Antenna Design, Simulation, Fabrication and Test Tailored for Engineering Technology Students

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Abstract

The need for qualified individuals to perform as antenna design engineers in the industrial community has become critical. It was determined through conversations with various antenna and RF company representatives there was a need for "application orientated" university graduates in this area. Therefore, the Electrical Engineering Technology department at Purdue University took on the challenge to create graduates to fill this niche.

The paper is focused on the design/analysis techniques required for various antenna types, specifically microstrip patch, dipole and helical, which can then be expanded to include many other types of antennas in the future. It was necessary to initially focus on antenna types that could be easily fabricated by the students in a laboratory environment.

The paper is limited to the discussion of the following items for the microstrip patch antenna, due to paper length considerations:

(1) Background information, design parameters and limitations, feeding methods, electro-magnetic field modes, and the mathematical methods required to accomplish the design.
(2) Simulation methods and results based on the Ansoft® HFSS simulation software.
(3) The fabrication methods utilized to create the physical antenna.
(4) The test methods used to verify the antenna's operating parameters using the Hewlett-Packard® 8753D RF vector network analyzer.
(5) The analysis results comparing the design, simulation and actual measurements.

The results obtained from this endeavor have proven to be of solid instructional value without the expense of purchasing a half-million dollar antenna test system. This method could potentially be of benefit to many other engineering technology programs.

I. Introduction

The goal to be achieved was to identify an effective method of teaching antenna design, fabrication, and analysis to Engineering Technology students. Antenna design is one of the most important fields in the RF communications industry, and currently one of the most overlooked topics at the college level. Many of the RF devices manufactured today use some form of antenna, whether it is for reception or transmission. Unfortunately, when studying these RF devices at the college level, the antenna design and analysis portion does not usually receive rigorous treatment.

One of the major obstacles encountered in antenna design, fabrication, and analysis, from a pedagogical perspective, is the cost. In order to fully analyze a fabricated antenna design, various types of costly RF test and measurement equipment are required. These devices might include, an RF generator, spectrum analyzer, vector network analyzer, and RF power meter. Each of these pieces of equipment can easily cost more than a new luxury car. Before an antenna design can be tested, it must be mechanically fabricated based on the theoretical design. Some modern antennas are even constructed as part of a Printed Circuit Board (PCB). Again, the equipment required to fabricate PCBs is very expensive, so the majority of designers use third party PCB houses to fabricate their devices. This process can also be very expensive, especially for prototyping and low volume production. Lastly, in order to design antennas, a solid mathematical foundation is required, along with a strong RF engineering background, because of the many complex mathematical concepts related to electromagnetic wave propagation, and the specific design concepts relating to the desired antenna application.

In an attempt to understand the methods used by other universities around the country to teach the theory, design, fabrication, and analysis of antennas, numerous collegiate web sites were visited. The search process investigated the methodologies not only to teach antenna design theories, but also the laboratory fabrication and testing of antennas. The search included major universities within the United States that have solid programs in Electrical Engineering Technology (EET), such as Penn State University, Arizona State University, Old Dominion University, University of Hartford, and others. Each of the mentioned universities included the theory and practical application of antennas within their communications courses, but none show any significant laboratory work in simulation, fabrication or testing.

There are commercial products to aid in the design, simulation, and modeling of antennas, such as Ansoft's Wave Propagation, Hewlett Packard's EESoft, and Remcom's XFDTD. Although these packages are a valuable asset in the entire scheme of antenna design, simulation, fabrication, and test, they do not tell the whole story. This software approach is the most popular method of teaching antenna design at most major universities. It is understandable that most would choose this method due to the great expense of the antenna fabrication and test equipment required, not to mention the university resources of faculty and laboratory space.

II. Approaches Considered

A considerable amount of time was devoted to considering various approaches to solving the problem of effectively teaching antenna design, fabrication, and analysis for Engineering Technology students. One of the possible approaches is a strictly theoretical approach to antenna design. This approach would be based almost entirely of previous findings and mathematical equations to calculate the various parameters needed for design. This approach would be educational and low-cost, but since the whole problem involves teaching antenna design, fabrication, and analysis to technology students, it does not require any hands-on aspects. Because of its downfalls, this project approach was rejected.

A second approach could involve an analysis of pre-fabricated antennas. Since engineering technology students would be working directly with the physical antenna designs, this approach seemed to fit the criteria quite well. It was decided, however, that the engineering technology students would lose valuable information included in the design of antennas by simply trying to analyze their operation from a pre-fabricated design.

A third approach that was considered involved a simulation-based analysis of antenna design. For this approach, engineering technology students would use antenna simulation software to model various types of antenna designs in order to analyze their characteristics. However, this approach would also negate the hands-on aspect of the engineering technology curriculum.

It was determined that a combination of all three alternate approaches provided the most effective solution. In order to effectively teach antenna design, fabrication, and analysis for Engineering Technology students several requirements are necessary. For ease of development, the requirements of the solution were broken down into several segments. Initially, various types of antennas were researched to determine which types would be effective instructional instruments. Then, from the research, three different types of antennas were selected as suitable for instructional purposes. The design parameters for each of the antenna types, was established, and the three theoretical antenna designs computed. After the antenna computations were complete, a written design procedure was documented. The written design procedure includes all of the necessary data to enable students to design the three selected antennas. Next, simulations for each of the antenna designs were performed using RF modeling software. After achieving the appropriate simulation results within a predetermined range of error, each of the three antennas were fabricated and tested. Finally the measured, simulated, and theoretical data for each of the antenna designs was analyzed, and the instructional materials were created.

III. Microstrip Antenna Design

A. Background

In its simplest form, a microstrip device can be defined as a layered structure with two parallel conductors separated by a thin dielectric substrate and the lower conductor acting as a ground plane. A microstrip transmission line is formed if the upper metallization is a long narrow strip. Similarly, if the upper conductor is a patch that is an appreciable fraction of a wavelength in size, the device then becomes a microstrip antenna.

The microstrip patch is designed so its pattern maximum is normal to the patch, creating a broadside radiator, which is accomplished by properly choosing a field configuration mode of excitation beneath the patch. Modes of operation are discussed below

Typically, microstrip patch antennas are found in aircraft, spacecraft, satellites, and missile applications, where size is a major factor. This is largely in part that the patch antennas can be placed in a cavity-backed configuration, meaning they can be placed underneath the skin of airborne applications, producing a low profile design. When the particular patch shape is selected and mode are selected they are very versatile in terms of resonant frequency, polarization, pattern, and impedance. Additionally, modern technology has allowed the addition of adaptive elements such as varactor diodes to control the resonant frequency, impedance matching, and polarization.

The patch antenna belongs to a class of resonant antennas, which is also the cause of its poor bandwidth. Conventional patch designs yield bandwidths as low as a few percent. This characteristic has become a major challenge in the design of the patch antenna. Other common disadvantages of microstrip patch antennas include their low efficiency, low power, high Q, and poor polarization purity.

B. Feeding Methods

Several configurations can be used to feed microstrip patch antennas. The four most popular methods include the microstrip line, coaxial probe, aperture coupling, and proximity. These four popular methods used to feed microstrip patch antennas are shown in Figure 1.

The microstrip line feed is one of the easiest to fabricate, and simple to match, using a quarter-wave transform method. Unfortunately, as the substrate thickness increases surface waves and spurious feed radiation increases, further limiting bandwidth.

A coaxial line feed involves a connection with the inner conductor of the coax to the center of the patch antenna, while the outer conductor of the coax is connected to the ground plane of the patch antenna. This method is also easy to fabricate, but much harder to design. Multiple fringes must be cut out on each edge of the patch to create an impedance match to the source.

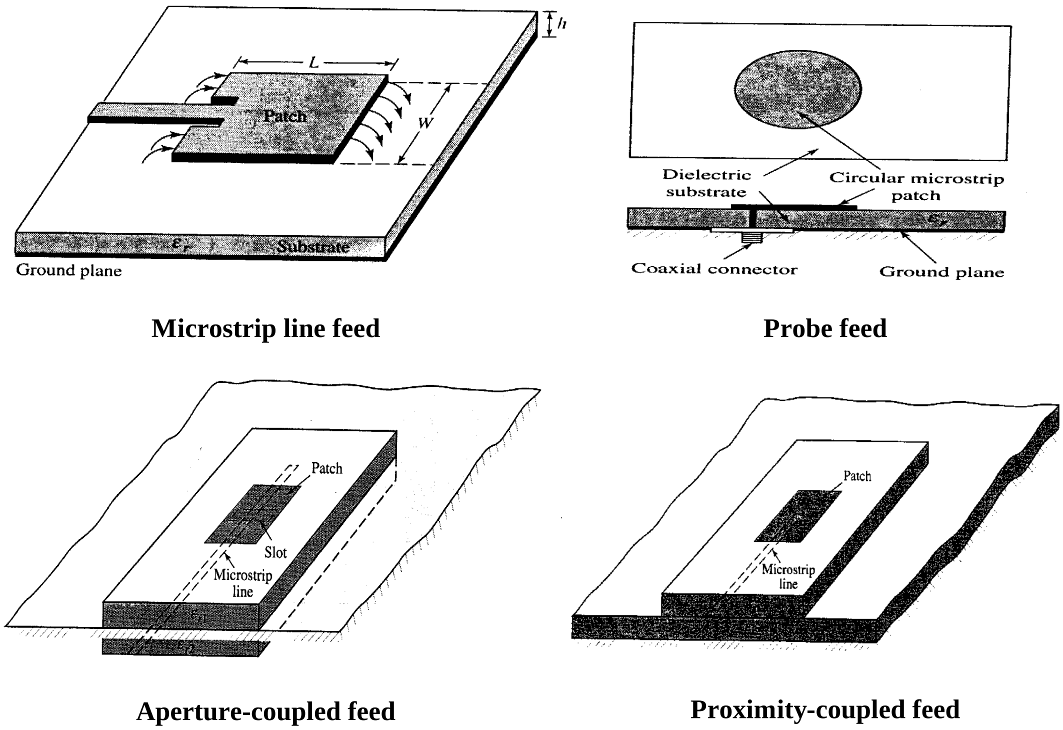

Figure 1: Typical Feed Methods for Microstrip Antennas

The aperture couple is the most difficult to fabricate and also has a narrow bandwidth. However, it is somewhat easier to model and has a lower spurious radiation. It consists of two substrates separated by a ground plane. The bottom side of the lower substrate includes a microstrip feed line whose energy is coupled to the patch through a slot on the ground plane.

Finally, the proximity coupling has the largest bandwidth, but is somewhat more difficult to fabricate. In this design, the length of the feeding stub and the width-to-line ratio of the patch can be used to control the match.

C. TEM Properties

The sectional sketch of a microstrip line in Figure 2 shows the conductor width and thickness, the substrate height and relative permittivity w, t, h, and ϵ_r, respectively.

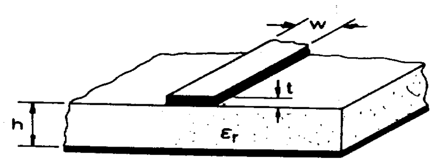

Figure 2: Microstrip Line

The substrate relative permeability μ_r is usually taken to be unity, and in most practical cases, the finite strip thickness can be neglected. For design purposes, knowledge of the wavelength λ is required of the wave guided in the microstrip and also the characteristic impedance Z_o of the line. The key factor of the calculation procedure rests on the fact that the structure would be readily analyzed if the dielectric material occupied all space. The conducting strip together with its image in the ground plane is then capable of supporting a pure transverse electromagnetic (TEM) wave.

To determine the dominant mode with the lowest resonance, one must examine the resonant frequencies. The mode with the lowest order resonant frequency is referred to as the dominant mode. The order of the modes of operation can be determined by placing the resonant frequencies in ascending order. For all microstrip antennas $h << L$ and $h << W$. If $L > W > h$, the mode with the lowest frequency (dominant mode) is the TM_{010} whose resonant frequency is given by;

$$fr_{010} = \frac{v_o}{2L\sqrt{\varepsilon_r}}$$

where v_o is the speed of light in free space. Additionally, if $L > W > L/2 > h$, the next order, or second order mode is the TM_{001}, whose resonant frequency is given by;

$$fr_{001} = \frac{v_o}{2W\sqrt{\varepsilon_r}}$$

If $L > L/2 > W > h$, the second order mode is the TM_{020}, instead of the TM_{001}, whose resonant frequency is given by;

$$fr_{020} = \frac{v_o}{L\sqrt{\varepsilon_r}}$$

If $W > L > h$, the dominate mode is the TM_{001}, while if $W > W/2 > L >> h$, the second order mode is the TM_{002}.

D. Patch Antenna Design Parameters

For all practical purposes, an elementary example is provided with all of the necessary design parameters, equations, and problem answers. Each step has been designed so that a student can work through each step of the calculations and compare their answers to the solutions of this guide, in a sequential fashion.

Again, to keep the design simplistic, a microstrip patch antenna has been chosen, fed by a matched 50Ω source, using the impedance matching technique of quarter-wave transform. The only specified requirements of this microstrip patch antenna design will be operating frequency, board material, and characteristic impedance. For this particular design, an SMA connector would simply be soldered onto the edge of the feed line, to introduce signals to and from the patch antenna. An example of this method of design is illustrated in Figure 3, shown below.

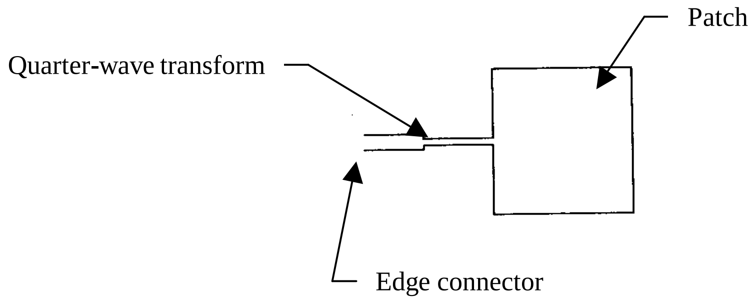

Figure 3: Example Patch Antenna

E. Design Exercise

Design a 3GHz square microstrip patch antenna on a 1.59mm substrate with a dielectric constant of 4.4 (FR4 printed circuit board material), and match the input impedance of the patch to the 50Ω characteristic impedance of the feed line using the quarter-wave transform method. The characteristics of the FR4 board material are provided below.

Material Type	FR4
Board Dielectric (ε_r)	4.4
Board Thickness (m)	1.5875E-03
Copper Thickness (t)	8mil

Design Procedure:

Step 1 – Calculate the patch width (w), given the frequency and dielectric constant.

$$w = \frac{c}{2 * f\sqrt{\varepsilon_r}} = \frac{3^{E8}}{2(3^{E9})\sqrt{4.4}} = 23.8366 \text{ mm}$$

Step 2 – Calculate the effective dielectric (ε_{eff}) of the microstrip transmission line.

The fringing fields about the two slots of the patch antenna makes the microstrip line appear wider electrically compared to its physical dimensions. Because of this, some of the waves travel in the substrate and some in the air, therefore an *effective dielectric constant* ε_{eff} is introduced to account for fringing and the wave propagation in the line.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \left(\frac{10h}{w}\right)\right]^{-1/2} = \frac{4.4+1}{2} + \frac{4.4-1}{2}\left[1 + \left(\frac{10*1.59^{E-3}}{2.38^{E-2}}\right)\right] = 4.0171\text{mm}$$

Step 3 – Calculate the effective open circuit or magnetic wall (Δ) beyond the edge.

Due to fringing effects, electrically the microstrip patch antenna looks greater than its physical dimensions. When considering the principle E-plane (xy-plane), the dimensions of the patch along its length have been extended on each end by a distance referred to as *ΔL*, which is a function of the effective dielectric constant and the w/h ratio. This distance is shown below in Figure 4. A practical approximate relation for the normalized extension of the length is given by;

$$\frac{\Delta}{h} = 0.412\frac{\varepsilon_{eff} + 0.300}{\varepsilon_{eff} - 0.258}\frac{w/h + 0.262}{w/h + 0.813} =$$

$$1.59^{E-3} * 0.412\frac{4.02 + 0.300}{4.02 - 0.258}\frac{\left(2.38^{E-2}/1.59^{E-3}\right) + 0.262}{\left(2.38^{E-2}/1.59^{E-3}\right) + 0.813} = 0.7250\text{ mm}$$

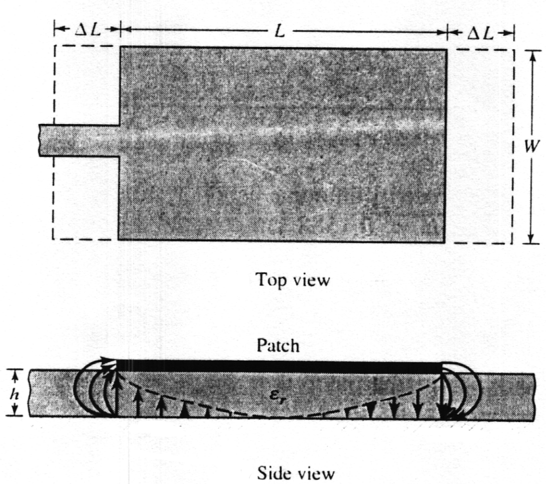

Figure 4: Physical and effective lengths of rectangular patch antennas

Step 4 – Calculate the resonant length (*l*) of the patch. (Refer to *Figure 6*)

$$l = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2\Delta = \frac{3^{E8}}{2*3.0^{E9}*\sqrt{4.0171}} - 2\left(7.2498^{E-4}\right) = 23.4970\text{ mm}$$

Step 5 – Since goal of this exercise is to design a square patch microstrip antenna, substitute the length from *step* 4 for the width, and recalculate ε_{eff}.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \left(\frac{10h}{w}\right)\right]^{-1/2} = \frac{4.4+1}{2} + \frac{4.4-1}{2}\left[1 + \left(\frac{10*1.59^{E-3}}{2.3497^{E-2}}\right)\right] = 4.0133$$

Step 6 – Recalculate the length (l) once more using the new value of the *effective dielectric constant* ε_{eff} calculated in *step 5* above.

$$l = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2\Delta = \frac{3^{E8}}{2*3.0^{E9}*\sqrt{4.0133}} - 2\left(7.2498^{E-4}\right) = 23.5086\,\text{mm}$$

Step 7 – Calculate the input conductance of the patch fed on the edge corresponding to the feed line. (Note this equation is highly simplified, and well suited for practical purpose designs).

$$G = \frac{l}{120*0.1}\left(1 + \frac{\left[2\pi(h)/100\right]^2}{24}\right) = \frac{2.3509^{E-2}}{120*0.1}\left(1 + \frac{\left[2\pi(1.59^{E-3})/100\right]^2}{24}\right) = 1.959^{E-3}\,\text{S}$$

Step 8 – Calculate the input impedance of the patch fed edge. Note that the resistance is not equal to simply the inverse of the conductance, but rather equal to the inverse of *twice* the conductance (this is due to the feed point being located in the center of the square patch.

$$R = \frac{1}{2G} = \frac{1}{2*1.959^{E-3}} = 255.23\,\Omega$$

This concludes the design procedures required for the microstrip patch portion of the antenna design. The next portion of the design involves the quarter-transform matching section, where the input impedance of the patch will be match to the characteristic impedance of the transmission line.

The design requirements for the quarter-transform section are as follows:

Frequency of Operation	3GHz
Transmission line characteristic impedance	50Ω
Input impedance at the feed of patch	255Ω
PCB Material	FR4

*Note that the characteristics of *w, t, h,* f_o, and ε_r are the same.

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Design Procedure:

Step 1 – Calculate the length ($l_{\lambda/4}$) of the λ/4 microstrip section.

$$l_{\lambda/4} = \frac{c}{4f\sqrt{\varepsilon_{eff}}} = \frac{3^{E8}}{4\left(3^{E9}\right)\sqrt{4.0133}} = 12.4790\,\text{mm}$$

Step 2 – Calculate the value R_{o2} for the quarter-wave transform match.

$$R_{o2} = \sqrt{Z_o * Z_{patch}} = \sqrt{50*255} = 112.97\,\Omega$$

Step 3 – R_{o2} is considered a low-Z region value, therefore calculate the variable B.

$$B = \frac{120\pi^2}{2*R_{o2}*\sqrt{\varepsilon_r}} = \frac{120\pi^2}{2*113*\sqrt{4.4}} = 2.4990$$

Step 4 – Calculate the width (w) of the λ/4 microstrip section.

$$w = (h)\frac{2}{\pi}\left\{B-1-\ln(2B-1)+\frac{(\varepsilon_r-1)}{2(\varepsilon_r)}\left[\ln(B-1)+0.39-\left(\frac{0.61}{\varepsilon_r}\right)\right]\right\},...$$

$$=\left(1.59^{E-3}\right)\frac{2}{\pi}\left\{2.5-1-\ln((2*2.5)-1)+\frac{(4.4-1)}{2(4.4)}\left[\ln(2.5-1)+0.39-\left(\frac{0.61}{4.4}\right)\right]\right\}=0.3707\,\text{mm}$$

Step 5 – R_o is considered a low-Z region value, therefore calculate the variable B

$$B = \frac{120\pi^2}{2*R_o*\sqrt{\varepsilon_r}} = \frac{120\pi^2}{2*50*\sqrt{4.4}} = 5.6461$$

Step 6 – Calculate the width (w) of the input section, attached to the coaxial feed line.

$$w = (h)\frac{2}{\pi}\left\{B-1-\ln(2B-1)+\frac{(\varepsilon_r-1)}{2(\varepsilon_r)}\left[\ln(B-1)+0.39-\left(\frac{0.61}{\varepsilon_r}\right)\right]\right\},...$$

$$=\left(1.59^{E-3}\right)\frac{2}{\pi}\left\{5.6-1-\ln((2*5.6)-1)+\frac{(4.4-1)}{2(4.4)}\left[\ln(5.6-1)+0.39-\left(\frac{0.61}{4.4}\right)\right]\right\}=3.0373\,\text{mm}$$

This concludes the design portion of the quarter-transform matching section of the microstrip patch antenna. At this point we have designed the complete patch antenna and matching network. The final design results are shown in Table 1, below.

Table 1: Design Results

Patch width	23.8366 mm
Patch length	23.5086 mm
$\lambda/4$ section width	0.3707 mm
$\lambda/4$ section length	12.4790 mm
Feed line width	3.0373 mm
Feed line length	Arbitrary

Congratulations, you have now successfully completed the design process for a 3 GHz quarter wave-transform match, microstrip patch antenna. The final product of the design process appears as shown in Figure 5.

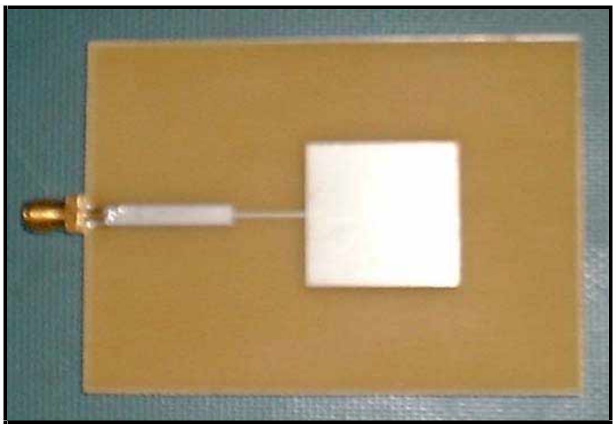

Figure 5: Patch Antenna Final Product

In conclusion, it should be noted that FR4 circuit board material should not be used when designing microstrip patch antennas, as it was in this particular design. The FR4 board material was used due to its availability, price, and familiarity, however it creates several obstacles, (mainly because of its high dielectric constant) for a successful patch antenna design. A board dielectric of 2.2 is highly recommended for a design of this nature, such as Duroid 5880.

III. Simulation and Measurements

It is important to note the difficulty involved when taking antenna measurements. Several expensive test components are needed, along with a suitable anechoic test chamber. In lab, just a single test component is available for antenna testing (the HP 8753D Network Analyzer). Additionally, an anechoic test range is not currently available. These factors limit in great part, what measurements can actually be performed, and the amount of error involved. Because of this, simulation results were used to compare actual test results for accuracy.

The following test and simulation (using Ansoft HFSS simulation software) data involved a 3 GHz Microstrip Patch Antenna. The plot, of Figure 6, shows the scatter parameter S_{11} for the Patch Antenna. This parameter conveys the amount of input reflection at the feed point. Ideally, the amount of reflection should be at a minimum for the antenna design frequency (3 GHz). Taking at look at the illustration, the least amount of reflection occurs at approximately 2.96GHz, which was very close to the designed frequency.

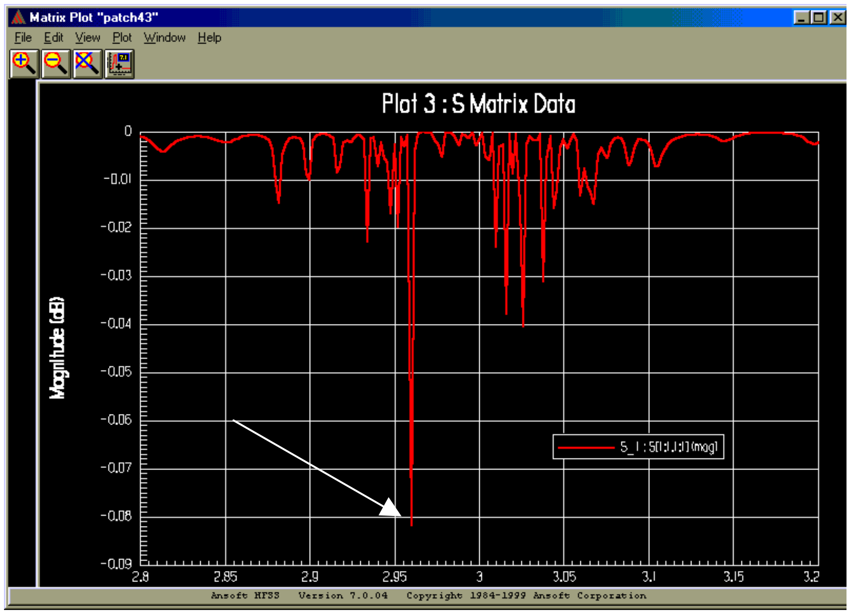

Figure 6: Ansoft HFSS Patch Simulation of S_{11} at 3GHz

After using the self-fabricated antenna test system to take S_{11} measurements on the patch antenna, the data was found to be conclusive. Refer to Figure 7.

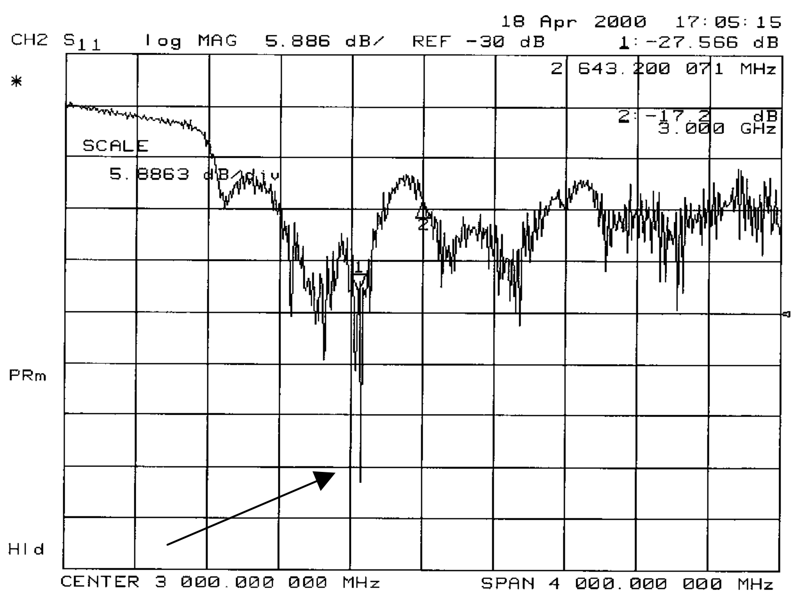

Figure 7: Measured S_{11} for the Patch Antenna at 3 GHz

Next, the data collected from the antenna test system were used, in conjunction with Microsoft Excel to produce a 2-D polar plot of the characteristic gain pattern of the patch antenna at 3GHz, shown in Figure 8.

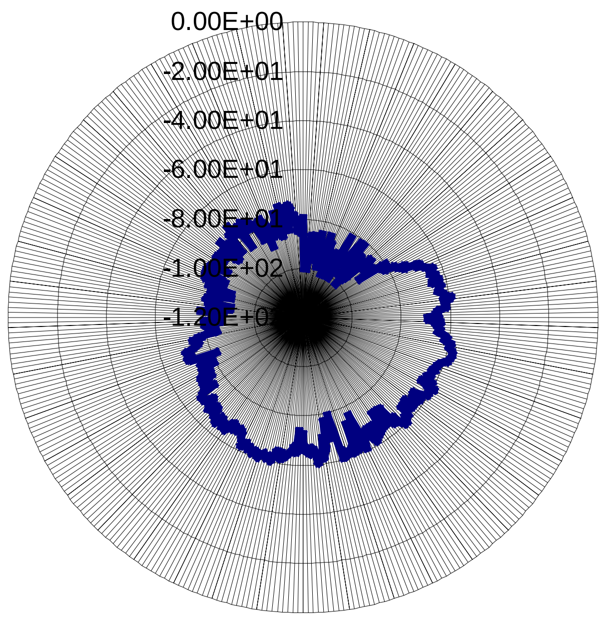

Figure 8: 2-D Polar Plot of 3GHz Patch Antenna

This two-dimensional plot represents a slice of how the three-dimensional radiation pattern would appear. An Ansoft HFSS simulation was run to create an idea of how the three-dimensional radiation pattern would appear, (shown in Figure 9).

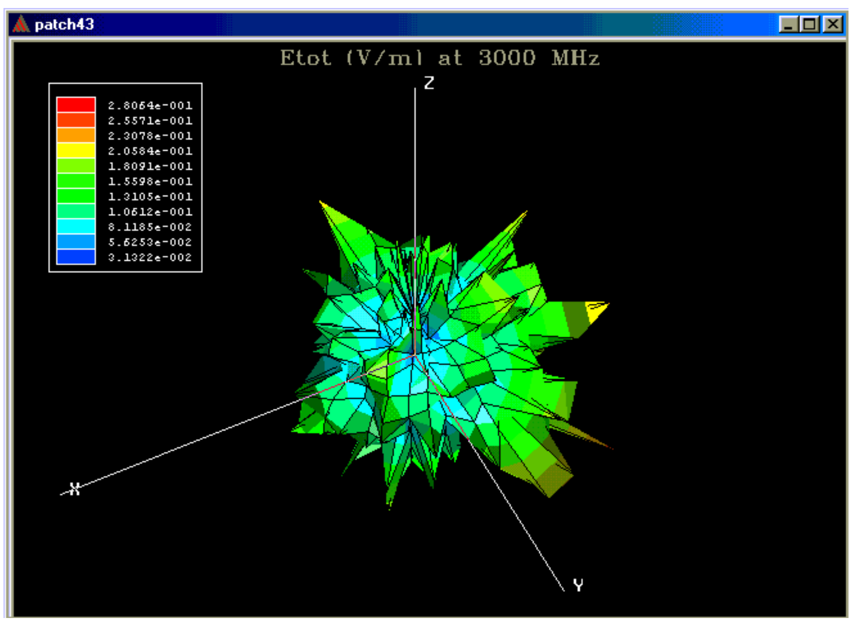

Figure 9: Ansoft HFSS 3-D Simulation of Patch Antenna at 3GHz

Overall, the microstrip patch antenna design functioned to a degree; however, the dielectric of the printed circuit board material drastically limits the abilities of the design, as far as its efficiency. Mainly the dielectric constant causes the quarter-wave transform matching section to become quite large, effectively creating a second radiator.

IV. Conclusions and Recommendations

The results of the antenna design project were overall very pleasing. Each step, for each of the three selected antennas, was completed successfully. The testing phase of the project was the most difficult. The difficulty in taking accurate measurements was significantly underestimated. The major setback in this area was the fact that our labs are not furnished with all of the necessary antenna test equipment. It eventually was discovered that some antenna measurements could be made with reasonable accuracy with the current test equipment and environment available. Mainly, it was possible to measure the impedance match of a test antenna, along with an abstract plot of the characteristic antenna 2-D polar plot.

Taking into consideration the amount of time and hard work this project required, the results are extremely pleasing. The department is now in a reasonable position to develop a complete course in RF antenna design within the Electrical Engineering Technology curriculum.

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