915 MHz Microstrip Antenna

by

Kenneth A. O'Connor

Under the supervision of

Dr. Tom Weller

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ABSTRACT:

A 915 MHz microstrip antenna will be designed, constructed, and measured/tested. The microstrip elements will be a quarter of a wavelength at the design frequency. Quarter-wave microstrip antenna theory will be discussed. The antenna will consist of two microstrip elements in a phased array. Antenna array theory will be touched upon with respect to beam steering. PCAAD 3.0 will be used to determine the inset feed length of a microstrip patch antenna required for a good impedance match. Agilent's Advanced Design System and Momentum will be used to simulate and layout the design. Simulation methods will be introduced as they apply to this design. The testing and measurement methods that were used will be discussed. Both, simulated and measured data will be compared and contrasted. Recommendations for improvement on the existing design will be given.

The Electrical Engineering Department at the University of South Florida requires each student desiring a Bachelor's Degree in Electrical Engineering to participate in a capstone design experience known as The Senior Design Project. In order to fulfill the Department of Electrical Engineering's design project requirement, I have designed, prototyped, and tested a 915 Megahertz (MHz) antenna. The antenna is to be used to transmit a signal from a group of sensors and associated circuitry back to a receiver in order to gather data. It is part of an overall design known as Project Nestwatch.

Nestwatch is a joint course between the University of South Florida and Tennessee Technological University. Each student designs, prototypes and tests a component in the overall system. The goal is to create a wireless sensor to gather data from a bird nest with regard to temperature, light intensity, and proximity. This sensor could be utilized by biologists/ecologists to study the nesting behavior of a particular bird. The collected data will be easily accessible as it will be posted to a website in real time. In addition, archives of the collected data will be available to the user.

The sensor should be minimally invasive and therefore be flat (or thin). So, the transmitter antenna should be flat, as well. So, the design specifications for this antenna are as follows:

- 915 MHz operation

- Flat or thin

- Compact

An idea for a design was recommended by Doctor Tom Weller. The design was to utilize two microstrip "patch" antennas in an array. But, a microstrip patch antenna radiates its maximum power in the direction normal to the plane of its surface. If this type

of an antenna were placed beneath a bird's nest, it would radiate its maximum power either directly into the ground, or directly up into the bird's nest. This is undesirable. It would be better if the antenna radiated its maximum power in a radial pattern around the nest. This would make it easy to receive the signal in any direction from the nest.

The microstrip patches were to be a quarter wavelength long at 915 MHz. This cuts down the overall size of the antenna by a half of a wavelength at 915 MHz. A brief explanation of this theory will be given.

The two elements were to be fed from the center using microstrip line. By varying the length of these feed lines, a phase delay could be achieved. This would allow for constructive interference to strengthen the signal in a particular direction. In a sense, it will steer the beam of the antenna off to one side. A brief explanation of this theory will be given, as well.

Thus a specific design requirement exists for the transmitter antenna to be utilized by Project Nestwatch. The following analysis will focus upon the theory, design, construction, and testing of a 915 MHz two-element quarter-wave phased-array antenna.

The design width of a microstrip patch antenna is given by

$$W = \frac{1}{2 \cdot f_r \cdot \sqrt{\mu_0 \cdot \varepsilon_0}} \sqrt{\frac{2}{\varepsilon_r + 1}} = 100.634mm \ [1].$$

f_r is the frequency of operation of the antenna (or the resonant frequency), μ_0 and

ε_0 are fundamental physical constants, and, ε_r is a property of the substrate. In the

general case, a microstrip patch antenna has a length of half of a wavelength at its

center frequency (915 MHz in this case), which is given by

$$L = \frac{1}{2 \cdot f_r \cdot \sqrt{\varepsilon_{r.eff}} \cdot \sqrt{\mu_0 \cdot \varepsilon_0}} - 2 \cdot \Delta L = 76.224mm \ [1]$$

$$\text{where } \Delta L = 0.412 \cdot h \cdot \frac{\left(\varepsilon_{r.eff} + 0.3\right) \cdot \left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{r.eff} - 0.258\right) \cdot \left(\frac{W}{h} + 0.8\right)} = 0.727mm \ [1].$$

A half-wavelength patch has an open circuit at the end opposite of the feedline. If

we measure the impedance a half a wavelength towards the feedline, we will see an

open circuit again. However, a quarter of a wavelength away, the open circuit looks

like a short circuit. This is known as a virtual short circuit [2]. For a quarter

wavelength patch, a channel is created and a long via is made to the ground plane at

the point where the virtual short circuit would be. This is an actual short circuit. This

concept is illustrated in Figure 1.

Since this design utilizes patches that are only a quarter of a wavelength in length,

the length is half of that calculated or 38.112 mm. So, the dimensions of each

microstrip patch have been designed.

As stated earlier, the edge of the microstrip patch represents an open circuit (an infinite impedance) while the center represents a short circuit (no or low impedance). So, this presents a problem when attempting to match the antenna with a standard 50-ohm feedline. Between the edge and the center of the patch, there is a point at which the impedance is 50 ohms with no imaginary part. Finding this "sweet spot" can prove to be difficult.

PCAAD 3.0 can be used to overcome this obstacle. Utilizing the procedure offered by Dr Tom Weller in Wireless and Microwave Instructional Laboratory #12 [3]. PCAAD allows the user to input the calculated dimensions of a microstrip patch and vary the position of a probe. Upon moving the probe to a certain position, the software computes the input impedance and plots the impedance on the smith chart. This is basically a trial and error method where values are tested and results reviewed until a satisfactory result is obtained. The inset feed length was determined to be 26.5 mm.

Since the width, length, and inset feed length of the patch are known, the individual patch design is complete. A representation of the patch can be seen in Figure 2. The feed network remains to be designed.

The basic idea behind the feed network is to achieve a phase delay between the two patches. This will result in both constructive and destructive interference. By tweaking the feedline lengths, constructive interference can be assured in the desired direction. Refer to Figure 3. Assume that the effective length from the feed point to the right patch is $\vartheta°$ at 915 MHz. Now, if the effective length from the feed point to the left patch is $\vartheta + 90°$ at 915 MHz then, at the edge of each patch, there is a $90°$

phase difference. Since the signals are traveling in different directions, their fringing fields are traveling in different directions at any instant in time as well. This introduces $180°$ of phase difference. Now, at the edge of each patch, there is a $270°$ phase difference. The distance between the two patches is $90°$ at 915 MHz in free space. So, as the signal leaves the left patch, it travels a distance of $90°$ in the air. So, by the time it gets to the edge of the right patch, it has moved through a phase difference of $360°$. This means that at this point, the signals are once again in phase and experience constructive interference.

In order to implement this theory in the design, both patches need to be fed from the center, with a $90°$ phase difference and $90°$ of physical distance between the two. First, the width of a 100-ohm line must be known. Since the feed point sees two transmission lines in parallel, they will need to be 100-ohm lines. This will look like 50 ohms. The width of a 100-ohm line can be calculated using a software simulation tool called Linecalc. Linecalc is contained in Agilent's Advanced Design System. The user need only input a few substrate properties and the desired impedance/electrical length, and Linecalc computes the physical dimensions [4]. The antenna will be constructed on FR4 substrate that is 59 mils thick. The substrate parameters can be seen in Table 1. According to Linecalc, the width of a 100-ohm transmission line on 59 mil FR4 is 0.63 millimeters (mm). The length of a $90°$ long line is 68.5746 mm.

Now, electrical length is given by $\vartheta = \beta \cdot d$ where $\beta = \dfrac{2 \cdot \pi}{\lambda}$ and d is measured relative to the wavelength. To determine the spacing between the two elements, the

distance d must be known for $\vartheta = 90°$. Since the wave will be traveling in free air, the free space wavelength should be used for this calculation. Solving for d, and solving the equation, it is shown that d is 81.911 mm.

I decided to divide this 81.9 mm space into two sections, a right half and a left half. The signal feedline will be fed in the middle of the right part of the feedline (see figure 3). This distance is one quarter of the total distance or 20.47775 mm. Using the equation above, this physical length represents $38.3779°$ in electrical length. So, the section of feedline on the left of the feedpoint must be $90° + 38.3779°$ in length. Since $38.3779°$ corresponds to one quarter of the total distance between the two patches, I simply added a section of line $38.3779°$ long to the left of the feedpoint. This leaves one half of the distance to achieve the remaining $90°$ of phase difference. I decided to meander the line up and then down. I split the length $\left(\dfrac{81.9mm}{2} \right)$ into 7 pieces. Three of the pieces are the width of the 100-ohm line and correspond to the vertical sections in Figure 3. The other four sections correspond to the four horizontal sections and are 9.8 mm in length. This spans the 40.95 mm.

To achieve the $90°$ of phase shift, I need to have 48.1 mm of line in the remaining 40.95 mm of space. This means that the meander should add 7.1 mm of physical length to the line. I have four sections of even length and one 0.6mm section to make up the 7.1 mm. Dividing 6.5 by 4, I get that each section of line should be 1.625 mm in length. Due to the limitations of the milling machine at the University of South Florida, I will round these off to 1.6 mm.

Now, the dimensions of the microstrip feed network have been designed. A representation of the feed network can be seen in Figure 4.

Agilent's Advanced Design System software (ADS) has within it, a CAD layout tool and a full-wave electromagnetic simulator called Momentum. A design such as this can be drawn in and then simulated to model the behavior of the actual device. During simulation, the software chops up the device into a number of small pieces (mesh) and then solves Maxwell's equations on each element. Once the device is behaving properly, the software will export a file that can be used on the milling machine to actually implement the device.

I drew the entire antenna into the layout tool in ADS. The resultant layout can be seen in Figure 5. I ran a number of simulations on the design in order to be fairly sure that every component in the design was working properly. I first ran a simulation on the patch by itself. The results were good with the value of S11 at –11.94 dB at 915.1 MHz (Figure 6). I also tested the feed network alone as a three-port device. Once again, the results were good with 88 degrees of phase difference between the two outer ports when driving the inner port (Figure 7). Finally, I simulated the entire antenna as a whole. I again obtained good results. I achieved –12.848 dB of return loss at 914.8 MHz (Figure 8). I then plotted the radiation pattern of the antenna (Figure 9). This plot shows that the maximum radiation has been shifted from the center ($0°$) to about $20°$ to the right.

Feeling rather satisfied with these results, I created the necessary file to have the antenna milled. After only one hour, I had my antenna in hand. I had to carve the vias (short circuits) at the end of each patch by hand. Once this process was complete, I

laid a bead of solder on the top and bottom of each patch along the edge of the via. Then I inserted copper tape through the slot. Next, I used a very wide soldering iron to melt the solder (now under the copper tape) in order for it to make the connection between microstrip and tape. When this was complete, I added the port. I soldered an SMA connector to the bottom of the antenna. This is possible because I had cleared away a small portion of the ground plane to avoid a short circuit. At this point the antenna was completely assembled and ready for measurement.

When I initially measured the return loss of the antenna, its center frequency was somewhere around 918 MHz. It is possible to "tune" the antenna to operate at the correct center frequency [3]. The procedure consists of cutting small strips of copper tape and sticking them in different places and at different lengths. It is a trial and error method. I tried placing strips in different places and finally found a "sweet spot" at the corner of one of the patches. I knew it was a good spot because the return loss increased a good deal and the center frequency shifted to 915 MHz. Then I added copper strips to all four corners. This seemed to help a great deal. The final antenna can be seen in Figure 10. I measured the return loss on the HP 8714 Vector Network Analyzer (VNA). This setup can be seen in Figure 11. I was able to achieve 19.15 dB of return loss at 915 MHz. These results can be seen in Figure 12.

Next, I measured the radiation pattern of the antenna using USF's anechoic chamber/antenna range. The range works in the following manner. The antenna to be tested is placed on a sort of turntable in the chamber. This turntable rotates $360°$. This setup can be seen in Figure 13. The chamber walls are lined with material that does not reflect radio frequency waves. Another antenna is placed in front of the chamber.

This antenna transmits a signal to the antenna under test (AUT). A diode detector is attached to the AUT and this is connected to a voltmeter. A computer and software program coordinate the whole measurement. The software measures the voltage across the diode detector, and then rotates the turntable $1.5°$. It repeats this process until the turntable has moved through the entire $360°$. It saves a spreadsheet-type file that can be used to plot the measured radiation pattern. The measured radiation pattern can be seen in Figure 14.

Upon comparison of measured versus simulated results, it seems that the measured results are slightly better than the simulated. For instance, the measured return loss is a little over one dB better than the simulated return loss. One possible reason for this discrepancy is that ADS automatically references its S-parameters to 50 ohms, regardless of the actual impedance looking into a port. Making a comparison of the simulated and measured radiation pattern, once again, it seems that the measured pattern is more desirable than the simulated. In the simulation, the maximum radiation occurred at about $20°$ from the center, while the measured maximum radiation occurred at about $27°$ from the center. One possible explanation for this discrepancy is that Momentum assumes that the ground plane under the antenna is infinite in dimension.

I feel that this process should be labeled a success. Although I had hoped to achieve maximum radiation at or around $45°$, the theory and measurement has taught me a great deal. In order to make this design better, I offer a few recommendations. First, a specification for this angle should be agreed upon in the beginning and then designed around. Second, decreasing the size of the area in between the two patches

could significantly reduce the size of the design. The additional required phase shift could be made up in the meandered section. I would also do more research into other methods for determining feedline inset length. Surely there is an equation in a paper somewhere. Finally, to serve the purpose as the transmit antenna for Project Nestwatch, there are other approaches that would most likely use less space than my current design.
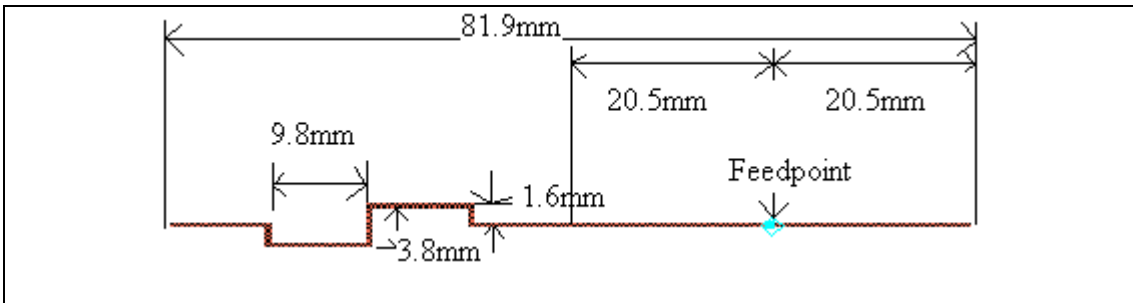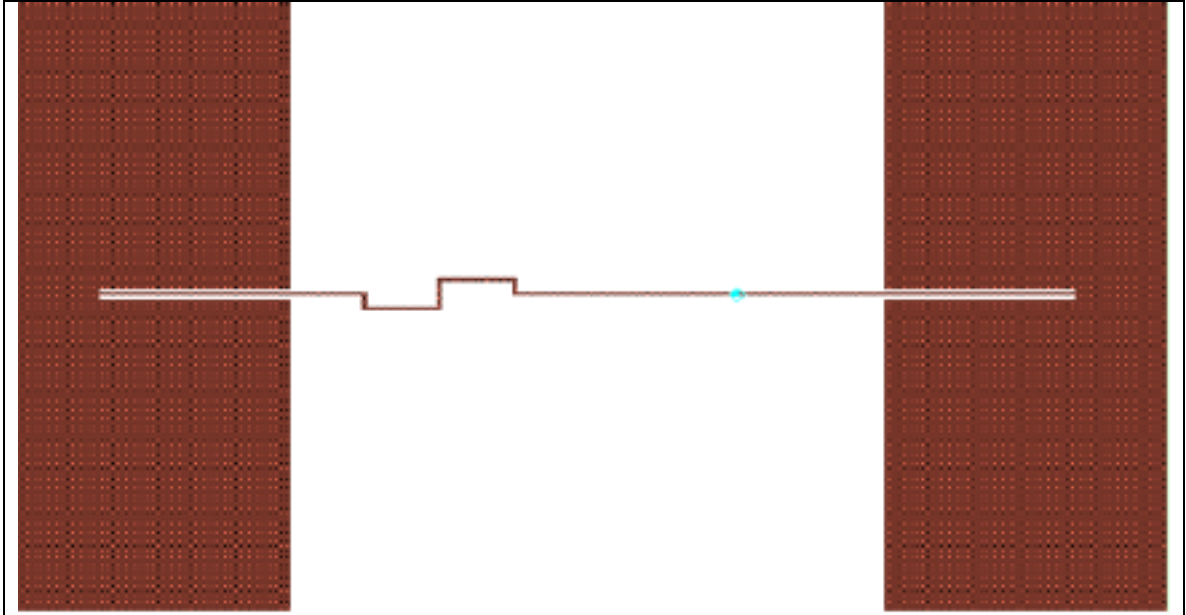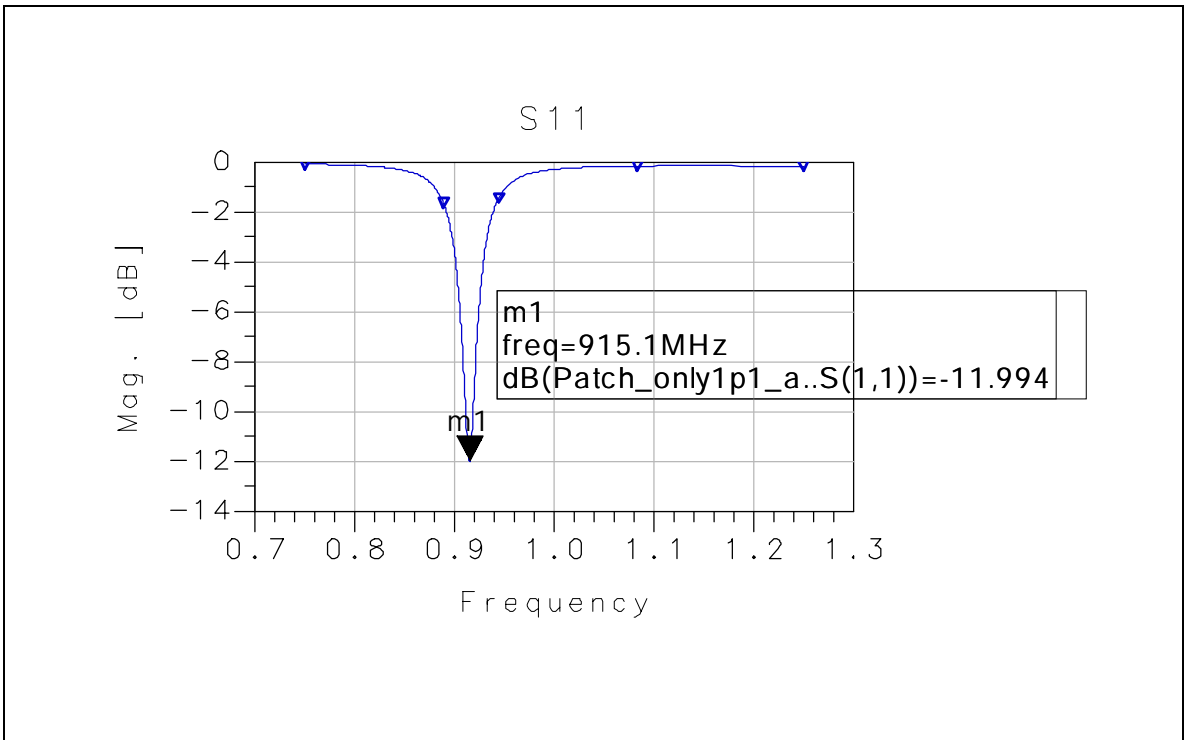
FIGURES AND TABLES:
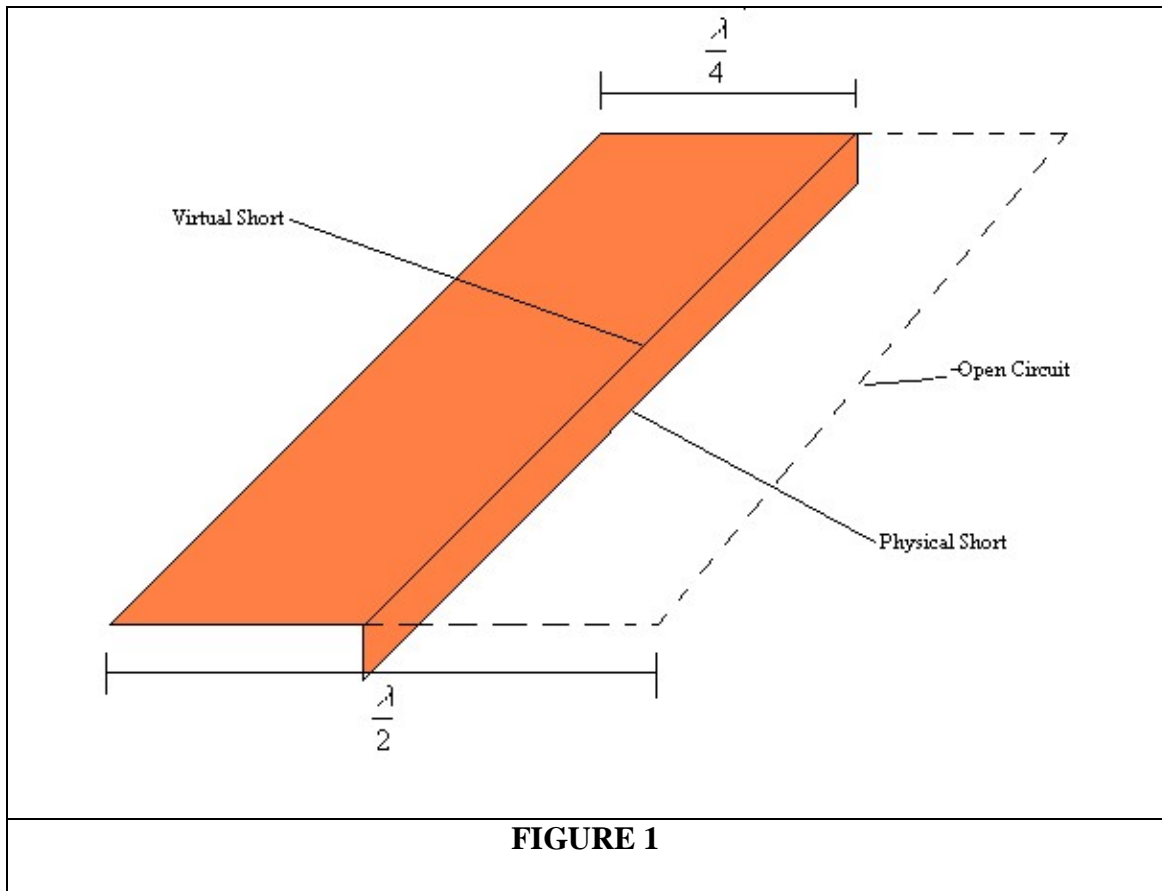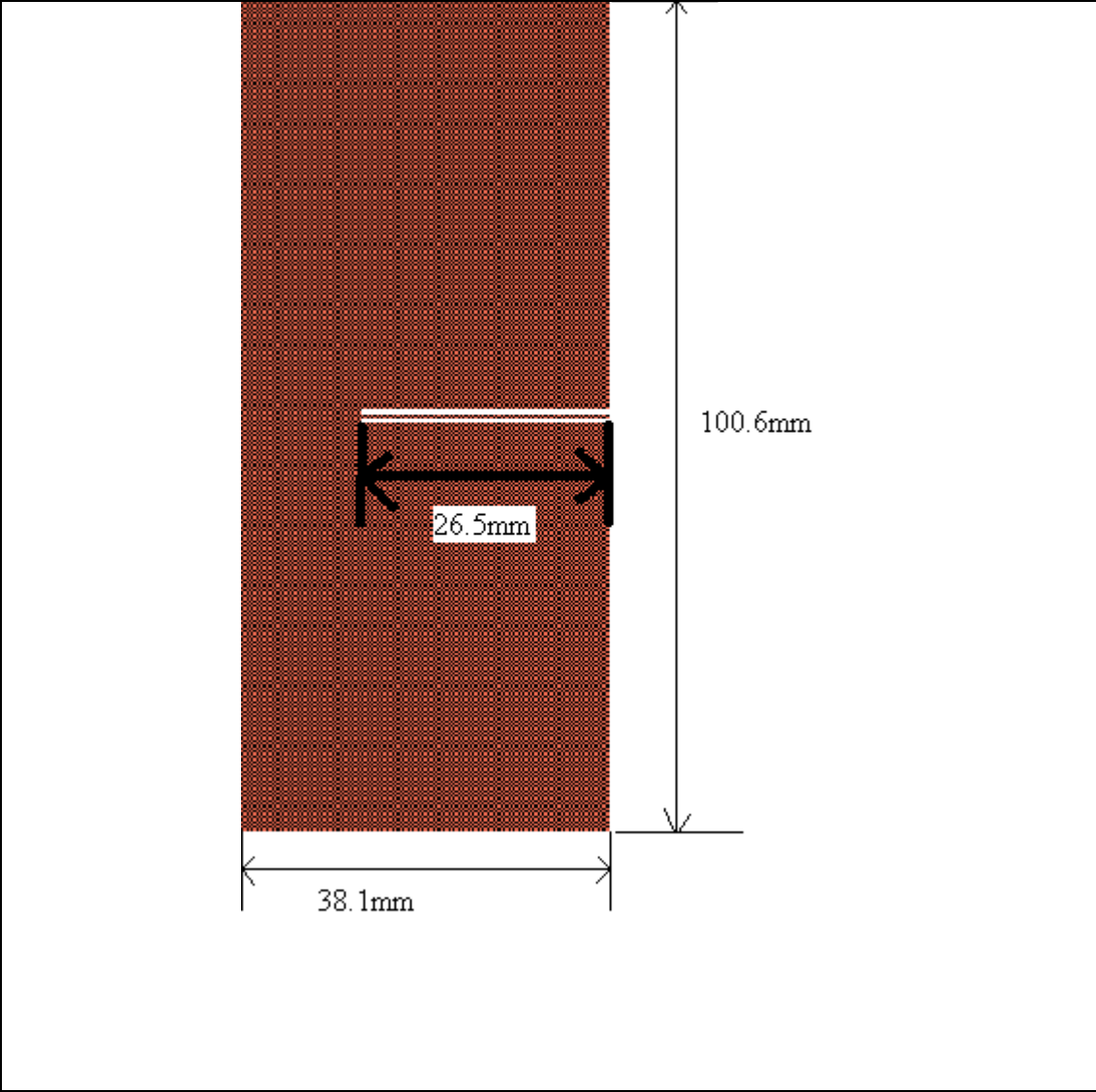
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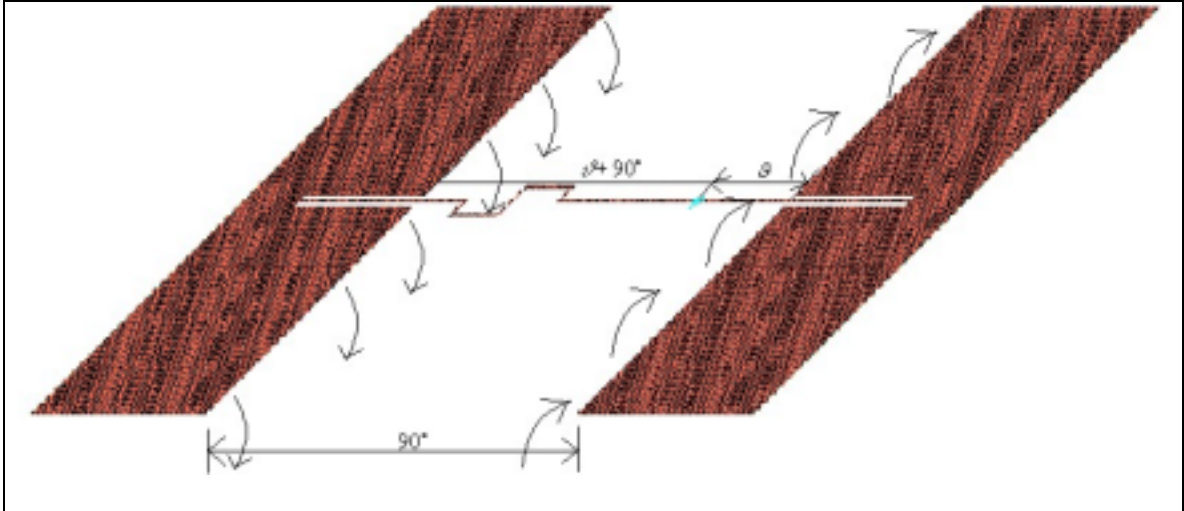
FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5
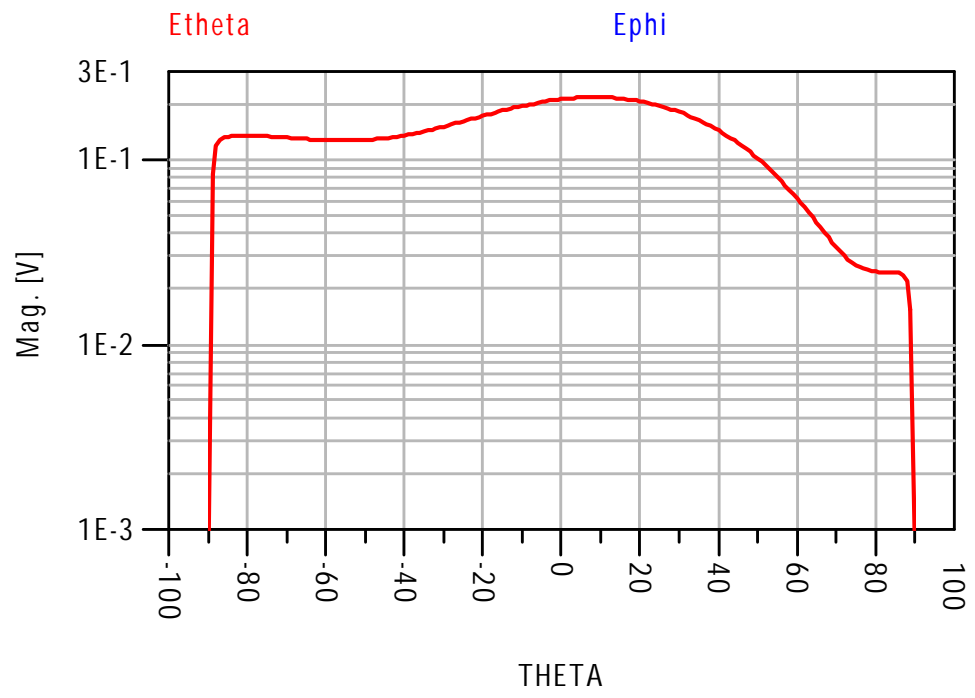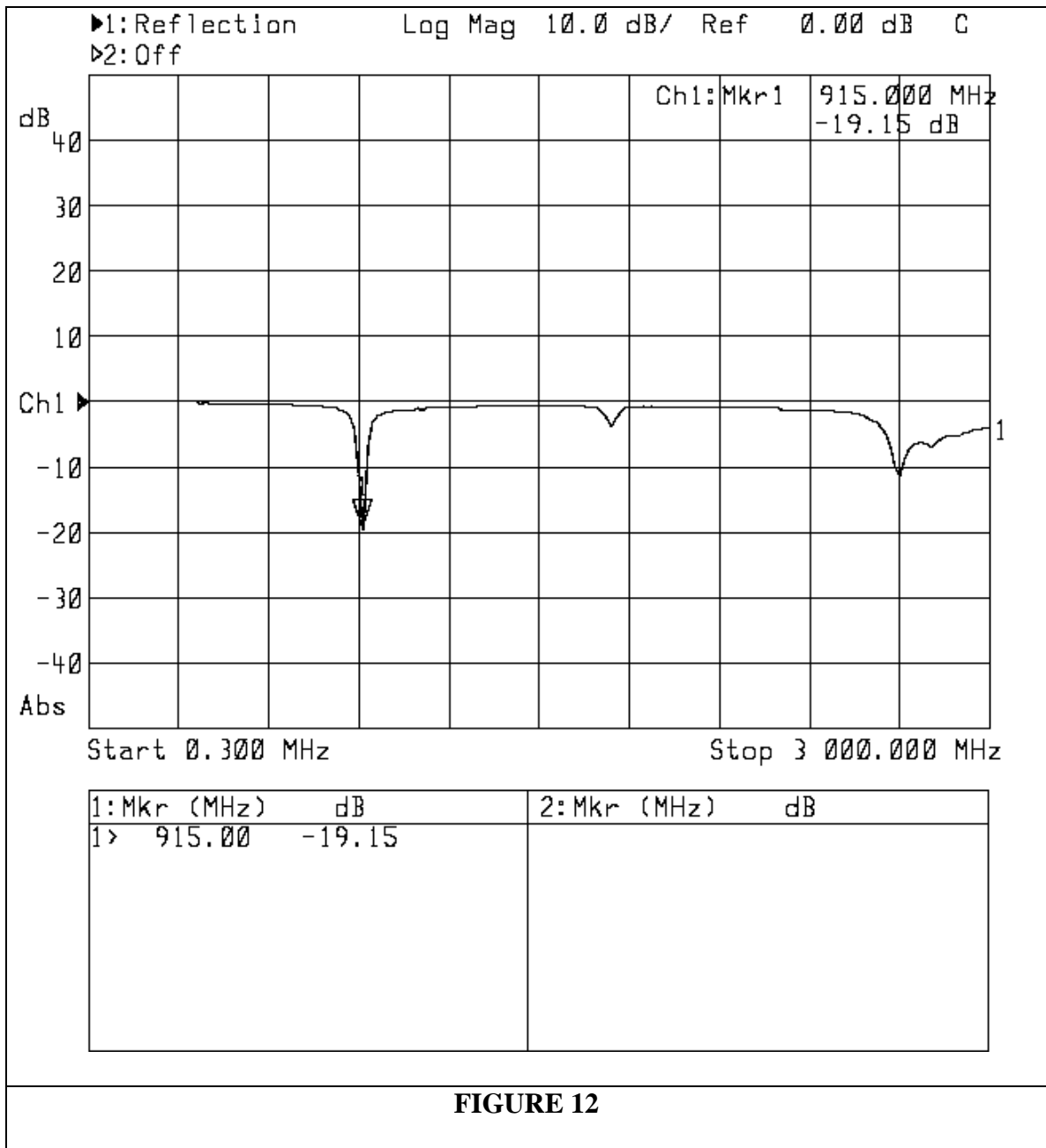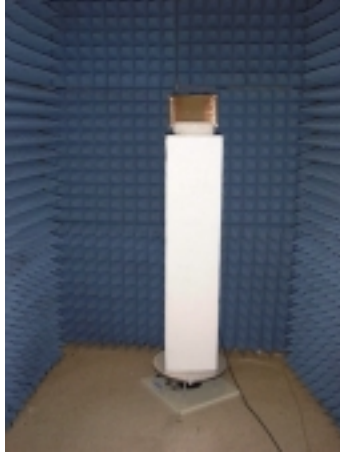

S11

m1
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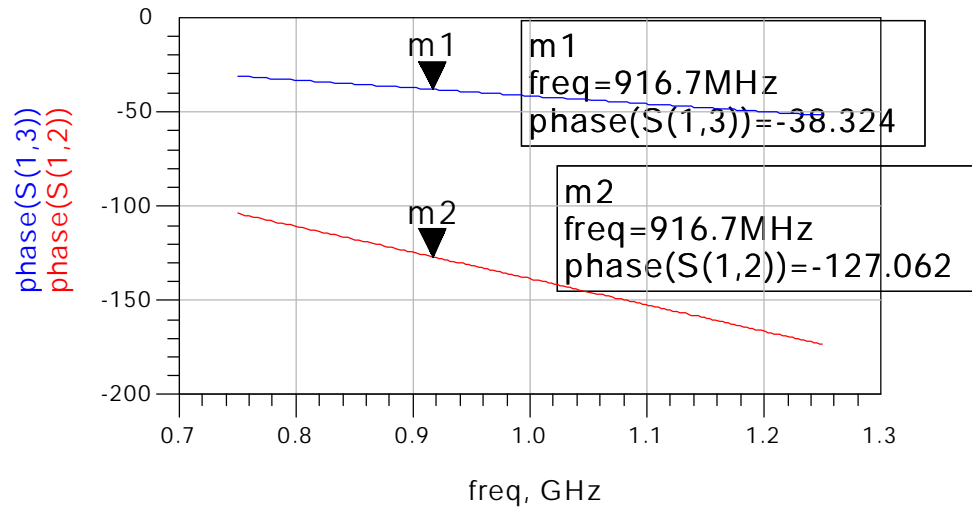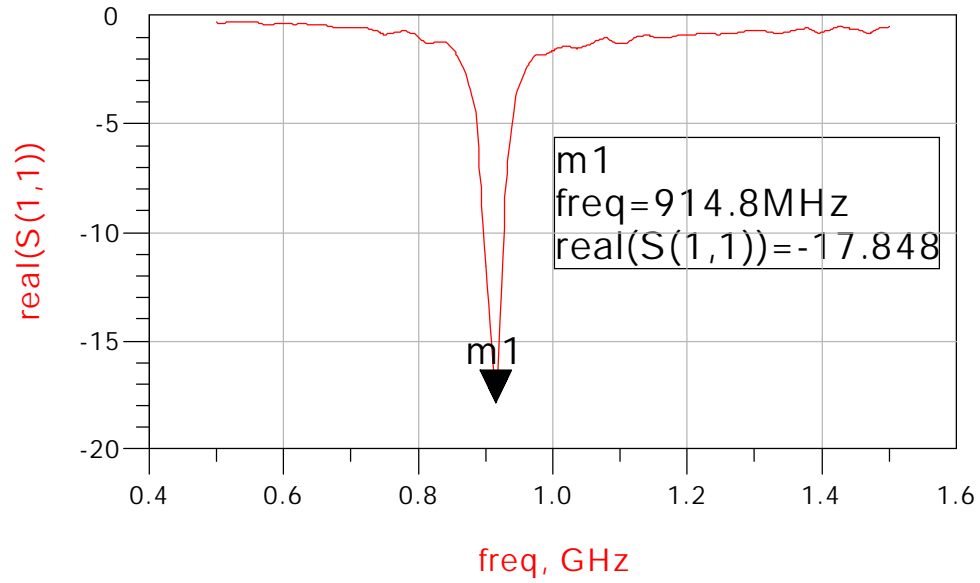
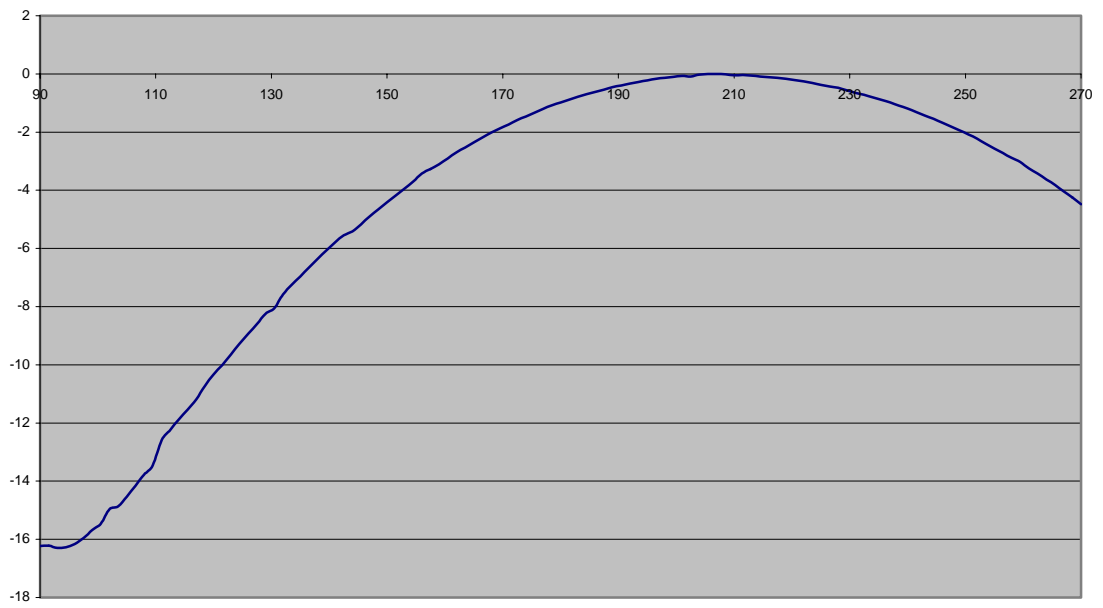**FIGURE 6**

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13

FIGURE 14

TABLE 1	
Substrate Height	59 mil
Metal Thickness	1.7mil
Relative Electric Permittivity	4.3
Relative Magnetic Permeability	1.00
Loss Tangent	0.022

REFERENCES:

[1] Balanis, Constantine A. <u>Antenna Theory</u>, John Wiley & Sons, Inc. 1997

[2] Garg, Ramesh; Bhartia, Prakash; Bahl, Inde; Ittipiboon, Apisack; <u>Microstrip Antenna Design Handbook</u>, Artech House, Inc. 2001

[3] Weller, Tom, "Dipole and Patch Antennas; Wireless Circuits and Systems Laboratory #12"

[4] Dunleavy, L. P., "Using the Linecalc Program in ADS; Wireless Circuits and Systems Laboratory Procedure #5"