Analysis and Design of ISM-Band Patch Antenna Array

By: John Herrmann, Zach Dyals, and Angel Arcia

Abstract- The objective of this report is to document the design, analysis, fabrication, and measurement of a directional antenna with a 50-Ω SMA connection. The aforementioned antenna is designed to operate in the 5.725-5.850 GHz ISM band. The key design constraints are as follows:

1. The device interfaces with a 50-Ω SMA line input
2. No active electrical components are implemented in the design
3. The total size of the antenna must fit within a 20cm x 20cm x 5cm rectangular bounding prism

I. Introduction

Antenna research was conducted to explore various methods of designing an antenna that operates both effectively and efficiently within the previously mentioned design constraints. After performing extensive research, the Yagi-Uda array and Microstrip Patch antenna array were deemed to be topologies that could effectively operate within the design constraints. Multiple designs, simulations, and analyses were conducted to provide insight on the advantages and disadvantages of both topographies. Ultimately the Microstrip Patch array was chosen due to its ease of impedance-matching with a 50-Ω SMA line input.

The ideal outcome of the design is to produce a highly directive antenna. As such, it is necessary to implement an array of patch antenna elements to promote greater directivity and gain. 1-element, 2-element, 4-element, and 8-element antennas were designed, simulated, and analyzed. For simplicity and ease of mathematical calculations, patch antenna elements were separated by a constant distance of λ/2. Furthermore, all elements were fed in-phase.

II. Single-Element Antenna Design

The single-element patch antenna is the basic building block needed to implement a multiple-element phased-array microstrip antenna. The design equations needed to construct a patch antenna were derived from a research paper titled *"Design and Performance Analysis of Microstrip Array Antennas with Optimum Parameters for X-band Applications"* [1]. Further citation of said paper is included in the Section XI.

The design equations and detailed calculations for antenna parameters are documented below:

$$v_o := 3 \times 10^{11} \quad \text{(Eq. 1)}$$

$$f_r := 5.7875 10^{9} \quad \text{(Eq. 2)}$$

$$f := f_r = 5.787 \times 10^{9} \quad \text{(Eq. 3)}$$

Figure 1a. Patch antenna calculations

$$\varepsilon_r := 4.3 \quad \text{(Eq. 4)}$$

$$\lambda_{air} := \frac{v_o}{f_r} = 51.836 \quad \text{(Eq. 5)}$$

$$h := 0.06 \cdot \frac{\lambda_{air}}{\sqrt{\varepsilon_r}} = 1.5 \quad \text{(Eq. 6)}$$

$$h := 1.48 \quad \text{(Eq. 7)}$$

$$W_p := \frac{v_o}{2 \cdot f_r} \cdot \sqrt{\frac{2}{\varepsilon_r + 1}} = 15.921 \quad \text{(Eq. 8)}$$

$$\varepsilon_{reff} := \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \left(1 + 12 \cdot \frac{h}{W_p}\right)^{-.5} = 3.784$$

$$DL := \frac{(\varepsilon_{reff} + .3)\left(\frac{W_p}{h} + .264\right)}{(\varepsilon_{reff} - .258)\left(\frac{W_p}{h} + .08\right)} \cdot h = 1.743 \quad \text{(Eq. 10)}$$

$$L := \frac{v_o}{2 \cdot f_r \cdot \sqrt{4.3}} = 12.499 \quad \text{(Eq. 11)}$$

$$L_p := \frac{v_o}{2 \cdot f_r \cdot \sqrt{\varepsilon_{reff}}} - 2DL = 9.836 \quad \text{(Eq. 12)}$$

$$W := \frac{v_o}{2 \cdot f_r} \cdot \sqrt{\frac{2}{\varepsilon_r + 1}} = 15.921 \quad \text{(Eq. 13)}$$

Figure 1b. Patch antenna equations continued from Figure 1a

The parameters of interest are those calculated by Equation 11 and Equation 13. Equation 11 indicates an ideal patch antenna length of 12.499 mm. This number deviates from the length calculated in Equation 12 due to the exclusion of the effective permittivity. The length calculated by Equation 12 was not initially used due to its magnitude. It was initially perceived to be too small to radiate efficiently at 5.7875 GHz.

Additionally, the ideal width calculated in Equation 13 was 15.921 mm. The design parameters for the antenna are detailed below:

- L= 12.499 mm (Antenna length)
- W= 15.921 mm (Antenna Width)
- H= 1.48 mm (Substrate Height)
- E.r= 4.3 (Permittivity of FR4)
- Mt= .038 mm (Metal Thickness)

The antenna was modeled in CST Microwave Studio and the results are illustrated below. Figure 2 illustrates the CST antenna model.

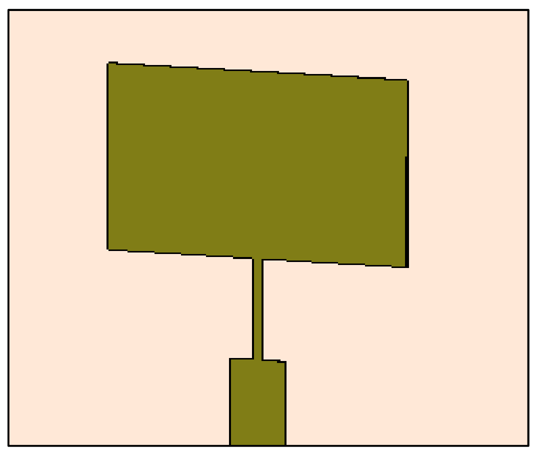

Figure 2. Patch antenna CST Model

The S11 and farfield realized gain plots are depicted in Figures 3 and 4, respectively. Additionally, Table 1 details antenna characteristics from the CST simulation.

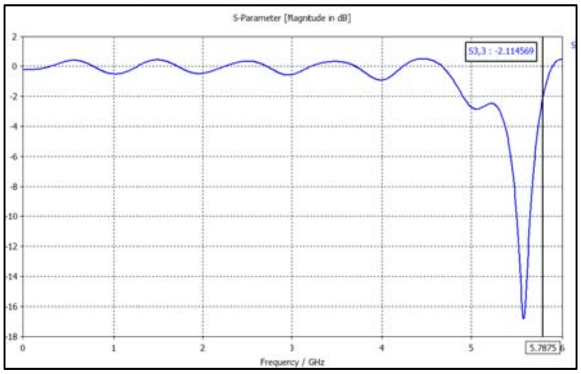

Figure 3. S11 plot for patch antenna

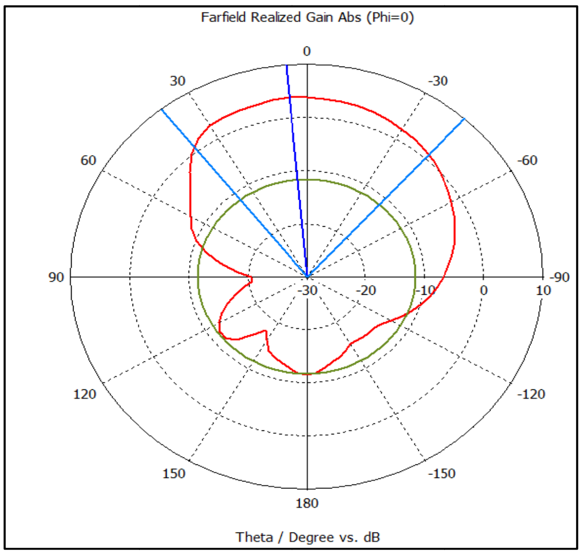

Figure 4. Farfield realized gain plot for patch antenna at 5.7875 GHz

Table 1. List of parameters for simulated antenna

Parameter	**Value**
Realized Gain at 5.787 GHz	3.90 dB
S11 at 5.725 GHz	-2.10 dB
S11 at 5.787 GHz	-1.90 dB
S11 at 5.850 GHz	-1.01 dB

A peak S11 of -2.10 dB and realized gain of 3.90 dB is deemed unacceptable for efficient antenna operation. As such, the antenna parameters derived from Equations 1-13 were modified until an efficient and effective antenna was produced. In order to shift the S11 minima towards the desired ISM band, the length L of the antenna was shortened. An antenna length of 10.40 mm was found to yield efficient radiation in the ISM band. Additionally, the width, W, was modified to further optimize the patch antenna.

A patch length of 25.4mm was found to produce a low S11 in the 5.72- 5.85 GHz frequency range. The antenna was modeled in CST Microwave Studio and the results are illustrated below. Figure 5 illustrates the CST antenna model. Moreover, the S11 and farfield realized gain plots are depicted in Figures 6 and 7, respectively. Table 2 details antenna characteristics from the CST simulation.

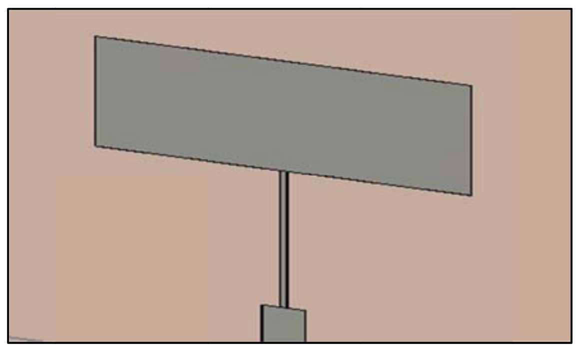

Figure 5. Modified patch antenna CST Model

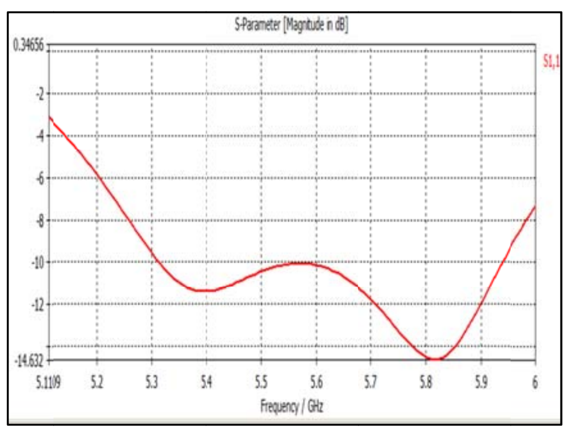

Figure 6. S11 plot for modified patch antenna

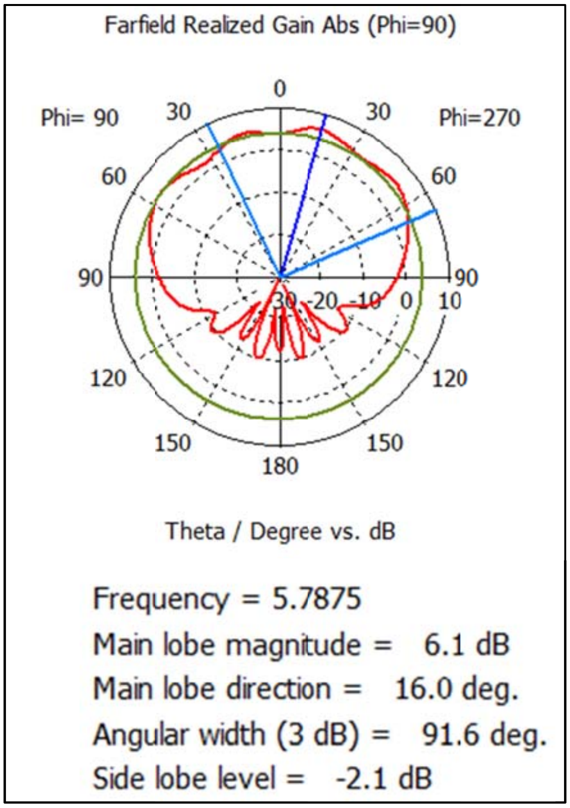

Figure 7. Farfield realized gain plot for modified patch antenna

Table 2. List of parameters for the simulated modified antenna

Parameter	Value
Realized Gain at 5.787 GHz	6.10 dB
S11 at 5.725 GHz	-12.50 dB
S11 at 5.787 GHz	-14.53 dB
S11 at 5.850 GHz	-14.59 dB

The S11 and realized gain values documented in Table 2 are all within acceptable ranges to deem the antenna an effective and efficient radiator in the ISM band. As such, the basic building block needed to implement a multiple-element phased-array microstrip antenna has been designed, simulated, and analyzed.

III. Two-Element Patch Antenna Array Design

In order to design an effective 2-element in-phase radiator, the distance between patch elements needed to be optimized to yield a peak gain. The antenna-array chapter in *Antenna Theory* by Balanis provides insight on the optimum antenna separation distance. The text identifies a separation distance of λ/2 as providing the optimal gain. In order to verify this notion, the antenna separation distance was swept from 0λ to λ. The maximum gain over the swept separation distance was indeed found to be at a distance of λ/2.

In order to implement an even number of in-phase patch elements, the feed network needed to be carefully designed. The distance from the 50-ohm SMA source to each patch element needed to be identical, or multiples of λ, in order to provide a uniform phase across all elements. A quarter-wave transformer was used to match the patch antenna to a 50-ohm microstrip line. Then a quarter-wave transformer was implemented to match a 100-ohm line with the previously mentioned 50-ohm microstrip line. Finally, the 100-ohm line was fed to a 50-ohm microstrip line and thusly the 50-ohm SMA.

The antenna array was modeled in CST Microwave Studio and the results are illustrated below. Figure 8 illustrates the CST antenna model. Figure 9 details the array dimensions. Moreover, the S11 and farfield realized gain plots are depicted in Figures 10 and 11, respectively. Table 3 details antenna characteristics from the CST simulation.

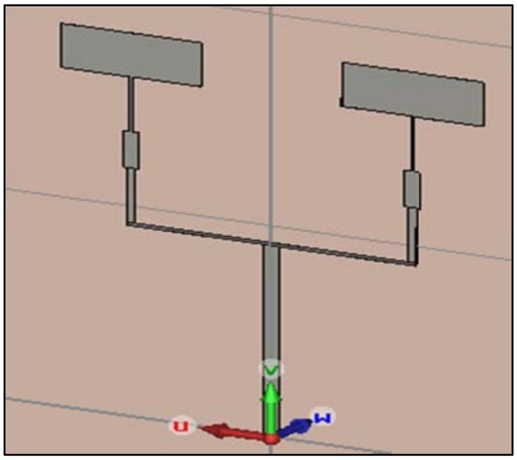

Figure 8. 2-element patch antenna CST Model

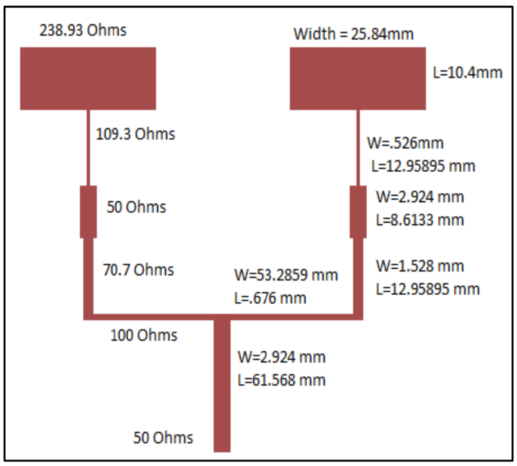

Figure 9. 2-element patch antenna PCB layout with dimensions

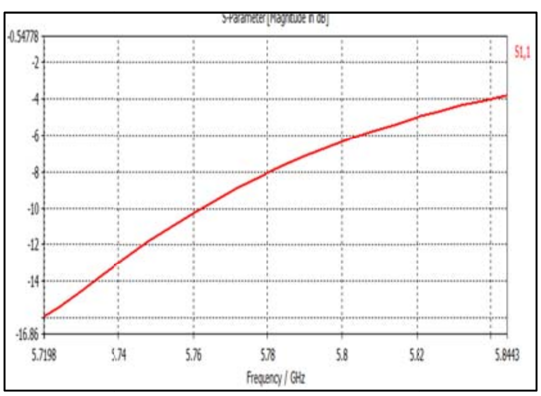

Figure 10. 2-element Patch Antenna S11

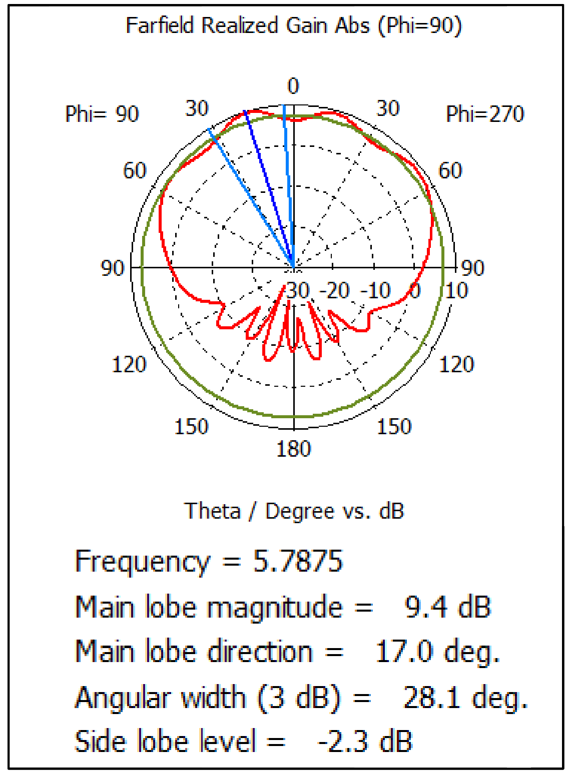

Figure 11. Realized gain plot for 2-element patch antenna

Table 3. List of parameters for the simulated 2-element antenna array

Parameter	**Value**
Realized Gain at 5.787 GHz	9.10 dB
S11 at 5.725 GHz	-15.50 dB
S11 at 5.787 GHz	-5.78 dB
S11 at 5.850 GHz	-4.00 dB

The S11 and realized gain values documented in Table 3 are within acceptable ranges to deem the antenna an effective and efficient radiator in the 5.70-5.78 GHz band. It is important to note the performance above 5.78 GHz is less than optimal. However, the 2-element phased-array antenna yields greater gain across the entire 5.725-5.850 GHz band than its single-element counterpart. Moreover, the 2-element array yields ~50% greater realized gain at the center frequency (5.7875 GHz).

IV. Four-Element Patch Antenna Array Design

The methodology used to implement the four-element patch antenna array is similar to the process used to create the two-element patch array documented in Section 3. The four elements were separated by a distance λ/2. Moreover, the elements were radiating in-phase. The microstrip feed structure was the main design challenge incurred during the four-element patch design. The antenna illustrated in Figure 9 was treated as a basic building block for this design. The basic building block was then copied and placed a distance of λ/2 away from the edge of the nearest patch element. Figure 12 illustrates the topology and its dimensions.

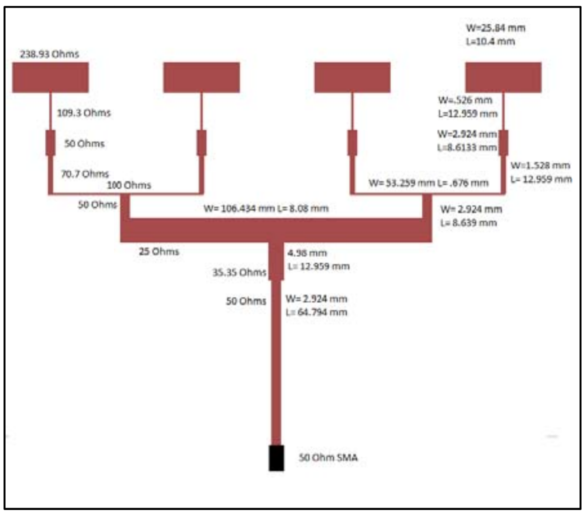

Figure 12. 4-element patch antenna PCB layout with dimensions

The two building blocks were connected by a 25-ohm microstrip line. The 25-ohm microstrip line was then connected to a 50-ohm microstrip line via a quarter-wave transformer. The antenna was then simulated. Figure 13 illustrates the CST antenna model. Moreover, the S11 and farfield realized gain plots are depicted in Figures 14 and 15, respectively. Table 4 details antenna characteristics from the CST simulation.

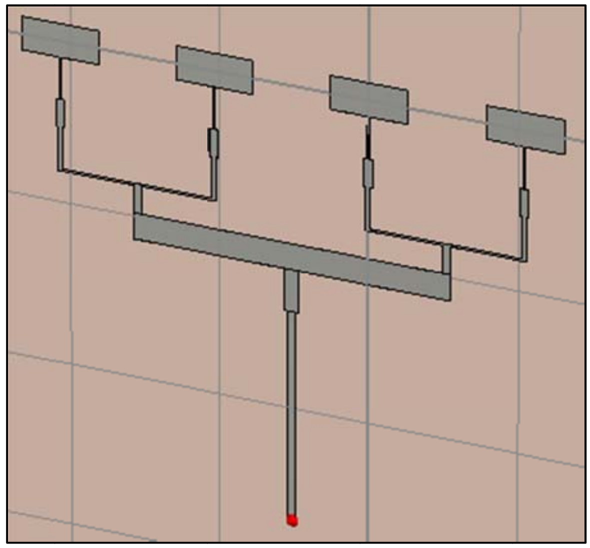

Figure 13. 4-element patch antenna CST model

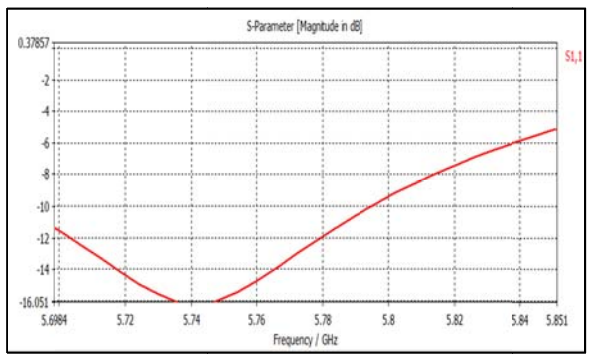

Figure 14. 4-element patch antenna S11 Plot

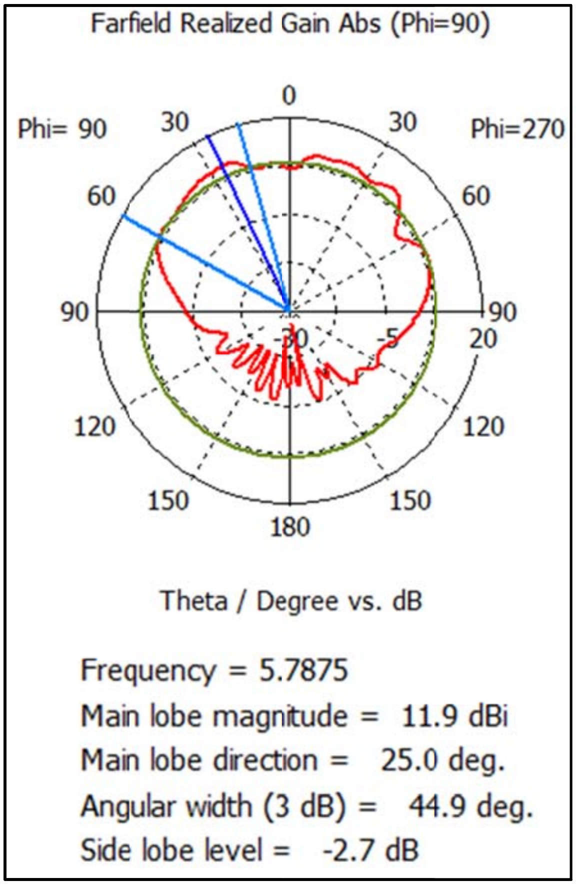

Figure 15. 4-element patch antenna Farfield Gain Plot

Table 4. List of parameters for the simulated 4-element antenna array

Parameter	Value
Realized Gain at 5.787 GHz	11.9 dB
S11 at 5.725 GHz	-15.40 dB
S11 at 5.787 GHz	-9.82 dB
S11 at 5.850 GHz	-5.26 dB

The S11 and realized gain values documented in Table 4 are within acceptable ranges to deem the antenna an effective and efficient radiator in the 5.70-5.78 GHz band. It is important to note the performance above 5.82 GHz is less than optimal. However, the 4-element phased-array antenna yields greater gain across the entire 5.725-5.850 GHz band than its single-element and 2-element counterparts. Moreover, the 4-element patch-array yields a ~95% greater realized gain at the center frequency (5.7875 GHz) than the single-element array and a 26% greater realized gain than the two-element array. It is worth mentioning that the increase in gain experienced with the 4-element array is rather small (when compared to the two element array). The slightly lower-than-expected gain could be due to a possible mismatch in the microstrip feed line or power dissipated in the FR4 substrate.

V. Eight-Element Patch Antenna Array

Multiple 8-element array antennas were designed, simulated, and analyzed. A detail derivation of the antenna dimension will not be given as the antennas were not produced. However, it is worth noting that the performance of the 8-element patch antennas provided insight on antenna design *do's and don'ts.* Figures 16, 17, and 18 illustrate the designed antennas. A short passage is included below each of the antennas that detail gain and possible problems incurred.

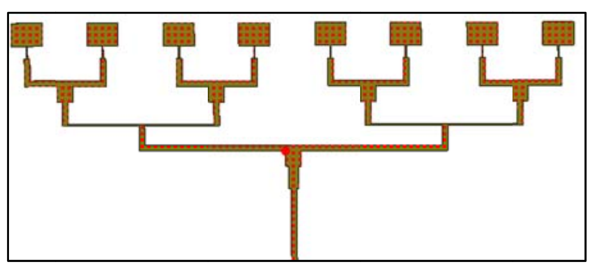

Figure 16a. 8-element patch antenna CST Model

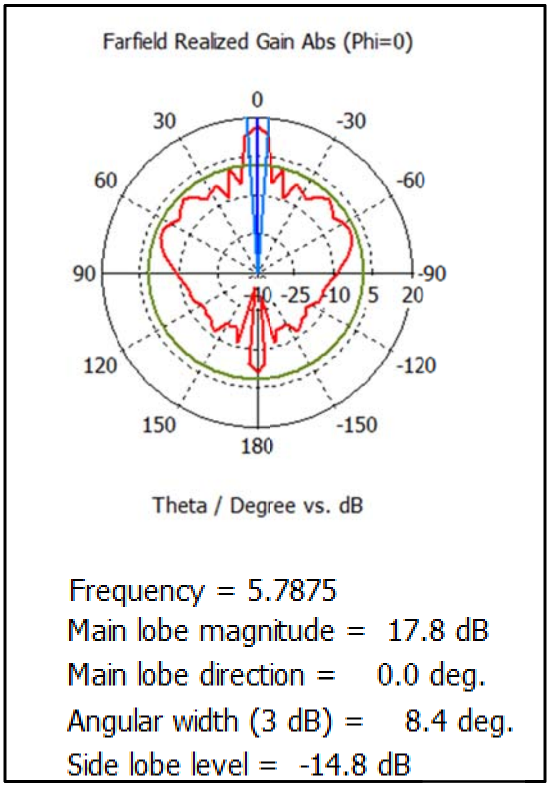

Figure 16b. 8-element patch antenna realized gain

Table 5. List of parameters for the simulated 8-element antenna array

Parameter	Value
Realized Gain at 5.787 GHz	17.8 dB
S11 at 5.725 GHz	-10.40 dB
S11 at 5.787 GHz	-9.82 dB
S11 at 5.850 GHz	-7.26 dB

The antenna depicted in Figure 16a produced the most desirable realized gain and S11 parameters over the ISM band. The 8-element array was designed using the patch illustrated in Figure 2. Although the gain and S11 parameters were exceptional for this antenna, it was ultimately not produced due to its size. It is believed that the FR4 substrate would have severely diminished the antenna's realized gain. This 8-element phased array provides great insight on the design of phased array antennas. In-phase multiple-element antennas can indeed produce a very directional radiation pattern if the feed line is designed appropriately. Additionally, mitered edges were added to this design. The mitered edges added .2 dB of gain and lowered the S11. As such, it can be said that mitered edges can help reduce reflections in the microstrip feed line.

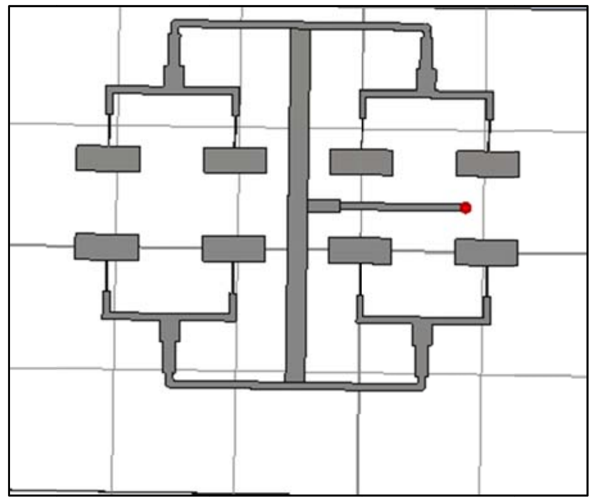

Figure 17. 8-element patch antenna CST Model

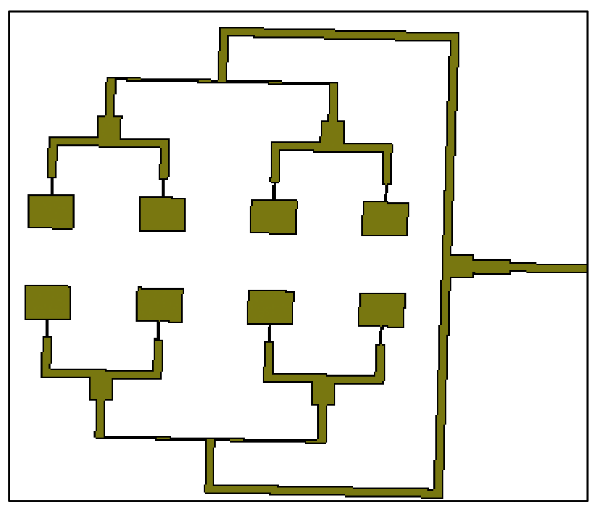

Figure 18. 8-element patch antenna CST Model

Figures 17 and 18 depict two additional 8-element phased-array antennas. The realized gain for the antenna documented in Figure 17 was 1.9 dB and the realized gain for the antenna documented in Figure 18 was 9.1 dB. Since both antennas demonstrate gain that is well below ideal-gain for an 8-element in-phase patch antenna array, it can be said that the microstrip feed line is possibly inducing undesirable effects.

After viewing the current graph for the antenna in Figure 17, it can be noted that microstrip feed lines placed rather close to the radiating elements induce coupling effects. These coupling effects result in an extremely inefficient antenna. Moreover, the 9.1 dB gain experience by the antenna in Figure 18 illustrates the losses that can arise from electrically long microstrip feed lines.

As previously mentioned, the antennas illustrated in Figures 16a, 17, and 18 were not produced. However, the *trial-and-error* process incurred during the design of these antennas was invaluable and provided insight on antenna design as a whole.

VI. Two-Element Experimental Results

The final 2-element design was converted from a CST document to an EagleCad gerber file (Figure 9). After the conversion was complete, the 2-element antenna was milled from a 59mil FR4 substrate. The final realized antenna is depicted in Figure 19.

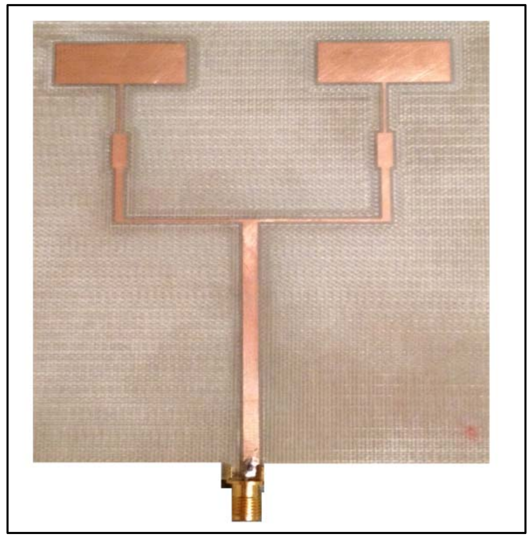

Figure 19. Final designed 2-element antenna

The antenna S11 was tested on an Agilent Network Analyzer in order to compare theoretical versus experimental S11 results. Figure 20 illustrates the S11 plot from the Agilent Network Analyzer. Furthermore, Table 7 depicts the S11 values for 5.725 GHz, 5.7875 GHz, and 5.85 GHz.

Table 7. List of S11 parameters from Agilent Network Analyzer

Parameter	Value
S11 at 5.725 GHz	-15.50 dB
S11 at 5.787 GHz	-15.78 dB
S11 at 5.850 GHz	-14.00 dB

The theoretical and experimental S11 values differ greatly. The experimental S11 varies from -15.78 dB to -14.00 dB over the ISM band while the theoretical S11 derived from CST varies from -15.50 dB to -4.00 dB.

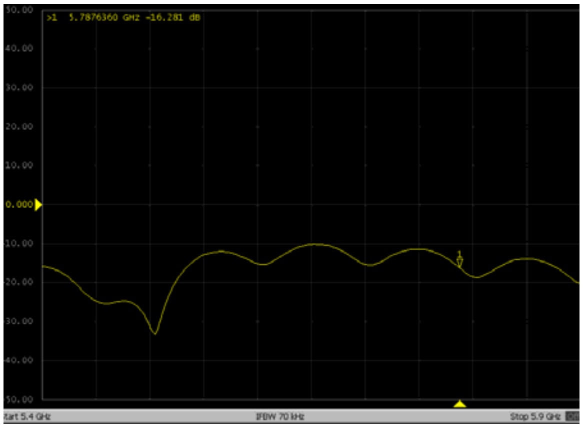

Figure 20. S11 plot for 2-element antenna from Agilent Network Analyzer

The 2-element patch antenna was sent to North Carolina State University's *PROJECT: Remote Educational Antenna Lab* for further experimental testing. The antenna was tested over a frequency range of 4.0 GHz to 6.50 GHz in steps of 3.12 MHz. Moreover, the antenna was rotated from 0 to 360 degrees in increments of 3 degrees. The azimuthal gain plot is depicted in Figure 21.

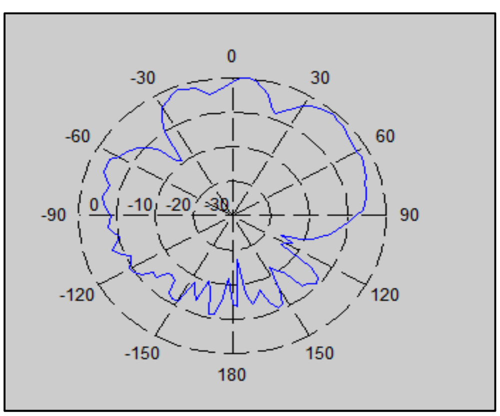

Figure 21. Azimuthal gain plot from NCSU Project REAL at 5.78 GHz

Figure 22 represents an additional gain plot. Table 8 lists the realized gain for frequencies of 5.72 GHz, 5.78 GHz, and 5.85 GHz. The maximum gain over the ISM band was found to be ~4.90 dB at the frequency of 5.85 GHz.

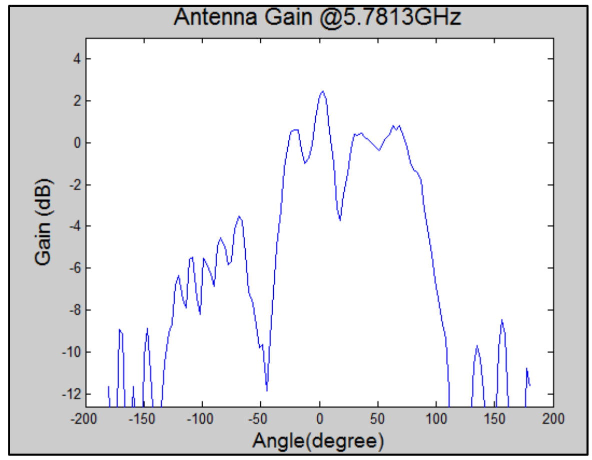

Figure 22. Gain plot from NCSU Project REAL at 5.78 GHz

Table 8. List of realized gain from NCSU Project REAL

Parameter	Value
Realized Gain at 5.72 GHz	0.70 dB
Realized Gain at 5.78 GHz	2.50 dB
Realized Gain at 5.85 GHz	4.90 dB

VII. Four-Element Experimental Results

The final 4-element design was also converted from a CST document to an EagleCad gerber file (Figure 12). After the conversion was complete, the 4-element antenna was milled from a 59mil FR4 substrate. The final realized antenna is depicted in Figure 23.

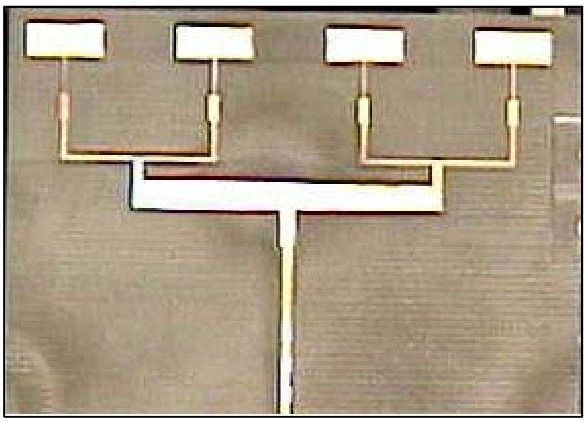

Figure 23. Final designed 4-element antenna

Once again, the antenna S11 was tested on an Agilent Network Analyzer in order to compare theoretical versus experimental S11 results. Figure 24 illustrates the S11 plot from the Agilent Network Analyzer. Furthermore, Table 8 depicts the S11 values for 5.725 GHz, 5.7875 GHz, and 5.85 GHz.

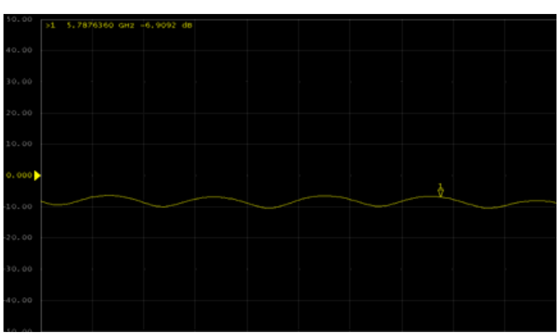

Figure 24. S11 plot for 4-element antenna from Agilent Network Analyzer

Table 8. List of S11 parameters from Agilent Network Analyzer

Parameter	**Value**
S11 at 5.725 GHz	-9.23 dB
S11 at 5.787 GHz	-6.91 dB
S11 at 5.850 GHz	-7.30 dB

The 4-element patch antenna was sent to North Carolina State University's *PROJECT: Remote Educational Antenna Lab* for further experimental testing. The antenna was tested over a frequency range of 4.0 GHz to 6.50 GHz in steps of 3.12 MHz. Moreover, the antenna was rotated from 0 to 360 degrees in increments of 3 degrees. The azimuthal gain plot is depicted in Figure 25.

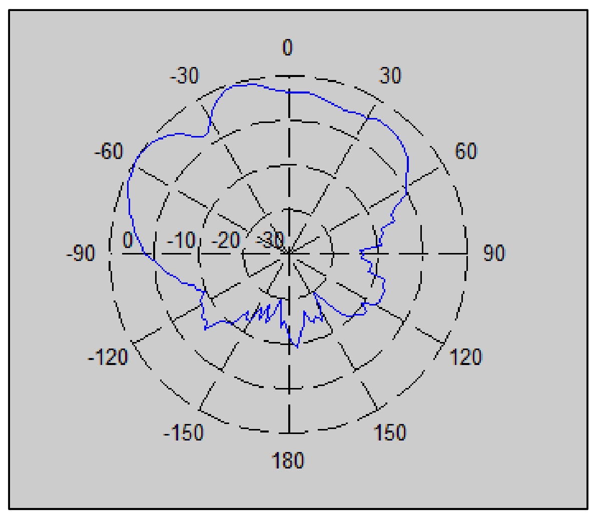

Figure 25. Azimuthal gain plot from NCSU Project REAL at 5.78 GHz

Figure 26 represents an additional gain plot. Table 9 lists the realized gain for frequencies of 5.72 GHz, 5.78 GHz, and 5.85 GHz. The maximum gain over the ISM band was found to be ~12.00 dB at the frequency of 5.85 GHz.

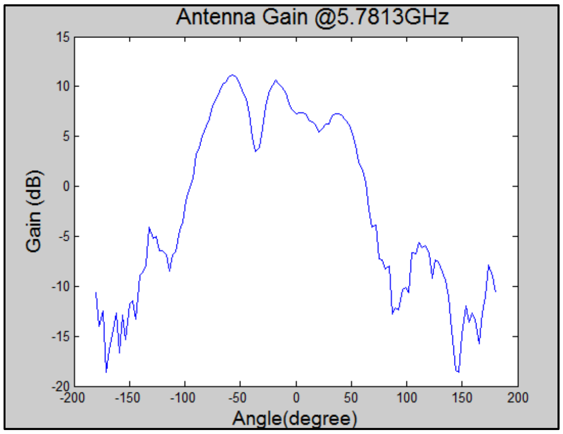

Figure 26. Gain plot from NCSU Project REAL at 5.78 GHz

Table 9. List of realized gain from NCSU Project REAL

Parameter	**Value**
Realized Gain at 5.72 GHz	10.11 dB
Realized Gain at 5.78 GHz	11.10 dB
Realized Gain at 5.85 GHz	12.00 dB

VIII. Cost of Materials

The 59mil FR4 substrate and SMA connector were not priced. Both components were provided by James Steinberg. Additionally, the shipping costs to NCSU's *Project: Remote Educational Antenna Lab* was approximately $12.00. Table 10 illustrates the total costs below.

Table 10. Table of design costs

Parameter	**Value**
FR4 59mil Substrate	N/A
50 Ohm SMA	N/A
USPS Shipping	$12.00
Total:	$12.00

IX. Discussion

The two-element antenna did not perform as well as expected. The maximum realized gain over the ISM band was -47.81% less than the theoretical maximum gain derived from CST Microwave Studio. This deviation could have resulted from the following:

1. FR4 substrate losses
2. Cold and/or broken solder joints
3. Electrically long 50-Ohm microstrip transmission line
4. Problems in converting CST file to EagleCad gerber file
5. Inherent limitations in the milling process
6. Improper calibration of NCSU REAL Antenna range
7. Antenna damage during shipping

The four-element antenna performed as expected.***** The maximum realized gain over the ISM band was 0.84% greater than the theoretical maximum gain derived from CST Microwave Studio. The relatively low deviation between the theoretical CST model and the experimental results indicate the CST model accurately depicts the operation of the 4-element patch array over the ISM band.

**Note: The NCSU Real Antenna Range produced varied results for the four-element antenna. The antenna was tested multiple times. The REAL Studio produced fluctuating results or no results at all (server failure). The fluctuation in results could be due to an incorrect solder joint or problems in calibration of the range. As the antenna was rotated 360 degrees, the solder joint could have been repositioned resulting in a variable S11 and thus a* *variable gain. The 12.00dB of gain was only produced once. All other trials gave either no value at all (server failure) or received gain different than the 12.00dB of gain listed above. Since this project is graded on maximum realized gain, the maximum realized gain over all of the trials taken was provided for both the two-element array and four-element array.*

X. Acknowledgements

- Marcin Morys
- Blake Marshall
- James Steinberg
- Mohammad Akbar
- NCSU Project: Remote Educational Antenna Lab

XI. References

[1]

Huque, Tanvir, Kamal Hosain, Shihabul Islam, and Al-Amin Chowdhury. *Design and Performance Analysis of Microstrip Array Antennas with Optimum Parameters for X-band Applications. IJACSA*. International Journal of Advanced Computer Science and Applications, 4 Nov. 2011. Web. 26 Nov. 2012.

[2]

Balanis, C. "Array Theory." *Antenna Theory: Analysis and Design, 3rd Edition*. 3rd ed. N.p.: Wiley-Interscience, 2005. N. pag. Print.

[3]

Stutzman, Warren. *Antenna Theory and Design*. 3rd ed. Wiley, 2012. Print.