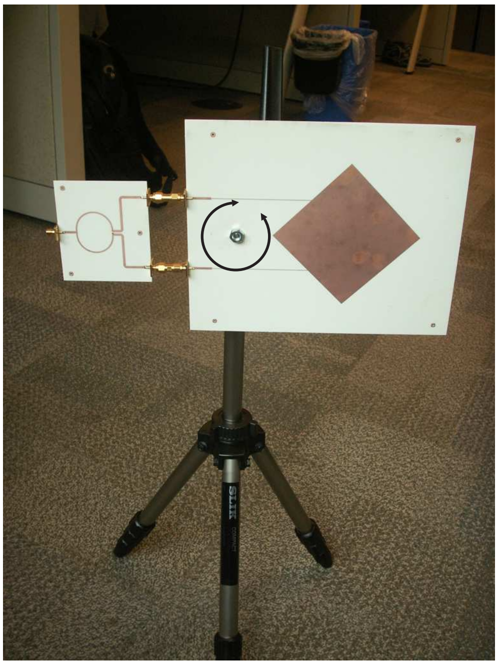


Figure 5: Mounting of the patch antenna with a 2-way Wilkinson power divider attached. The arrows denote the way the antenna is rotated in Section 3.4.

2. Attach the SMA cable to the input of the power divider. The two ports are now excited in phase.
3. Rotate the patch such that it is at $45°$ to the reference antenna. Refer to Figure 5.
4. Record the s_{21} value measured by the network analyzer.
5. Rotate the patch by $90°$, hence cross-polarizing the two antennas.
6. Record the s_{21} value measured by the network analyzer.
7. Compare the transmission levels (s_{21}).

3.5 Circular Polarization

Now we will introduce a phase difference between the two feed signals by replacing the Wilkinson power divider with a quadrature hybrid. This power splitter also maintains an equal power split between the 2 output ports, except that the one port lags the other by 90 degrees. Thus, we can create circular polarization from the patch.

1. Attach the quadrature hybrid to the patch.

2. Attach the SMA cable to the input of the quadrature hybrid.
3. Rotate the patch such that it is at $45°$ to the reference antenna. This is the same orientation as shown in Figure 5.
4. Record the s_{21} value measured by the network analyzer.
5. Rotate the patch by $90°$.
6. Record the s_{21} value measured by the network analyzer.
7. Compare the transmission levels (s_{21}). Do you expect a change when the patch is rotated? By how much? How does the measure power level compare to the linear-to-linear polarization case?

4 Network Analyzer Calibration

This section describes the procedure of how to calibrate the network analyzer. Square brackets [] denote a hard button on the front panel of the network analyzer and round brackets () denote a soft button on the screen of the network analyzer.

1. Press [Preset] $\rightarrow$ (OK). Setting the instrument to a default state.
2. Press [Start], enter 800 MHz. Press [Stop], enter 1 GHz. Setting the frequency range of interest for the measurement.
3. Press [Cal] $\rightarrow$ (2-Port Cal) $\rightarrow$ (Reflection).
4. Connect the appropriate Short/Open/Broadband Load calibration standards to Port 1 and 2 and press corresponding soft buttons on the screen..
5. Press (Return).
6. Press (Transmission). Connect the Short/Open/Broadband Load calibration standards to Port 1 and 2 and press corresponding soft buttons on the screen..
7. Connect a Through standard.
8. Press (Port 1-2 Thru) to measure the standard.
9. Press (Return)
10. Press (Done) to enable the calibration.
11. Check the calibration by making sure the calibration is selected to be ON. Connect the Through calibration standard to make sure the reflection s_{11} is less than -40 dB and the transmission s_{21} is near 0 dB.