Ultra-Wideband Antenna

EE198B

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Introduction

Ultra-wideband (UWB) communication systems have the promise of very high bandwidth, reduced fading from multipath, and low power requirements [1]. For our project, we designed an UWB antenna for a handheld communications device with a bandwidth of 225 to 400 MHz, a voltage standing wave ratio (VSWR) of less than 1.5 to 1, and an efficiency of greater than 75 percent. The antenna had to be resistant to body effects, which means that if the communications unit is put up to the user's head or put on a large metal surface, that the radiation pattern will not be greatly affected. Our antenna also had to be small enough to fit on the communication device, which was ten inches high, by three inches wide, by one inch thick.

Theory

The main concept behind UWB radio systems is that they transmit pulses of very short duration, as opposed to traditional communication schemes, which send sinusoidal waves. The role that UWB antennas play in all of this is that they have to be able to transmit these pulses as accurately and efficiently as possible.

For this project, we had four main parameters that we had to satisfy. Those parameters were the bandwidth of the antenna, the VSWR of the antenna, the efficiency of the antenna, and the radiation pattern of the antenna. These parameters will help us understand if the antenna we are designing will be the optimal design for our application.

The first parameter that we had to consider for our design is the bandwidth. The bandwidth is basically the frequency (or frequencies) that the antenna is designed to radiate. In many cases, i.e. narrowband systems, the bandwidth specified for an antenna is very small because there is just one frequency that the antenna is required to radiate. In our case, we had to be able to radiate signals with frequencies between 225 MHz and 400 MHz. This required us to limit the antenna designs that we considered to strictly broadband antennas. The second parameter that we had to take in to account for our design is the VSWR of the antenna. The VSWR is defined as [2]

$$\mathrm{VSWR} = \frac{V_{\max}}{V_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|}. \qquad (1)$$

The voltage reflection coefficient, Γ, is defined as

$$\Gamma = \frac{V_o^-}{V_o^+} = \frac{Z_L - Z_o}{Z_L + Z_o}, \qquad (2)$$

where Z_L is the load impedance and Z_o is the characteristic impedance. This reflection coefficient is also equivalent to the scattering parameter s_{11}. The characteristic impedance is considered to be the impedance of the antenna for our purposes. The incident wave V_o^+ and the reflected wave V_o^- can also be related through the following equation for the total voltage on the line:

$$V(z) = V_o^+ e^{-j\beta z} + V_0^- e^{j\beta z} = V_o^+ [e^{-j\beta z} + \Gamma e^{j\beta z}], \qquad (3)$$

where β equals $\frac{2\pi}{\lambda}$. The VSWR is a way of calculating how well two transmission lines are matched. The number for the VSWR ranges from one to infinity, with one meaning that the two transmission lines are perfectly matched. In regards to antenna design, a VSWR that is as low as possible is desired because any reflections between the load and the antenna will reduce the effectiveness of the antenna. The third parameter that we took into account for our antenna design is the efficiency of the antenna. The radiation efficiency of an antenna is defined as [2]

$$e = \frac{P_{RAD}}{P_{IN}} \qquad (4)$$

where P_{RAD} is the power radiated by the antenna and P_{IN} is the power supplied to the antenna. The efficiency of an antenna is a measure of how much power is lost in radiating a signal from the antenna.

The fourth parameter is the radiation pattern of the antenna. This parameter is highly dependent on the application of the antenna. In the case of the antenna our group designed, we had to have an omnidirectional radiation pattern. This means that the radiation pattern had to be spread evenly 360 degrees around the antenna. The reason for this is because since the location of the transmitter is not fixed, you want to spread the radiated signal out as far as possible so the receiver will be able to pick up the transmitted signal.

One aspect of choosing a UWB antenna design that is important is ensuring that the design will not cause the pulse to spread when it is transmitted. Another aspect that is important is making sure that the antenna will be highly efficient in radiating electromagnetic energy. This is due to the fact that the transmit power used in UWB systems is very low (-41.3 dBm/MHz) [1]. Finally, the UWB antenna needs to be broadband enough to handle the bandwidth requirements for UWB (a fractional bandwidth greater than 20% [3]).

Our first challenge for this project was trying to decide what antenna design to use for this project. We needed a design that would be able to meet our specifications and also be small enough to fit on the communication device. One of the first designs that our group considered was the planar diamond dipole antenna [4]. This antenna has the advantage of having a low profile and a large bandwidth. Unfortunately, for the frequency range that we are designing the antenna for, the diamond dipole would have ended up being to large for our application. This is because substrate-based antennas have to have a length roughly proportional to the width of the antenna [5]. If we were to design such an antenna with a length of 1/4 λ, with

$$\lambda = \frac{c}{f} \tag{5}$$

With c = 2.998×10^8 m/s and taking f to equal 225×10^6 Hz, then ¼ λ would equal 13.1 inches. Coupled with the fact that we would have to use a thicker substrate to increase the efficiency of the antenna, our group decided this would not be a feasible antenna for our application. Another antenna design that we considered was the planar inverted-F antenna, or PIFA antenna. This is a very popular antenna design for mobile phones [6] because of its small size and its resistance to body effects, which is an antenna characteristic we were looking for. Unfortunately, this design also had many of the same drawbacks as the diamond dipole antenna design, such as large size and low efficiency. We finally decided on the dual-L monopole design. This design had the benefits of being easy to design, as well as being easy to construct.

The dual-L monopole antenna is a design based on the open-sleeve monopole antenna [7]. This antenna consists of two copper tubes with the ends bent at ninety degree angles. The purpose of having the ends of the elements bent is to reduce the length of the antenna. One of the elements is connected to the ground plane, while the other is a base fed monopole element. The length of the element connected to ground should roughly be half that of the monopole element. By adjusting the distance between the two elements and also by changing the diameter of the tubes, the VSWR of the antenna can be adjusted. The radiation pattern of the antenna is also affected by the distance between the two elements. If the distance between the two elements is $\frac{\lambda}{8}$, the radiation pattern will be roughly bi-directional. If the spacing is less than $\frac{\lambda}{8}$, then the radiation pattern will be nearly omnidirectional [7].

Simulation

To obtain computational results for the dual L shape design, CST Microwave Studio (CST MWS) electromagnetic simulations were performed. The MWS method is based upon the explicit solution of Maxwell's equations in differential form in the time domain. The design was optimized using the CST optimizer which was a matlab script. To optimize the antenna, 1200 iterations were performed altogether and 10 hours were used. From the computational results, optimized dimensions, return loss curve, both 2D and 3D far field radiation characteristics, animation of the Surface current distribution, Electromagnetic and Magnetic field flows of the antenna were obtained. The optimized dimensions are shown in figure 1.

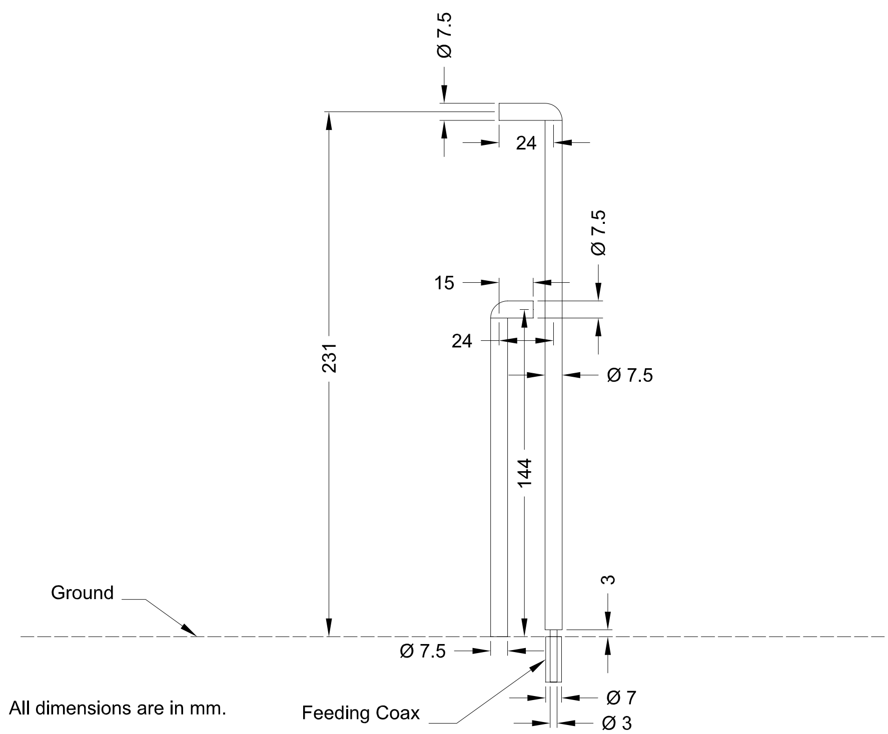


Figure 1: Optimized dimensions of the dual L shape antenna

As it can be seen the dimensions met the design requirements provided by the Lawrence Livermore lab. Below is the solid model of the antenna design (Figure 2 and 3). A box was drawn to define the mesh analysis (simulation boundaries with air).

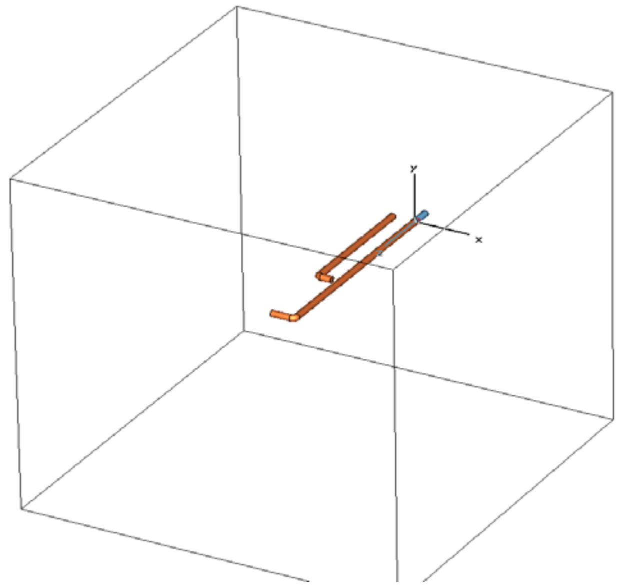


Figure 2: Mesh analysis for the antenna (box with air in it)

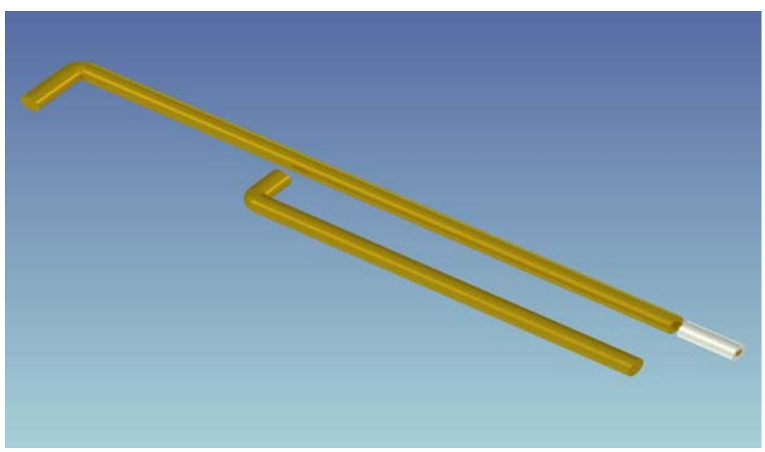


Figure 3: Solid model of the antenna

After several simulations of the optimized design for one port analysis, we obtained the S parameter curve (return loss curve) as shown in figure 4. Between 270 MHz and 404 MHz simulated return loss curve was below 1.9 VSWR (~ 11dB). Though the specifications required the antenna to have a VSWR below 1.5 (~ 14dB), the results were fairly similar to what was expected.

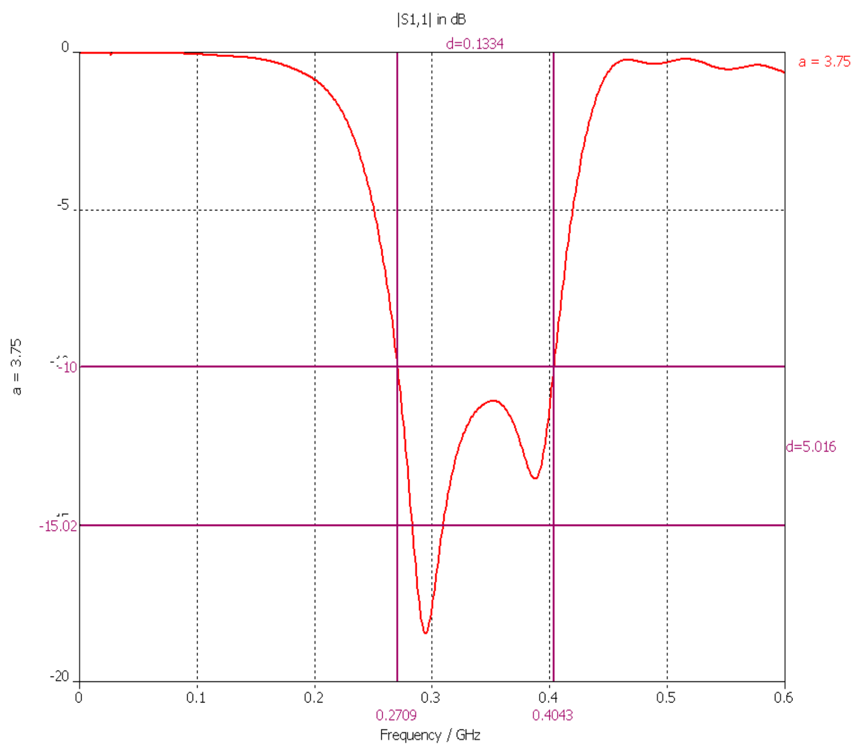


Figure 4: Return loss curve of the antenna

Next, the far field two dimensional radiation patterns were obtained and analyzed (figure 5). The best fit omni directional curve was obtained at 350 MHz and at this frequency, the efficiency (91%) and the gain (6dB) of the antenna were exceptional (figure 6). As shown in figure 6, the red color (highest gain) was omni directional (constant at all the angles). These clearly met the specifications of the antenna.

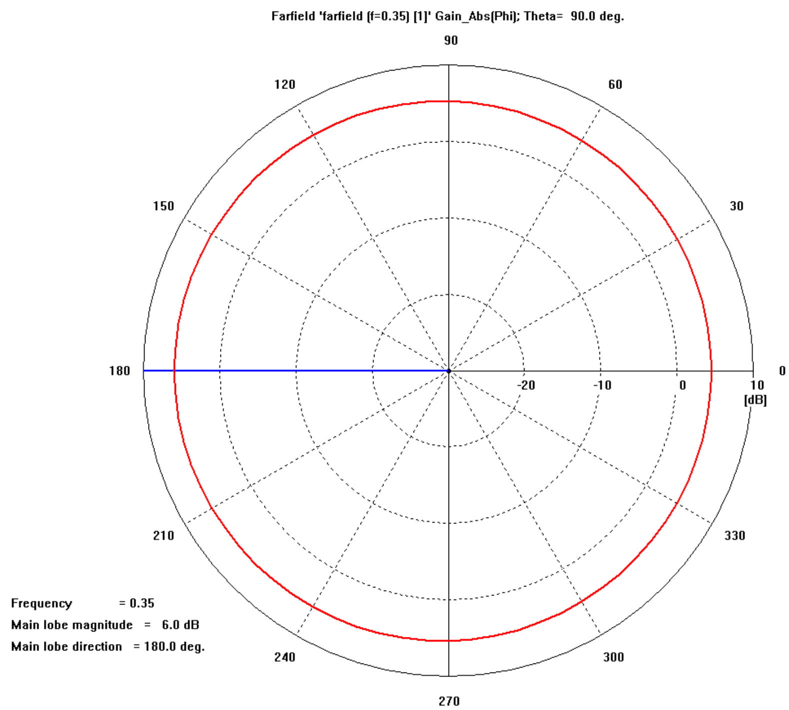


Figure 5: 2D radiation pattern at 350 MHz.

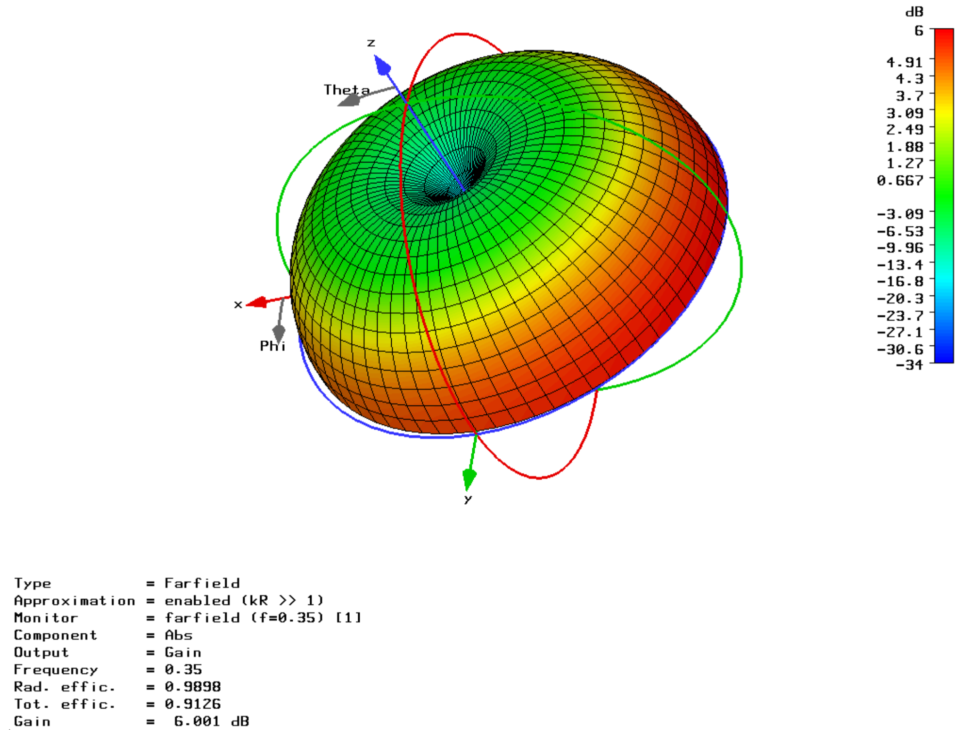


Figure 6: 3D radiation pattern at 350 MHz

Finally, the Surface currents, Electromagnetic field, Magnetic field were computed and an animation of the flows was obtained (figure 7, 8 and 9). A maximum of 9.38 A/m at 300MHz of surface current was obtained and it was at a maximum closer to the feed. And a maximum of 5963 v/m electric field was seen close to the edges and bends of the antenna. From the electromagnetic theory, we studied that the radiation is at a maximum at the edges of any coaxial cable antenna and the results confirmed it. Finally a maximum of 9.25 A/m magnetic field was obtained at 300 MHz and it was distributed along the bottom half of the long tube.

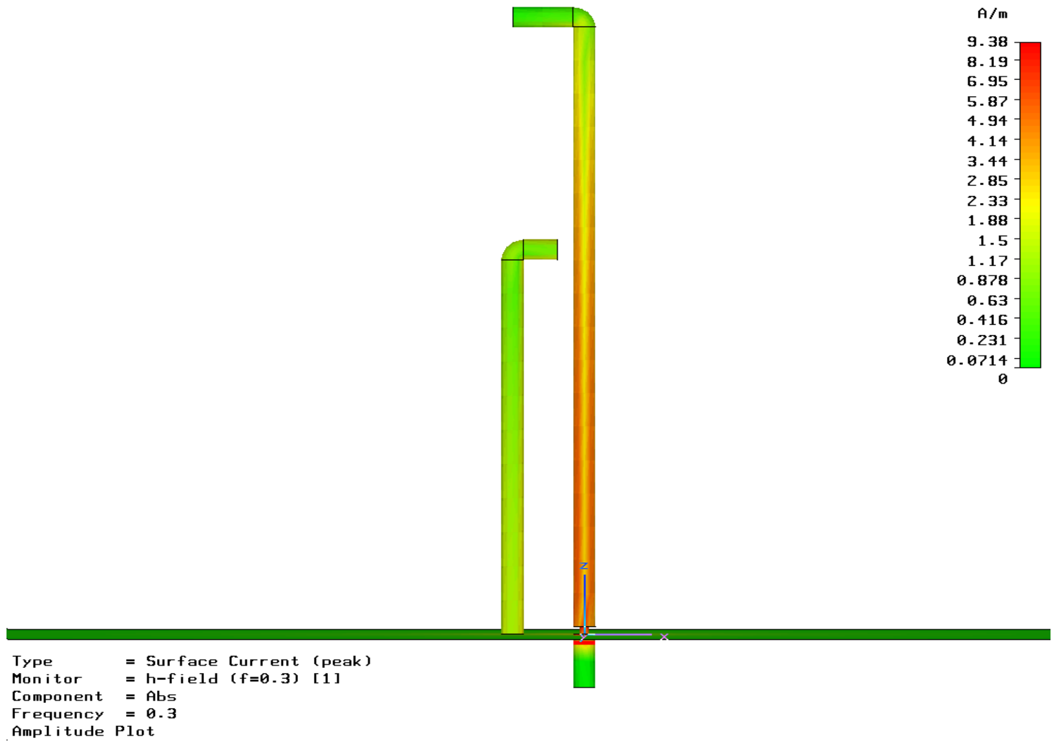


Figure 7: Surface current distribution at 300 MHz

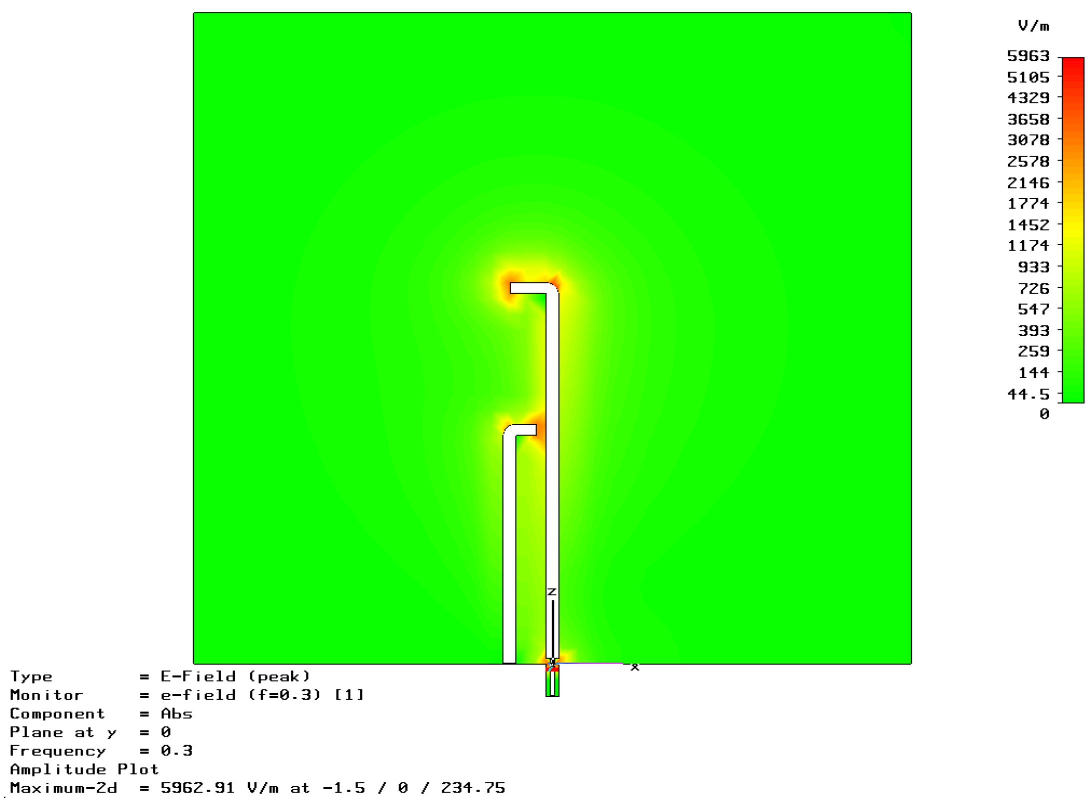


Figure 8: Far field Electric field distribution at 300 MHz

Figure 9: Far filed Magnetic field distribution at 300 MHz

Overall, the CST Microwave Studio optimizer gave us very promising computed results and it made it easy to build our actual prototype. One downside of this simulated program we encountered was the simulated results of the sharp bends of the antenna due to the complications of the Maxwell equations at those edges and taking an unusual long time to simulate.

Antenna Construction

<u>Tools List</u>
Hack Saw
Skill Saw
Drill
Tubing Cutter (item#73325, model#14T0180)
Tubing Bender (No. 101-3/8)

Standard file
Soldering gun and solder
Glue gun

Materials List
4ft. 5/16” Outer diameter copper tubing
1ft. by 2ft. copper sheet (X 2)
1ft. by 2ft. plywood board (X 2)
SMA connecter (female)

The antenna structure to be built consisted of three main components; a ground plane, the radiating tubular elements and its coupling counterpart, and a standardized connection interface for testing on the network analyzer. It was determined that the most suitable material for the structure was copper being that it was the most accessible of the better conductors. Thus material for the ground plane and the radiating elements (L-shaped rods) was made out of copper sheet and copper pipe respectively. For the connection interface a standard female SMA connector with a solder able lead was used. A brief description of each components construction follows.

Ground Plane

The simulations performed assumed an infinite ground plane for the antenna. Thus our approach was to make the ground plane a big as feasibly possible. It turned out that the only available copper sheet found was 2’ x 1’. Thus the ground plane was made of a 2’ x 1’ copper sheet. The sheet was mounted onto a ¾” piece of plywood using general glue for an adhesive. A small hole wide enough to feed the 5/16” pipe through was made at the center of the plane. This hole is where the SMA connector would be fitted.

Radiating Elements

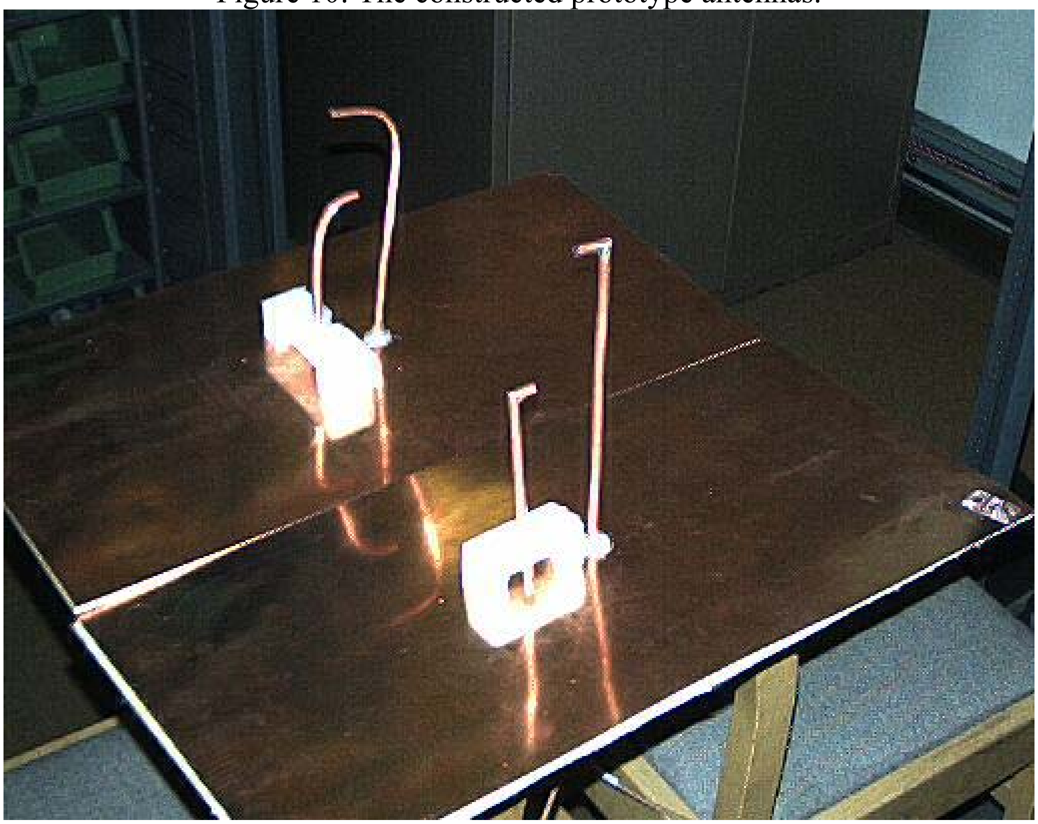
The radiating elements, or the two L-shaped rods, were made of 5/16” copper tubing. The most difficult step in the construction was making the required right angles. Two techniques were employed. The first technique was to use a standard tube bending tool and the second technique was to cut the pipe at a 45° angle and then attach the remaining pieces together such that a right angle was formed. The first technique, using the tubing bender, turned out to be extremely inaccurate. The tubing bender tool was unable to create a right angle bend, thus making the dimensions very inaccurate. The second technique, where the tubing is cut and re-attached, proved to give much better results in terms of matching the specified dimensions of the antenna. The procedure for this technique is to first cut the tubing at a 45° angle at a point where both remaining side will have enough length to be one of the two legs of the antenna. After cutting, the tubing is then soldered together such that a right angle is formed. Lastly, both sides of the connected pipe are trimmed using a standard tubing cutter to match the dimensions of the design. This technique produced accurate dimensions for the constructed model. However, two prototype antennas were built, one using each of the described techniques. This allowed us to determine which construction technique produced better results.

Connecting the rods to the base was fairly tricky. The shorter of the two rods was merely soldered onto the ground plane at the appropriate distance from the longer radiating rod. The shorter rod could also be used for tuning by leaving it unconnected but supported onto the ground plane by insulating foam. Connecting the longer rod involved suspending the rod 3mm above the ground plane. The only feasible way of doing this with the tools available was to use general glue as a supporting insulator between the ground plane and the rod. The most suitable insulator would have a dielectric constant closest to air ($\varepsilon_r = 1$).

SMA Connector

In order to test the antenna on a network analyzer a female SMA connection interface was built onto the ground plane. The connector was installed such that its base was shorted with the ground plane copper sheet and its inner conductor was shorted to the radiating element of the antenna, or the longer of the two L-shaped rods.

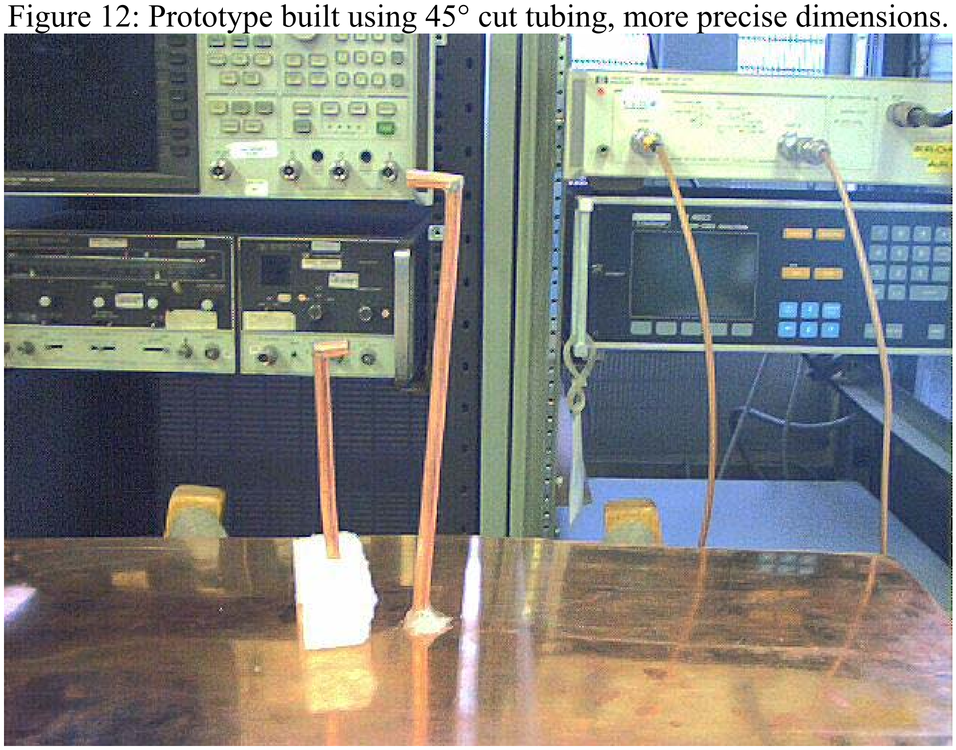
Figure 10: The constructed prototype antennas.



The following figures show the dramatic difference in the precision of the right angle achieved by the 45° cut structure and the bent structure.

Figure 11: Prototype built using bent pipe, suffers from imprecise dimensions.

Figure 12: Prototype built using 45° cut tubing, more precise dimensions.



Antenna Testing

For testing the antenna there are four main characteristics to be measured; Standing Wave Ratio, efficiency, proximity insensitivity, and directionality. The standing wave ratio is determined indirectly from the reflection coefficient or S_{11} parameter of the antenna. The S_{11} parameter is immediately obtainable from the network analyzer. In our testing we are looking for an S_{11} magnitude of -10dB across 270MHz-400MHz. The efficiency is measured by taking the ration of receiver antenna power output over transmitter antenna power output. This measurement requires a setup that includes both a transmitter antenna and receiver antenna where the transmitting antenna has well know characteristics. In a similar fashion directionality can be measured. The basic procedure is to rotate the receiver antenna in the field of the transmitter antenna and record the results over the entire 360° range. Often this procedure is performed in an anechoic chamber to eliminate environmental noise or reflections that would alter the receiving antenna's response. With our antenna we seek to have an omnidirectional response which means having a consistent gain at all angles relative to the transmitter. Lastly, to measure proximity insensitivity, the antennas response is measured as a function of distance from a human body. Ideally the antennas response should not be affected by it's proximity to surrounding objects.

Results

After the two prototype antennas were constructed they were brought into the lab for testing. There were four main characteristics that needed to be measured, Standing Wave Ratio, efficiency, proximity insensitivity, and directionality. Due to time constraints and lack of facilities only the SWR was measured. The other parameters to be tested required a setup that we did not have at our disposal. For instance, to measure directionality an anechoic chamber that suppresses noise and reflections in the testing environment is needed. For the other parameters a transmitter/receiver system would need to be setup which we were unable to do. Thus we focused on finding the best SWR for our antenna. To measure the SWR of the antenna we use S_{11} parameter measured by the network analyzer. The SWR results showed to be comparable to the simulation's predictions. We found that the antenna had a -10dB or lower response in the bandwidth of 265MHz-411MHz. This fell closely within the range predicted by our simulations, -10dB or lower at 270MHz-400MHz, as shown by figures 13 and 14 below.

Figure 13: S_{11} parameter for prototype antenna

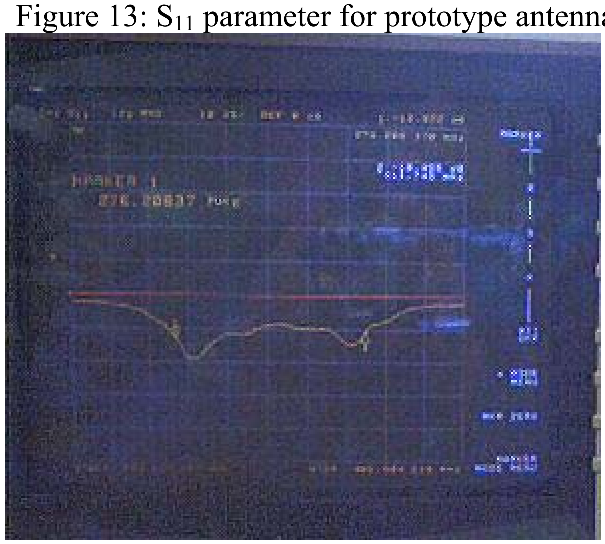
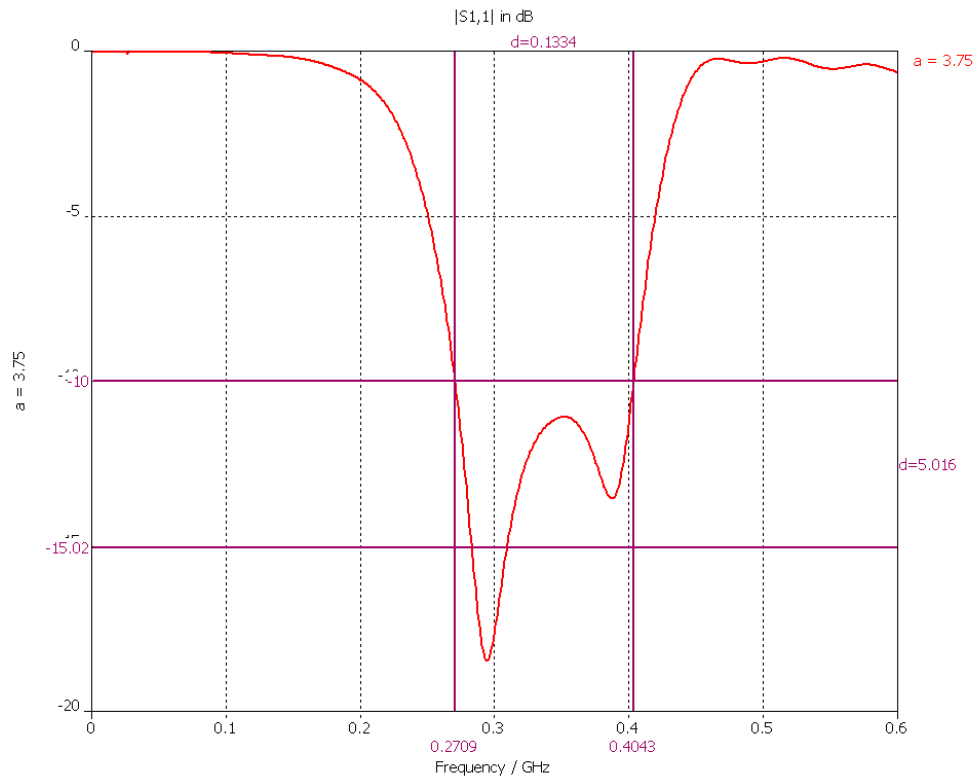


Figure 14: S_{11} parameter for simulated antenna



It was found that the antenna constructed with precise right angles displayed a better SWR than the antenna with the bent right angles. Ideally more testing and refinement of the antenna structure would need to be done to arrive at the most effective design.

Conclusion

An antenna was designed, built, and tested to meet the defined specifications. There was great success in finding a suitable structure, the inverted double-L topology, that showed promising simulation results for performance and construction feasibility. However, the results acquired show that the antenna design and structure need more refinement in order to achieve an ultimate design that would have a more solid performance under the defined specifications. Main goals for a later design would be to achieve a lower SWR across the bandwidth and better proximity insensitivity.

References

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