University of Arkansas

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Patch Antenna- Properties and Characteristics

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ELEG 4783 by

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Project Overview

The goal of this report is to design and evaluate a patch antenna operating within a center frequency range of 2.0 GHz to 3 GHz, based on a geometry selected during the class session on April 3. The antenna was built on a 15 cm × 15 cm substrate, and a coaxial feed was used in the HFSS model. The feed point was selected to optimize input impedance and minimize the S11 reflection coefficient. At least five feed locations were tested which for this report meant doing a parametric sweep meaning a lot more positions were testes, with their coordinates and S11 values recorded in a table to identify the best-matched configuration.

A variety of performance metrics were analyzed in HFSS. These included the S11 vs. frequency plot to determine the actual resonant point and the -10 dB bandwidth. The software also provided values for gain, directivity, and input impedance (both real and imaginary), which were plotted and studied. The radiation, directivity, gain pattern and half-power beamwidth (HPBW) were also included and visualized with both 3d and 2d polar plots to help characterize the antenna's directional performance.

The report features a sketch of the modeled antenna in HFSS along with a photograph of the physical build. After fabrication, the antenna was tested, and its measured performance was compared to the simulation results. These values were shown side-by-side in a table to highlight how close the real-world measurements aligned with the design expectations.

As an extended investigation, the report compares the L-shaped patch antenna design to a standard rectangular patch, with both modeled at 2.45 GHz. The comparison examines differences in gain, directivity, impedance, and bandwidth. The goal was to explore tradeoffs and performance variations introduced by altering the shape of the patch and see how that affected the radiation.

The width and length of the patch were calculated using Rectangular microstrip patch formulas. This report also covers the general thought process behind patch antenna design and points out how small design choices, like the feed pin size or its dielectric around coax size, can affect performance. These issues are discussed in Appendix A, where one of the key problems faced during the build is explained. Appendix B explores an idea about using different widths for each leg of the L-shaped antenna and what problems that might cause. Appendix C includes all the recorded data on the rectangular patch antenna, which was also designed to resonate at 2.45 GHz and was used to compare the special L-shaped design to a more standard one. While simulation tools like HFSS help show what to expect, building and testing the antenna in real life gave important insights into where things can go off from the design.

Derivations

Radiation of patch Antenna

The radiation from a patch antenna is primarily governed by the standing wave pattern formed by the voltage along the transmission line, which is why it is often referred to as a voltage distribution antenna. The voltage and current distributions across the antenna can be visualized as standing waves, as shown below:

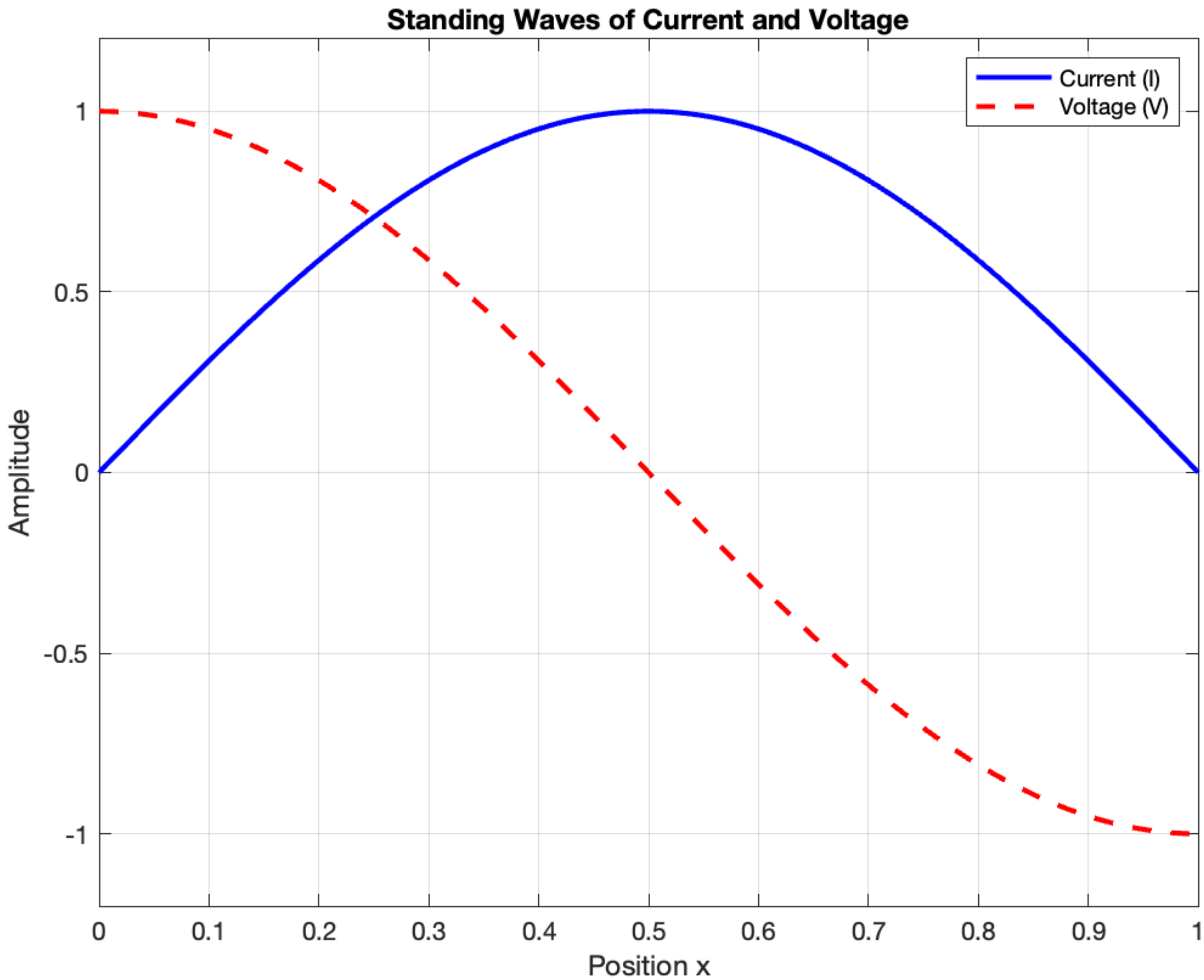

Figure 1:Standing waves of voltage and current in Patch antenna

The voltage exhibits a standing wave pattern due to the fringing fields at the antenna edges. These fields result in a varying electric potential along the length of the patch. A common method of analyzing this behavior is through the magnetic field distribution, where the magnetic fields propagate along the antenna edges. The variation in the stray electric field (E-field) along the edge indicates that the voltage also varies in a manner consistent with the presence of a changing magnetic field.

Starting from the bottom edge, this method allows the derivation of the E-field using Maxwell's equations. Since the patch length is half a wavelength, the antenna behaves similarly to two half-wavelength dipoles spaced by half a wavelength, reinforcing its radiation characteristics.

Width of regular patch Antenna

For maximum efficiency, the width of a patch antenna was designed using a specific formula which can also just be thought of as the length of the legs of a dipole antenna. The derivation of the patch width starts from the fundamental relationship: where f is the resonant frequency. The effective wavelength is then halved (as the patch length is typically and a correction factor is introduced to account for dielectric loading, which alters the effective propagation velocity within the substrate; er is the relative permittivity of the dielectric substrate. This equation ensures optimal radiation performance by balancing the trade-off between bandwidth, radiation efficiency, and impedance matching.:

$$W = \frac{c}{(2\ f_r)} sqrt\left(\frac{2}{(\varepsilon_r + 1)}\right) \tag{1}$$

Length of regular patch Antenna

The length of a regular patch antenna is important as it sets the standing waves for voltage something that the is desired is for the standing waves to be set from half a wavelength apart to where one of the ends is positive max at one and then the other is negative max at the other end this non the less will be set by direction of propegatin to where if fed from a microstrip the length of athe antenna is physicaly slightly lower due to how the frinding makes the strip slitly bigger for accuracy this Is also accounted for with he with eq:

$$L = L_{eff} - 2\Delta L \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\,\frac{h}{W}\right)^{-0.5} \tag{3}$$

$$\Delta L = \frac{0.412h(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{\left((\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)\right)} \tag{4}$$

Feeding the port:

Feeding the port an important parameter to calcite the idea is to match the input zo of the antenna to the zo of the feed this can be done by going along the patch antenna until the standing waves of the voltage and current distribution make a ratio equal to 50ohms which is the impedance of the feed. Xp is the variable that is used to denote how much distance from the edge of the wall the coax needs to be moved in.

$$Z_a(\Delta x_i) = Z_{a(\Delta x_i = 0)} \cdot 2^{\sqrt{n\Delta x_i \cdot L}} \tag{5}$$

$$Z_a \approx 90\,\frac{\varepsilon_r^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2 \tag{6}$$

Directivity of Patch Antenna

The final important parameter of the half-wave dipole antenna is its resistance, which relates to the total power radiated divided by the square of the current (where the 2 comes from rms of the current). This results in the following expression when generalized :

$$D = \begin{cases} \frac{6.8W}{\lambda} & \text{if } W < \lambda \\ \frac{8W}{\lambda} & \text{if } W > \lambda \end{cases} \tag{7}$$

Path to Designing the L shaped patch antenna

The most challenging part of this project was designing the L-shaped patch antenna. Visualizing how standing waves behave is not intuitive, and constructing a structure that shows measurable improvement, especially when using an asymmetrical shape, added complexity. The design process began with a basic rectangular patch antenna. From there, variables were adjusted while carefully observing changes in both the dimensions and overall structure of the antenna.

The development process started by designing a patch antenna with a lower carrier frequency than the target of 2.45 GHz. The student found this approach useful and noted that Bluetooth typically operates near this frequency. Starting with a lower frequency provided a more manageable baseline for sweeping the patch length, initially without including the second leg of the L-shape. This continued until a minimum S-parameter value was observed. Once further improvements plateaued, the second leg was introduced, and its length was incrementally adjusted. This resulted in another reduction in the S-parameter, indicating improved antenna performance.

The first usable S-parameter value came after calculating the length and width for a 2 GHz patch antenna. The width was determined to be 45.7 mm and the length 35.6 mm, based on equations labeled as Formulas 1 through 4. From this point, the length of the first leg of the L-shape was swept.

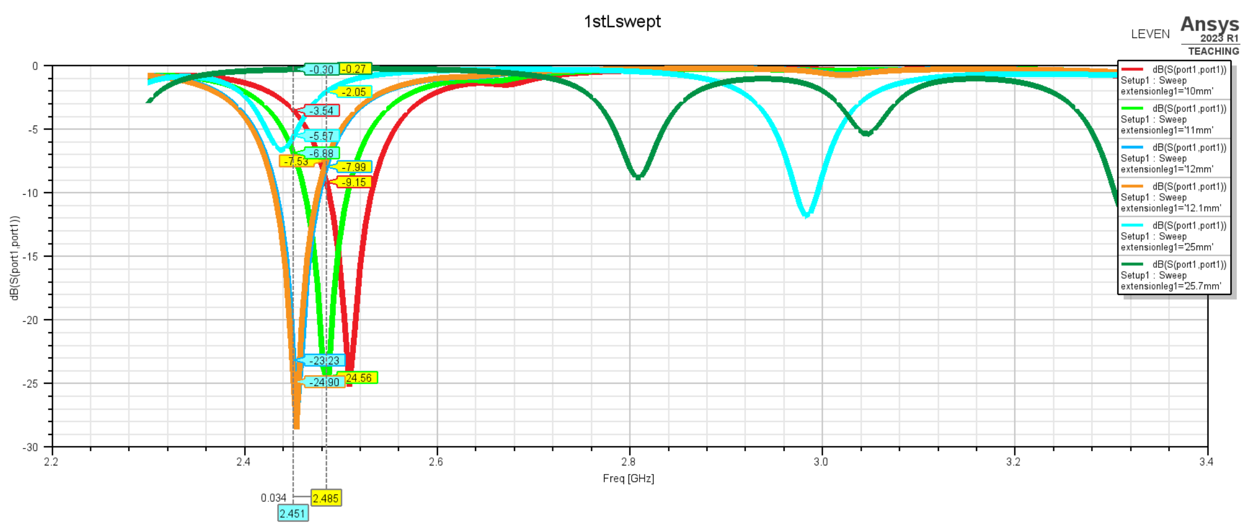

Figure 2: Parametric analysis of antenna Leg1 Nominal else values

Once Leg 1 was optimized at 12.1 mm, attention turned to sweeping Leg 2. The purpose was to further refine the carrier frequency and improve the match between the antenna and the feed line. Since the width affects the range of achievable impedance values, it plays a key role in how closely the antenna can be matched. For example, if the impedance varies between 80 ohms and 140 ohms, matching to a 50-ohm system is limited. The sweep of Leg 2 led to the final value used in the design.

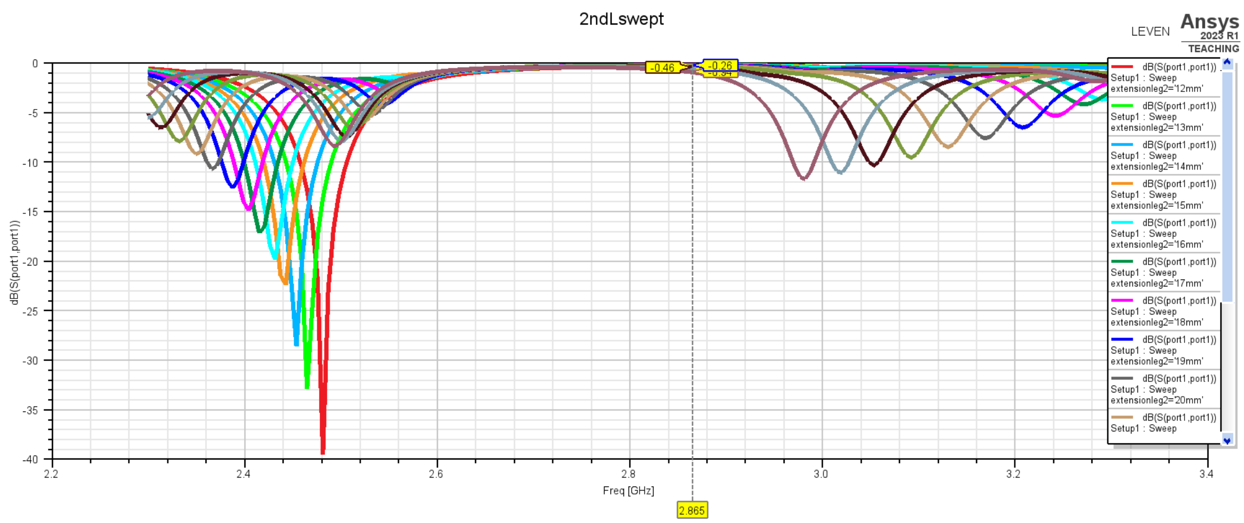

Figure 3: Parametric analysis of antenna Leg2 Nominal else values

After the leg dimensions were finalized, the feed point was fine tuned. Initial parametric sweeps took the port placement into account, leaving the feed location on-center. The feed position was then adjusted from the edge of leg 1 of the patch until optimal matching was achieved which for the final design was in the center which was found to be 1.5mm towards the inside of the leg.

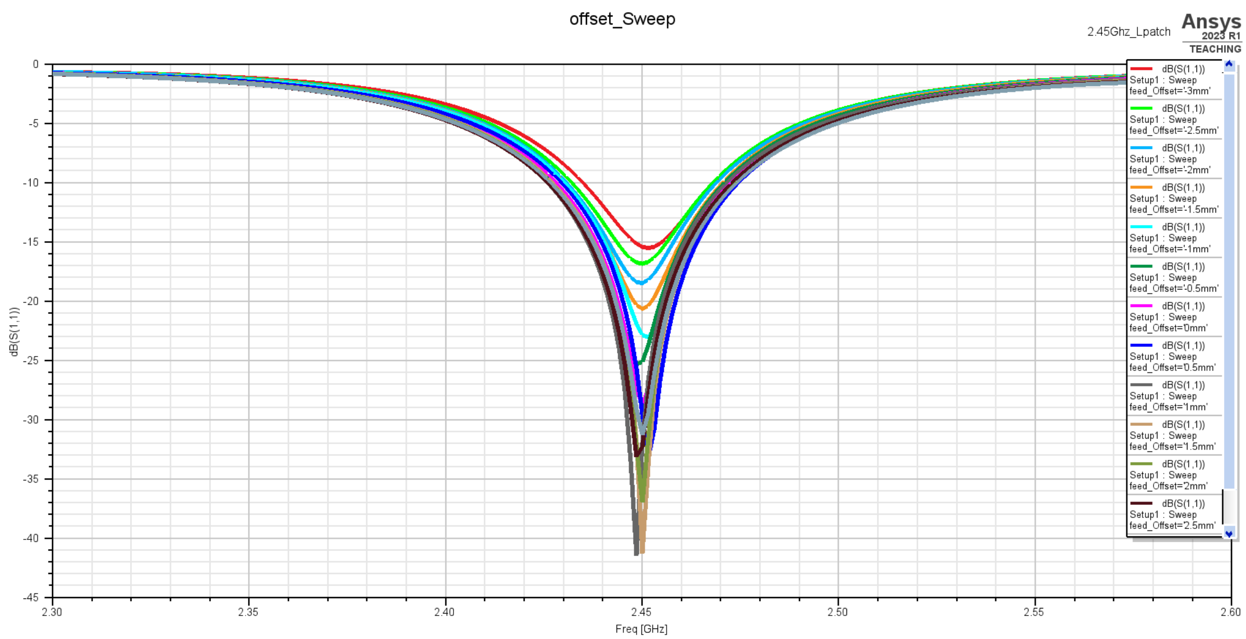

Figure 4: Parametric analysis of antenna Coax feed position Nominal else values

The final values selected for the antenna are summarized in the table below, along with their corresponding positions in the analysis model. These are provided for transparency and are accompanied by a final frequency sweep to show the overall performance.

Table 1: Dimensions for the L-shaped antenna

Dimensions of L shaped Patch Antenna	
Patch width (same for both legs)	45.7mm
Leg 1 length	58.24mm
Leg 2 length	59.7mm
Coaxial feed distance from Leg 1 edge	24.35mm
Coaxial dielectric sheath radius	3.175mm

Probe (inner conductor) radius	.381mm
Coax dielectric height	6.5mm
Gnd plane whole radius	.9525mm
Substrate dimensions	150 mm × 150 mm

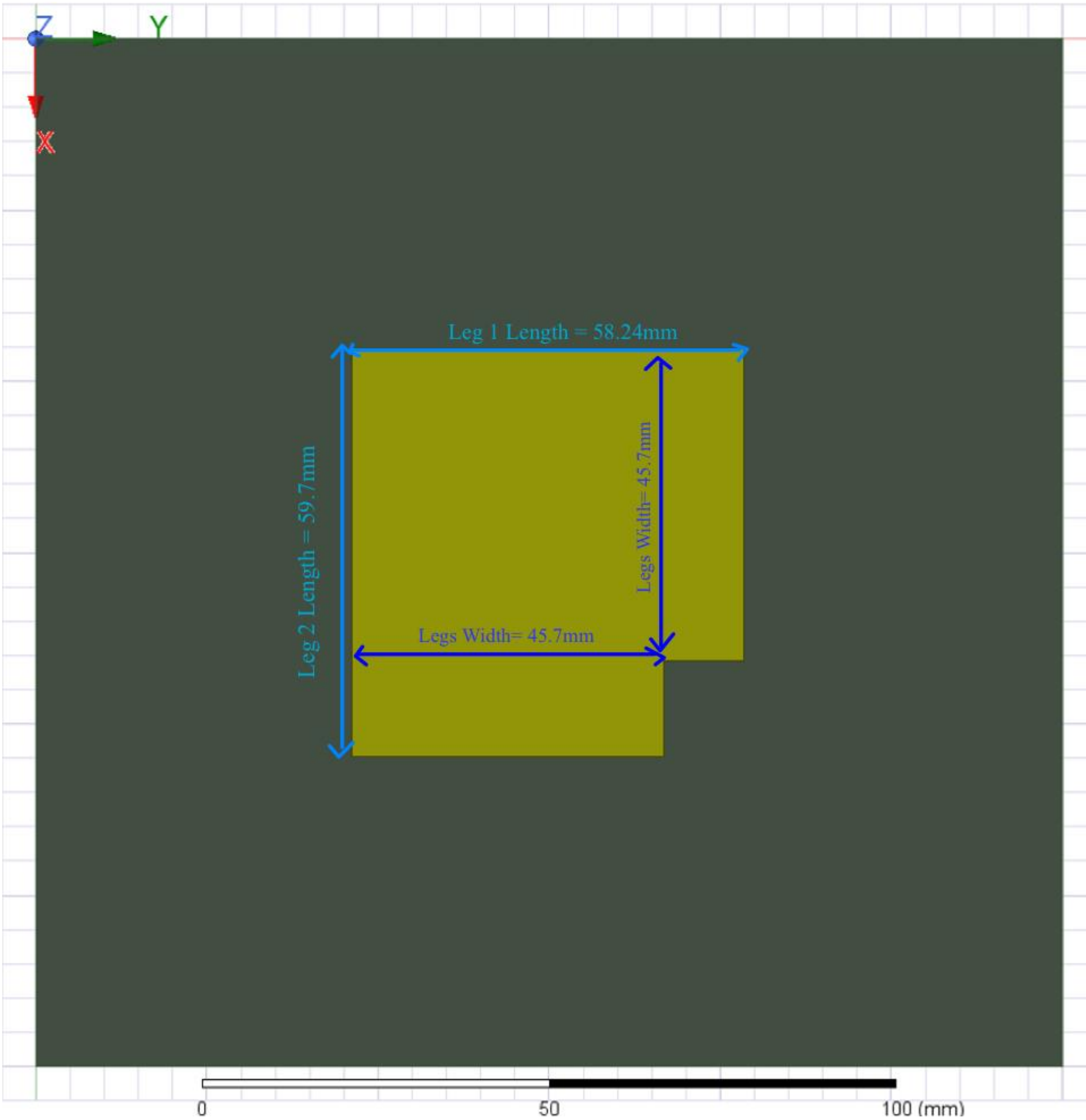

Figure 5: L-shaped patch dimension width and length of legs

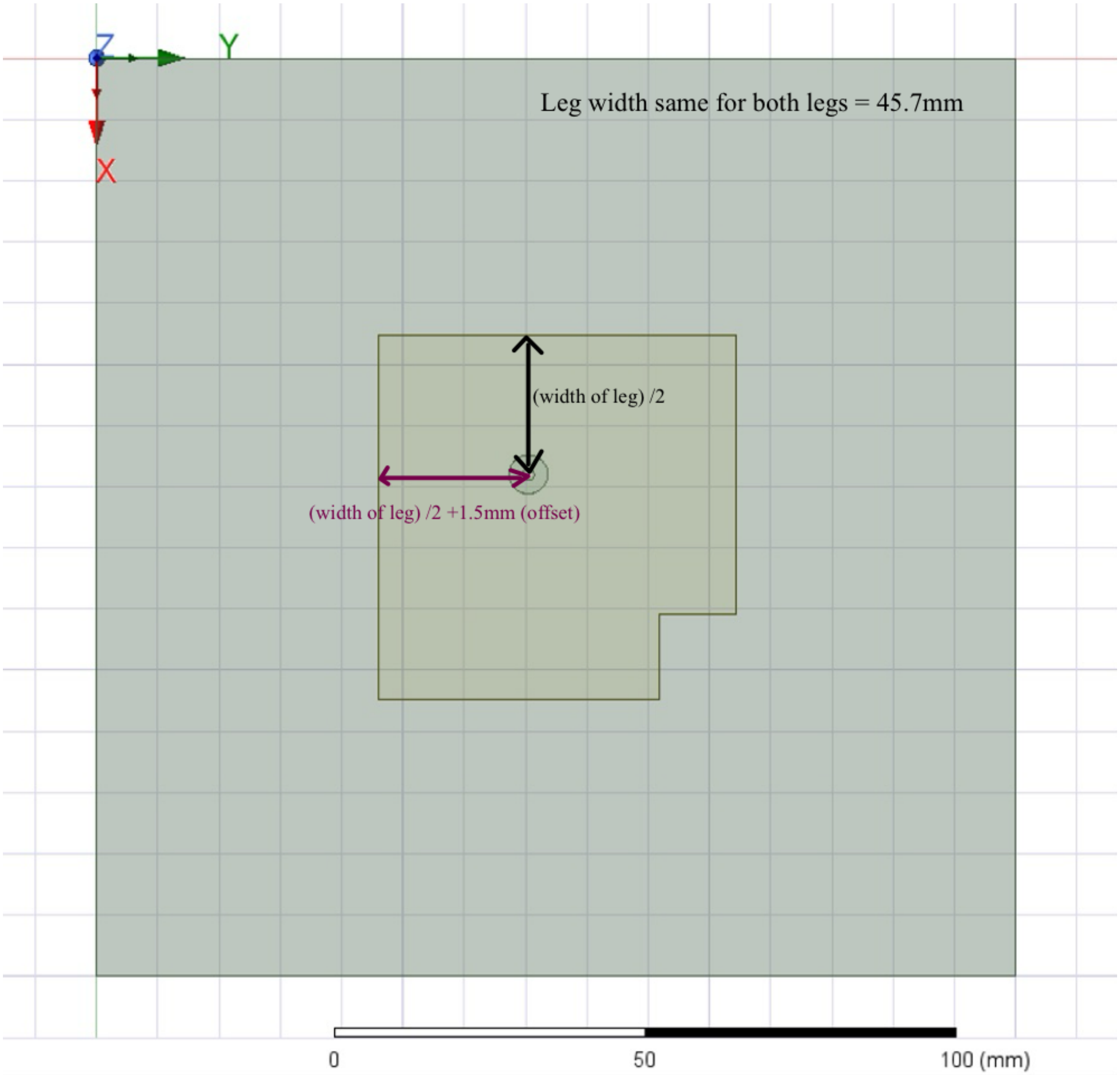

Figure 6: L-shaped patch coax feed position

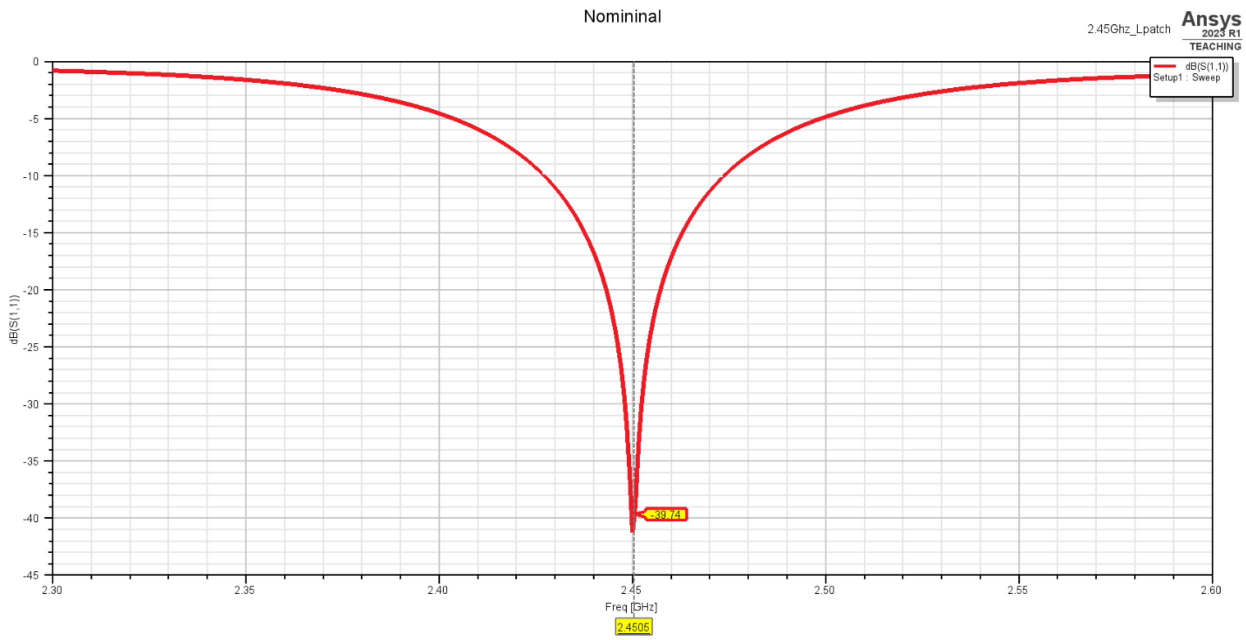

Figure 7: S-Parameter Analysis of an L-Shaped Patch Antenna for 2.45 GHz Frequency Sweep

Note: The bandwidth between the -10 dB points is 0.0468 GHz.

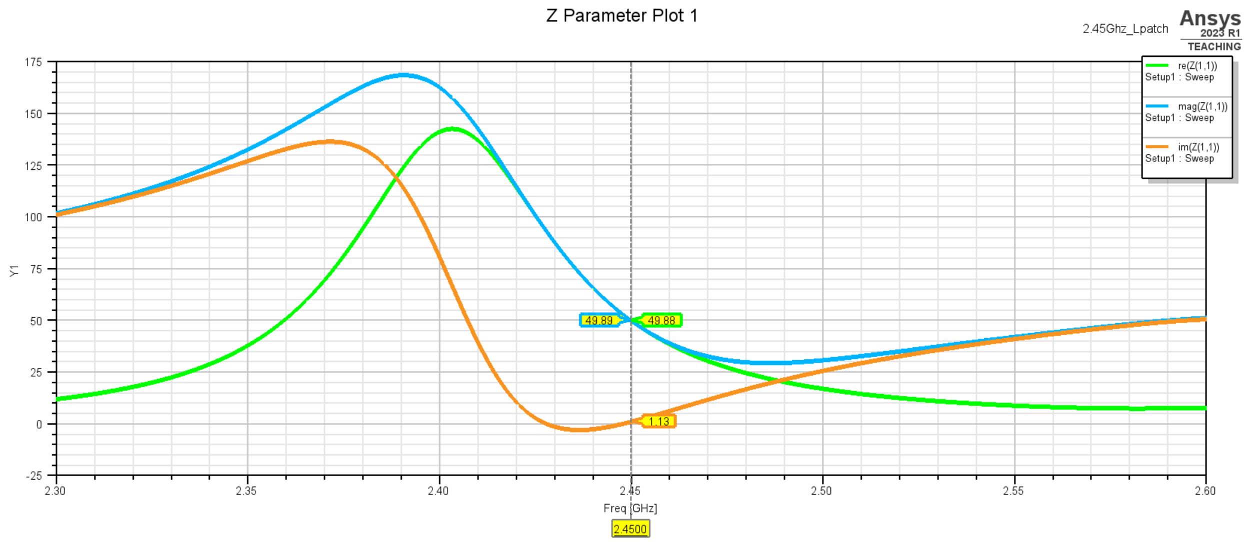

Figure 8: Z-Parameter(impedance) Analysis of an L-Shaped Patch Antenna for 2.45 GHz Frequency Sweep

Note: The input impedance magnitude is 49.89 Ω, with a real part of 49.88 Ω and an imaginary part of 1.13 Ω at 2.45 GHz.

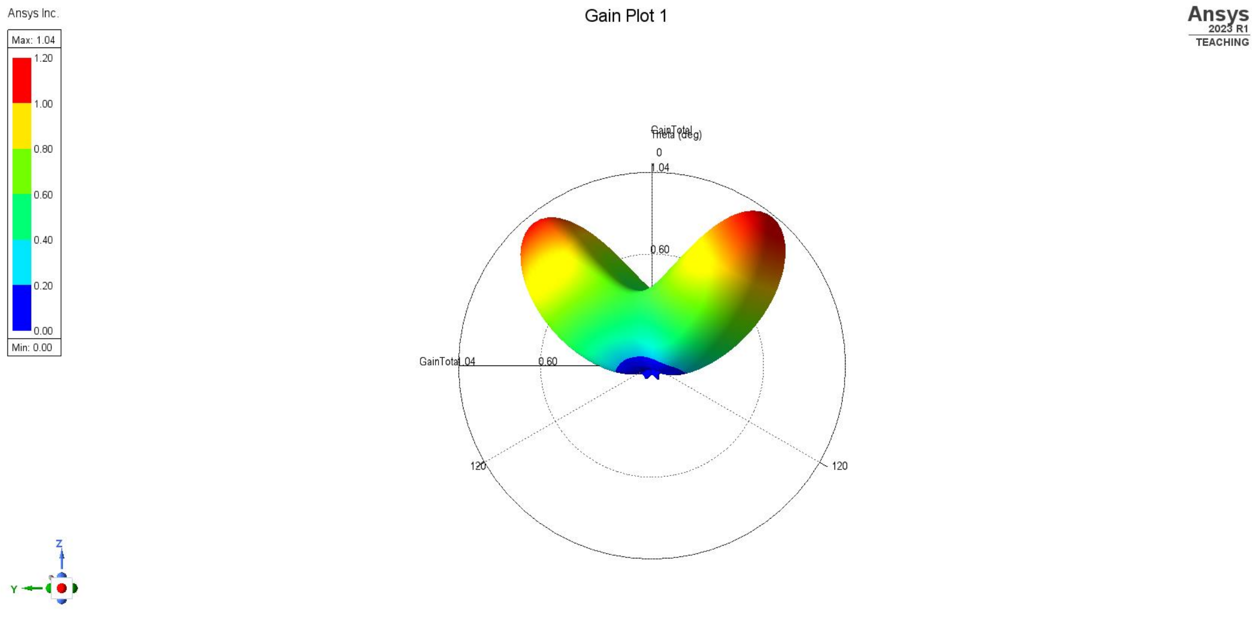

Figure 9: 3D Polar Plot of L-Shaped Patch Antenna Gain at 2.45 GHz

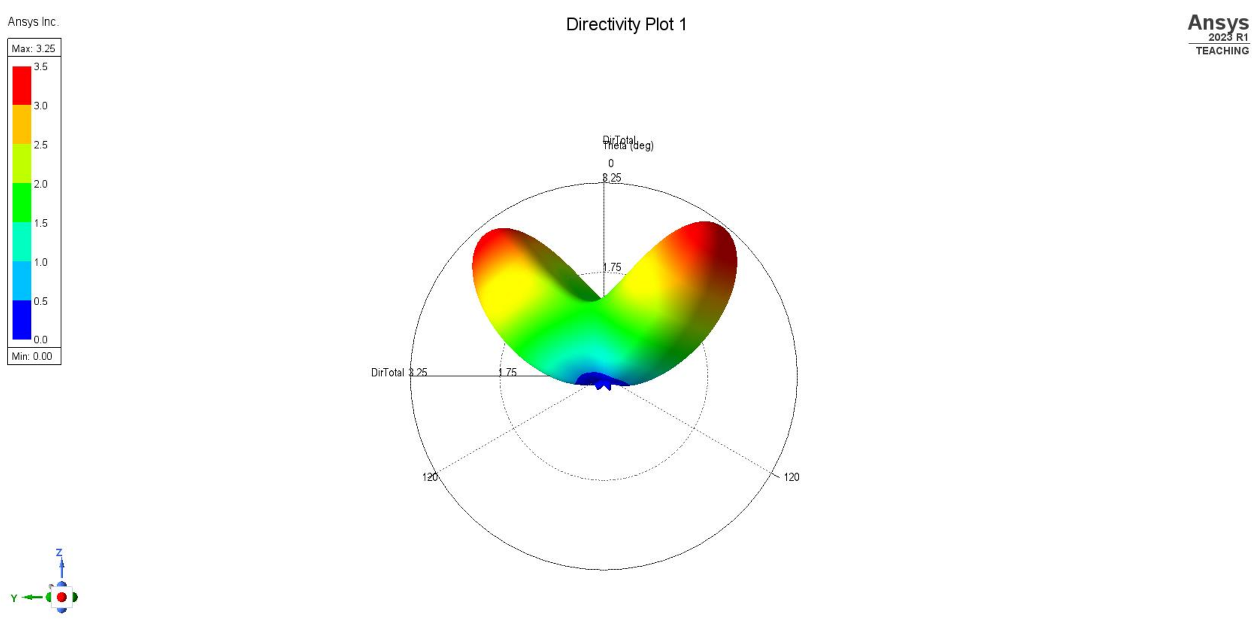

Figure 10: 3D Polar Plot of L-Shaped Patch Antenna directivity at 2.45 GHz.

Figure 11: L-patch 2D Gain: Phi Sweep at Theta = 40° (where maximum gain was observed at the main lobes)

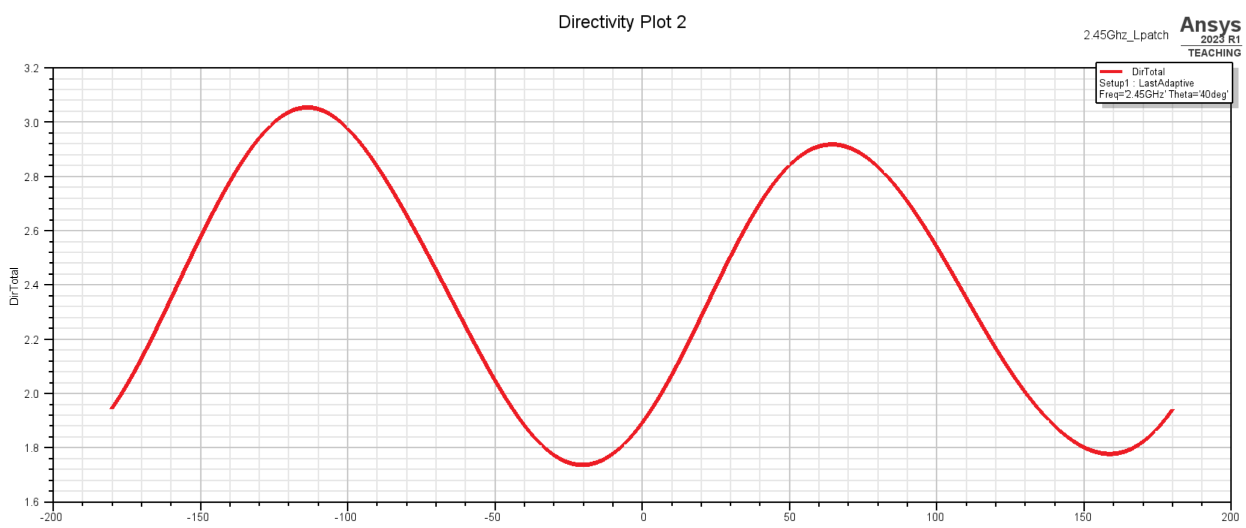

Figure 12: L-Patch 2D Directivity: Phi Sweep at Theta = 40°

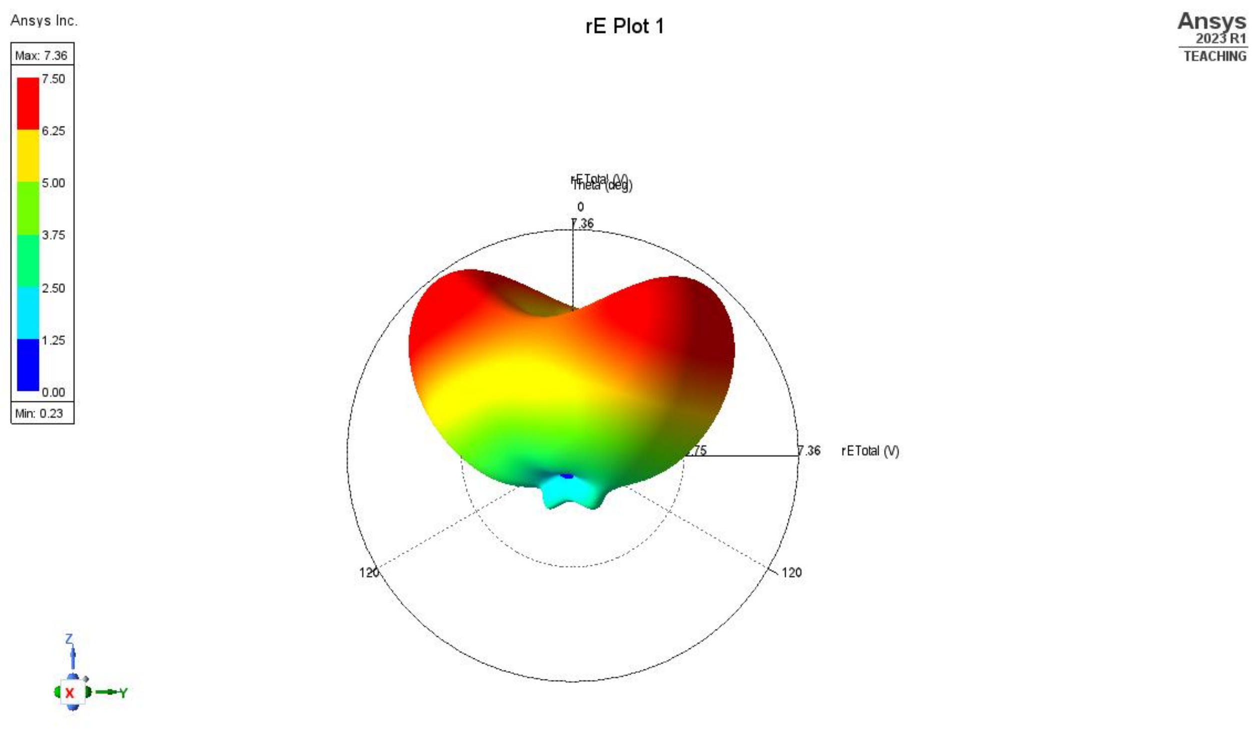

Figure 13: 3d Radiaiton pater for L shapted patch anteanna (realized gain)

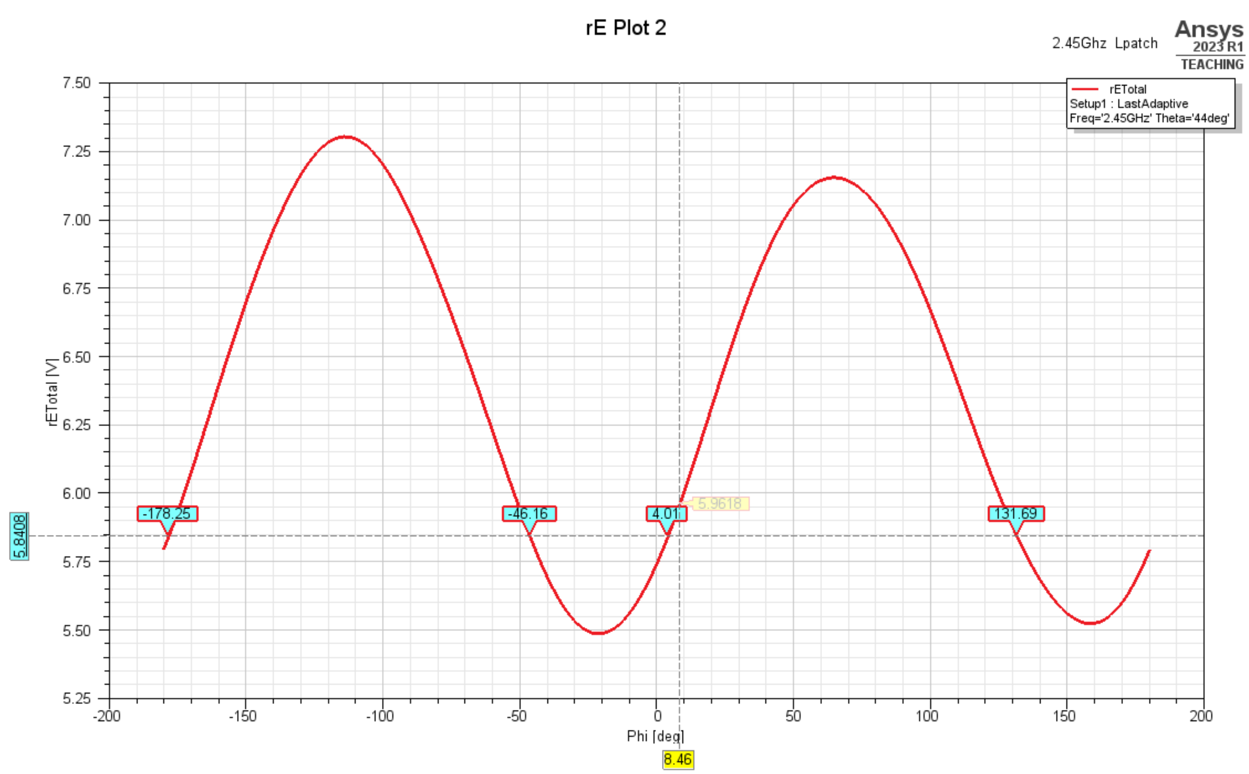

Figure 14: 3d Radiation patern for L shaped patch antenna (realized gain) along the phi 45 deg circle from

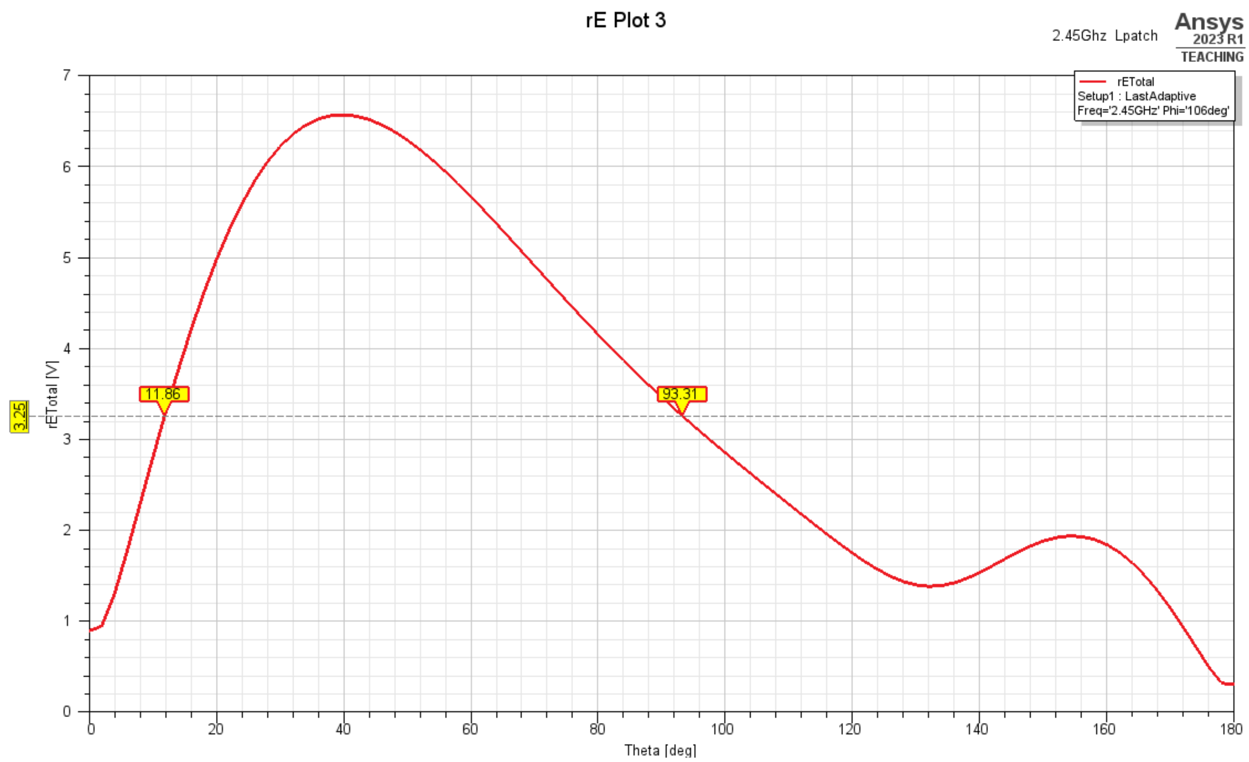

Figure 15: 3d Radiation pater for L shaped patch antenna (realized gain) along the theta 106deg line the cute ration paten from z-xy plane

From the impedance graph in Figure 8, it could be observed that the antenna was resonating close to the designed frequency, with an input impedance of approximately 50 ohms and an imaginary component of 1.13 ohms. This small imaginary value suggests that the actual resonant frequency only slightly deviated from the intended design frequency. Another key parameter plotted was the 2D pattern for gain and directivity, which complemented the 3D polar plots. The directivity remained consistently high across the selected slice (with phi held constant and theta swept), indicating strong directional behavior.

However, this does not imply uniform radiated power. As shown in Figure 14, where the realized gain was plotted along the same slice, the power dropped to half its peak value only over a small angular range. These values and graphs help demonstrate if one was standing in the direction of the antenna what location would get the most amount of signal as in head on looking at it from the side the top and so on which later on will be compared to the rectangular antenna and be seen that the strongest location is piacular for this antenna.

Results of the L shaped Patch Antenna

The performance of the L-shaped antenna was measured after manufacturing. Due to time constraints, fabrication could not be completed in Fort Smith. Instead, the antenna was produced using a lathe that introduced minor imperfections into the design. These defects were not severe enough to throw the resonance significantly off, but they may have contributed to slight shifts in performance. After fabrication, the antenna was soldered onto a coaxial pin and measured for impedance matching at the designed resonant frequency. The following will go more in depth in the reason this makes sense and further explain the defects.

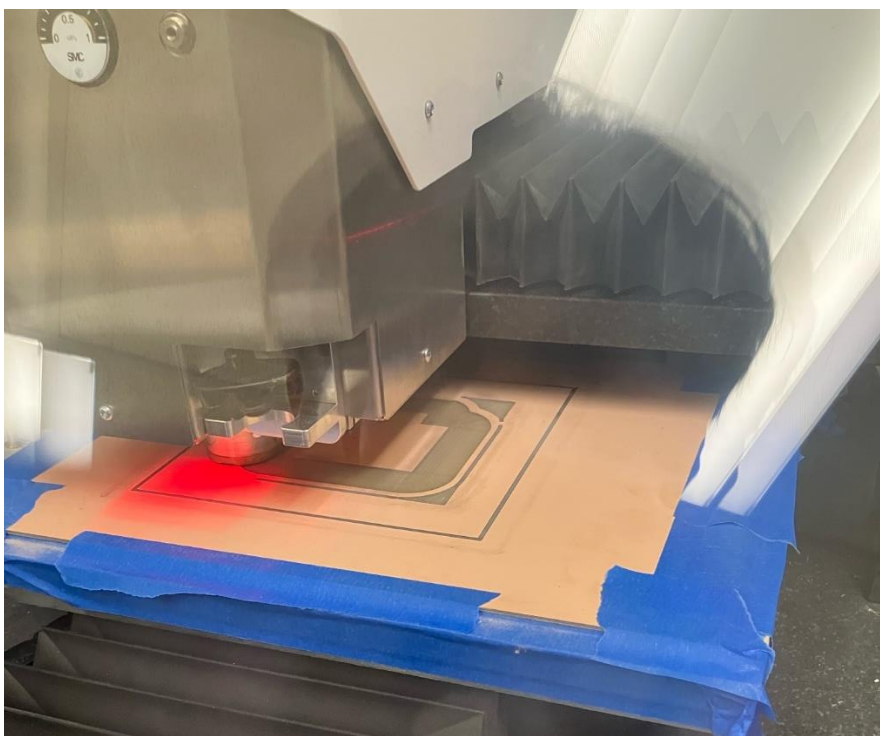

Figure 16: lathe manufacturing of the L-shaped patch antenna

The focus was on evaluating how closely the physical antenna matched the theoretical model from simulation. The recorded plots shown below highlight a key observation: the resonant frequency was centered around a 43.52 + j1.14 impedance position on the Smith chart. This position suggested that part of the impedance mismatch at 2.45 GHz was likely due to factors in the physical build, possibly involving the coaxial cable used. Manufacturing defects or slight variations in the coax could have caused a deviation from the expected 50-ohm line impedance.

Data plotted from both the physical antenna and the simulated model in MATLAB showed that if the impedance had been matched exactly to 50 ohms, the difference in resonant frequencies would have been smaller. The simulation showed a resonance at 2441.51 MHz, while the measured antenna showed 2432.44 MHz a 9 MHz gap. In relation to the target 2.45 GHz, the simulated antenna aligned more closely, while the measured antenna showed a larger offset at 2.423 GHz.

The variation in resonant frequency was likely influenced by the fact that the antenna was milled using a fancy CNC machine which not meant for actual production but more so prototyping. This method provided enough precision for testing but lacked the fine accuracy expected in full scale manufacturing. Additional variation may have come from solder applied around the coaxial pin to ensure mechanical stability and electrical contact, possibly altering the local impedance.

The process highlighted the importance of accurate impedance matching at resonance. Better matching allows more tolerance for imperfections in manufacturing and assembly. For prototyping, achieving strong resonance alignment plays a critical role in overall antenna performance.

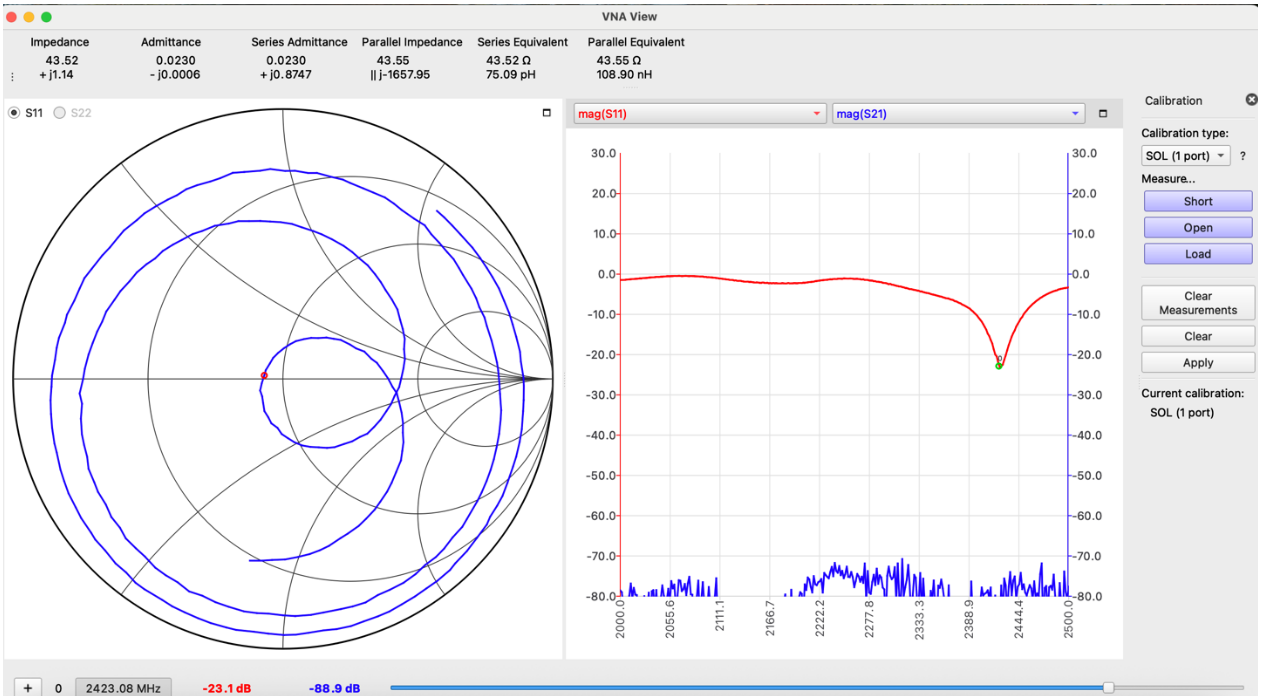

Figure 17: Measured magnitude of S parameter in DB for L-shaped patch antenna

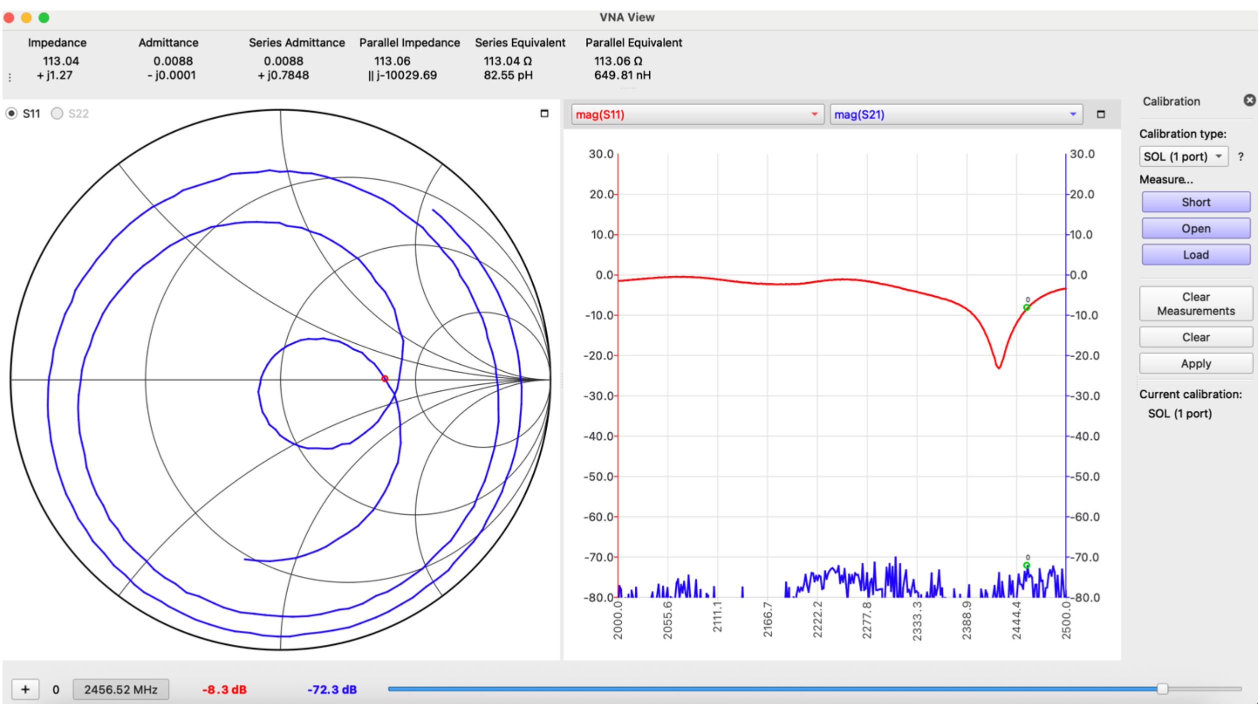

Figure 18: Measured magnitude of S parameter with curser on designed frequency

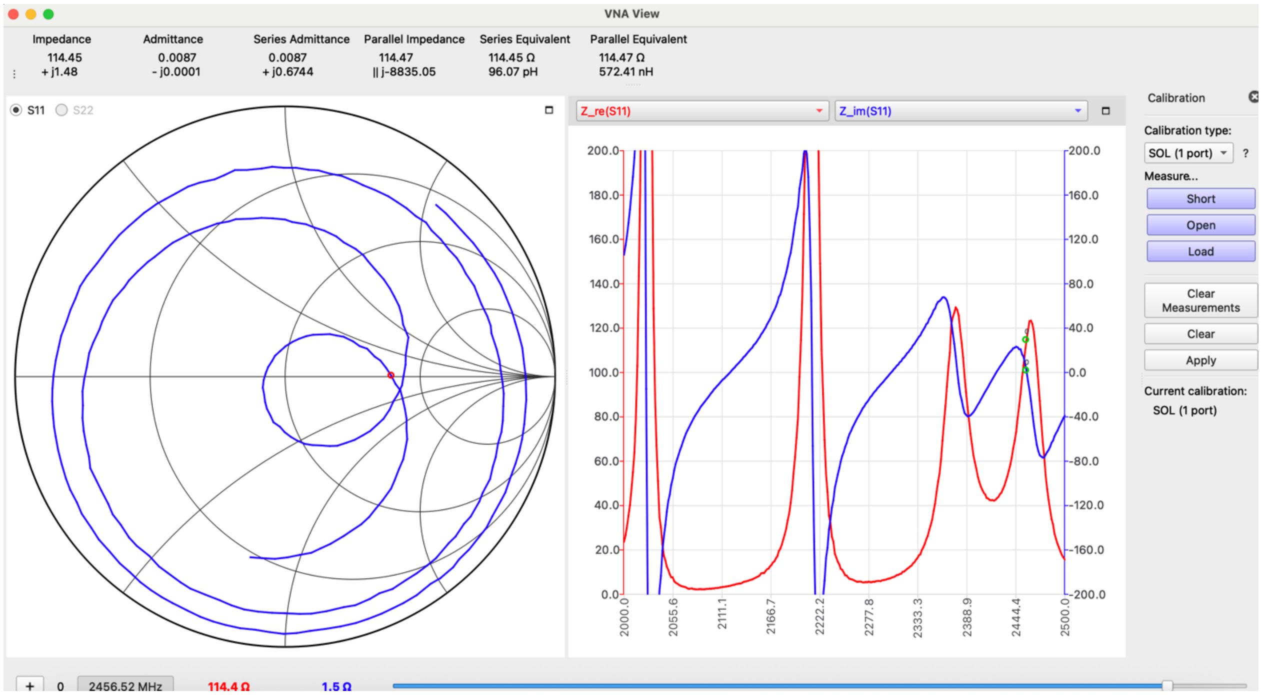

Figure 19: Measured impedance for L-shaped patch antenna

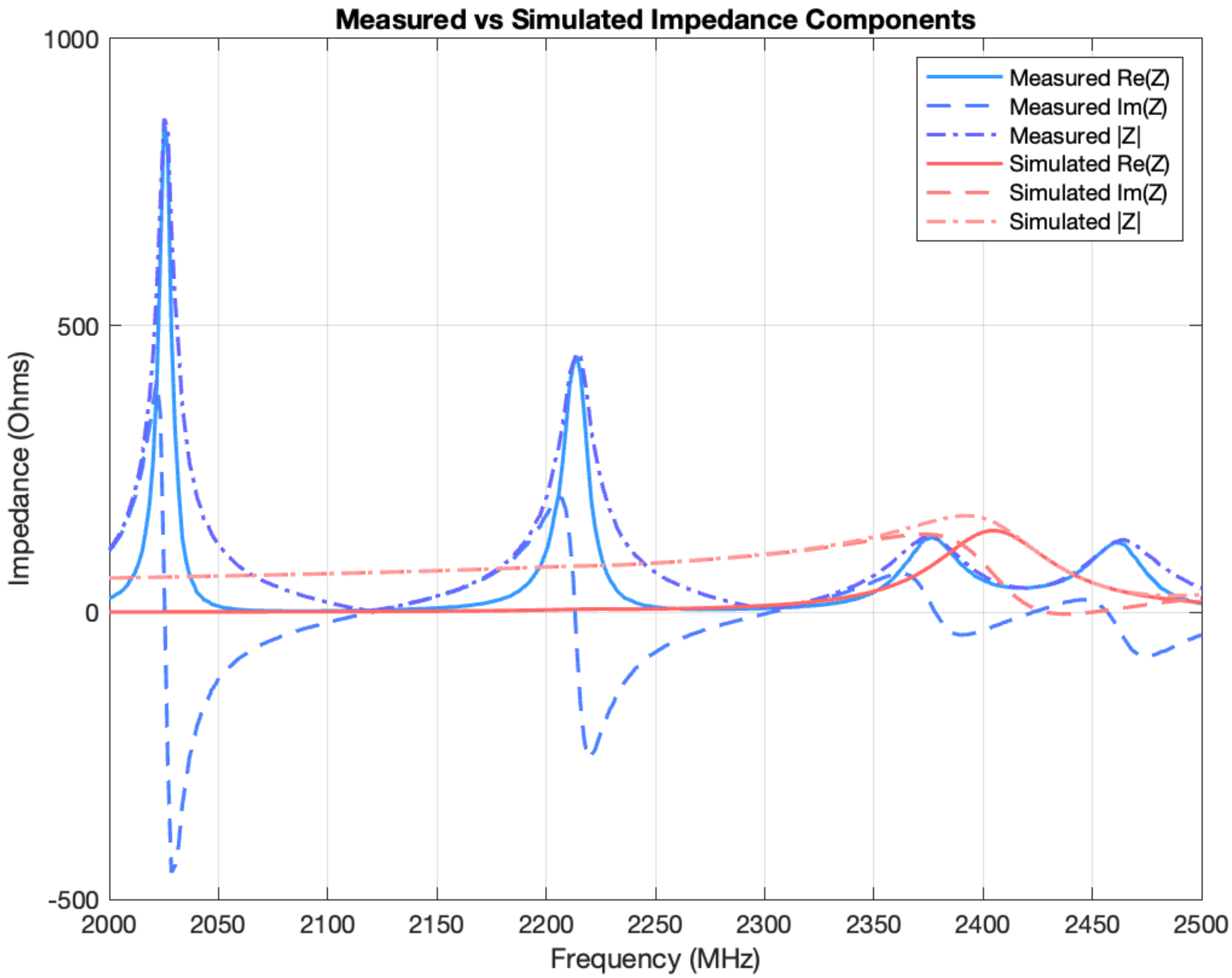

Figure 20: MATLAB plot of measured vs simulated impedance

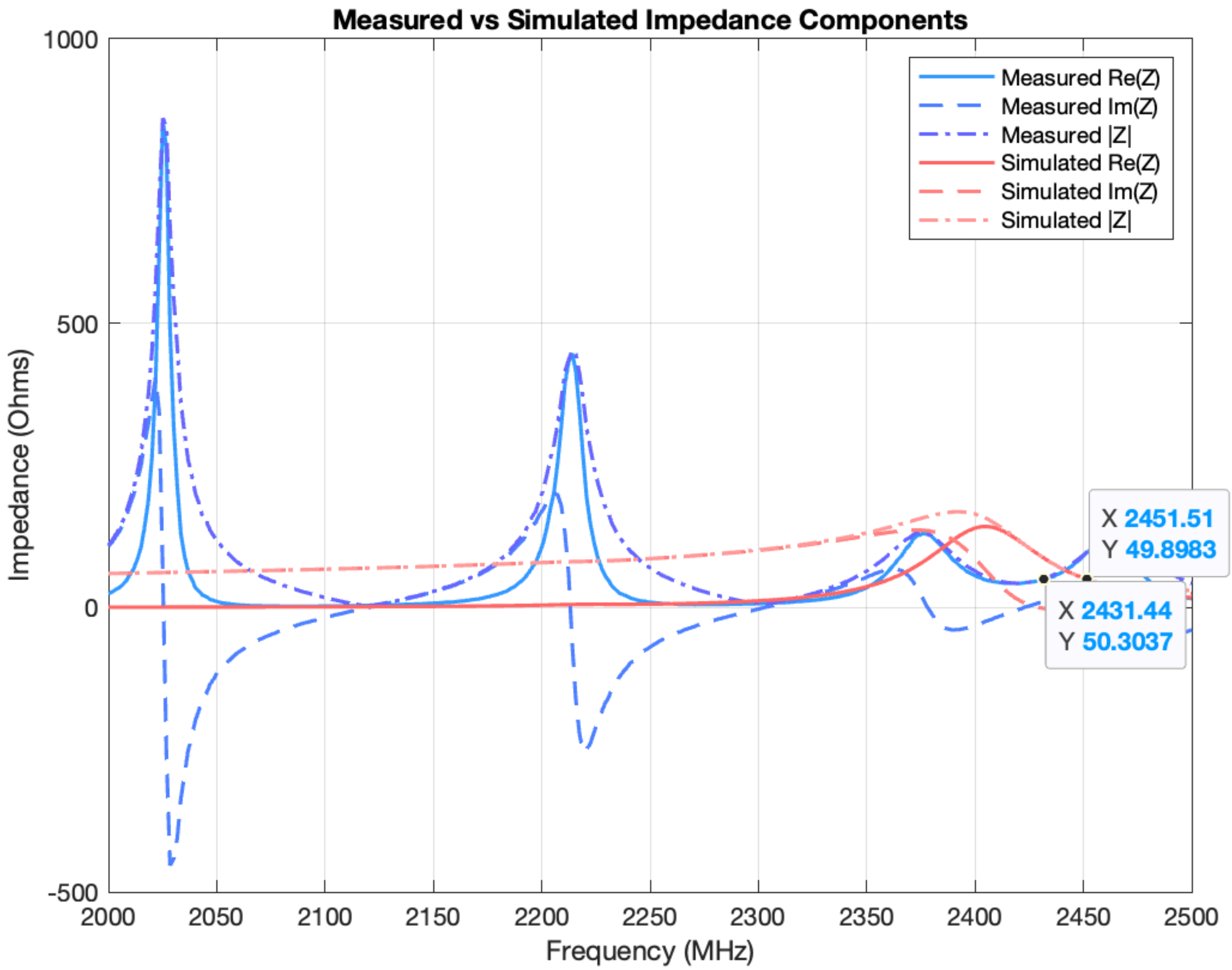

Figure 21: MATLAB plot of measured vs simulated impedance with curser on magnitude of 50ohms

Table 2: Parameters for the L-shaped Simulated vs Measured

Simulated vs Measured		
	Simulated	Measured
Resonance freq	2.45Ghz	2.423Ghz
Impedance	49.88 + j1.13	43.52 + j1.14
-10db S bandwidth	.0468Ghz	.058Ghz
S min	-39.74DB	-23.1DB

The lathed L shaped antenna had the same dimension as discussed in the path to the L shape patch antenna and is shown below. It was important for the author to not add much Sauder with the thinking that the bare minimum would keep the design as close to simulated.

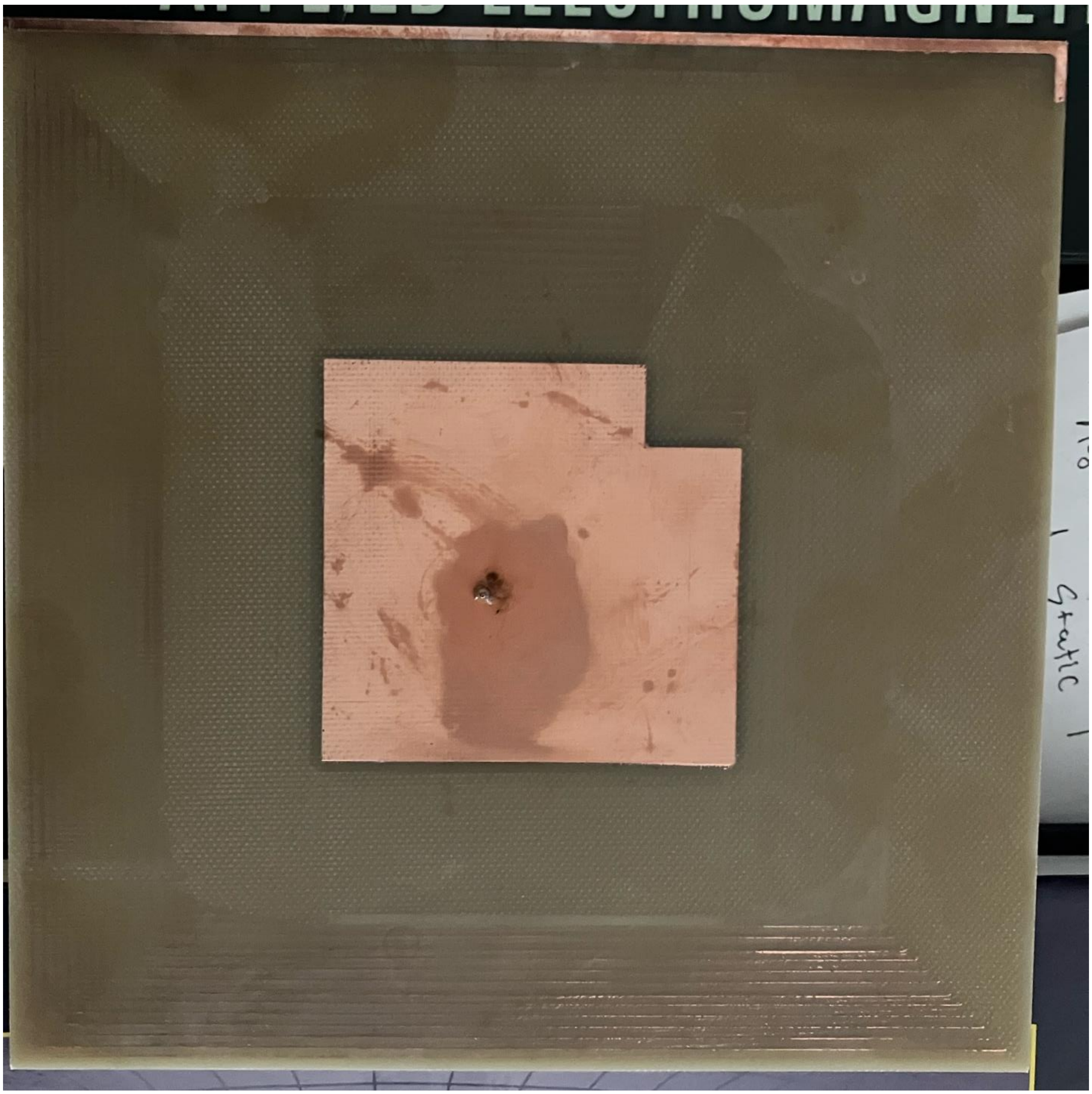

Figure 22: Top side of the physical made L shaped patch antenna

Figure 23: Bottom side of the physical made L shaped patch antenna

Patch Shape Comparison between rectangular and L shaped design

Simulations of a patch antenna were also performed to examine how a specially shaped antenna differs from a standard rectangular patch antenna. The rectangular patch antenna (used as the reference) was compared to the custom-shaped design in terms of radiation pattern, directivity, gain, efficiency, impedance, and S-matched bandwidth. Both antennas were designed to operate at 2.45 GHz.

The recorded values are presented in Table 2 and also in the appendix, where further details can be found, including plots that show how these values were derived. These values start to highlight that while an L-shaped patch antenna may offer unique advantages, it also has drawbacks, and its application may be limited to specific niche uses. The comparison will begin with an analysis of the table, followed by a discussion of the radiation fields.

Table 3: Parameters for the L-shaped antenna vs rectangular patch

L-patch vs normal Patch comparison		
	L Patch	Rectangular Patch
Max gain	1.04	2.25
Max Directivity	3.25	4.73
Efficiency	32%	47.5%
S Bandwidth	0.0468Ghz	0.0564 GHz
Z at 2.45Ghz	49.89 ∠ 1.30° Ω	51.38 ∠ 3.18°

The first noticeable difference is that the L-shaped patch antenna has a lower directivity compared to the rectangular patch antenna. This lower directivity can be linked to the efficiency differences, which can be calculated by comparing the maximum gain and maximum directivity. Efficiency can be indirectly inferred by dividing the maximum gain by the maximum directivity. Gain represents the ratio of radiated power in a particular direction compared to the input power, while directivity indicates how concentrated the radiation is in that direction. In this case, the lower efficiency of the L-shaped antenna can be attributed to factors like increased surface area, which leads to higher resistive losses and potential leakage due to the longer edges of the antenna.

It's also worth noting that the bandwidth difference between the L-shaped and rectangular patch antennas is minimal, with a difference of 0.01 GHz. Depending on the application, this might be significant the narrower bandwidth of the L-shaped antenna could be a disadvantage in some cases. However, it could also be seen as an advantage in applications requiring more tightly controlled frequency responses. As for impedance matching, the L-shaped patch provides a closer match to 50 ohms, though this is easily adjustable. Interestingly, the impedance range for the L-shaped patch was higher, which could be due to the broader field distribution resulting from the longer antenna edges.

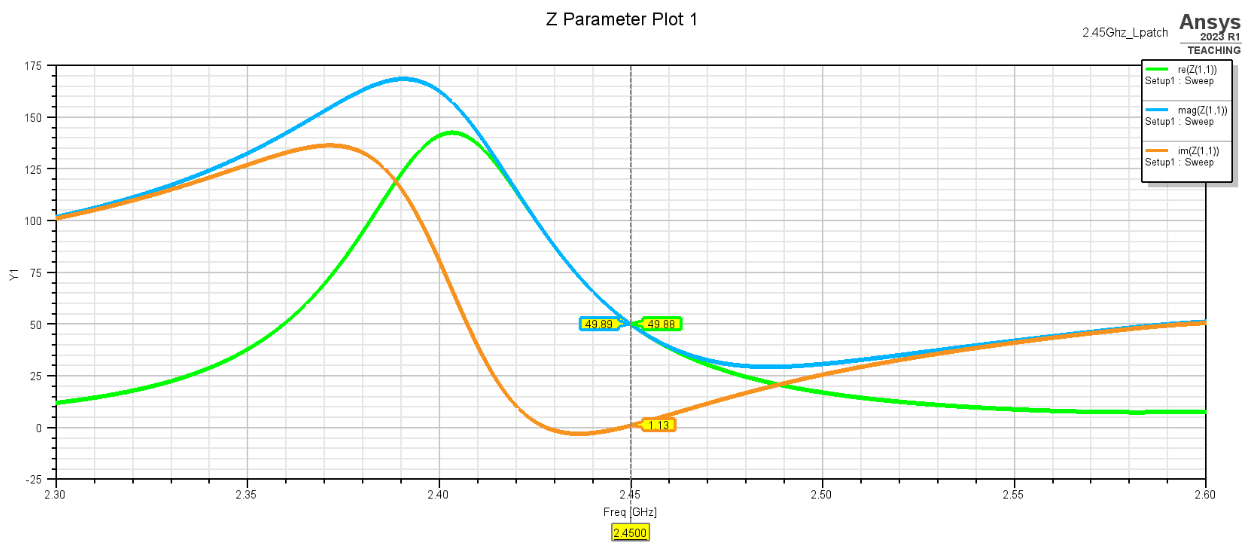

Figure 24: Z-Parameter(impedance) Analysis of an L-Shaped Patch Antenna for 2.45 GHz Frequency Sweep

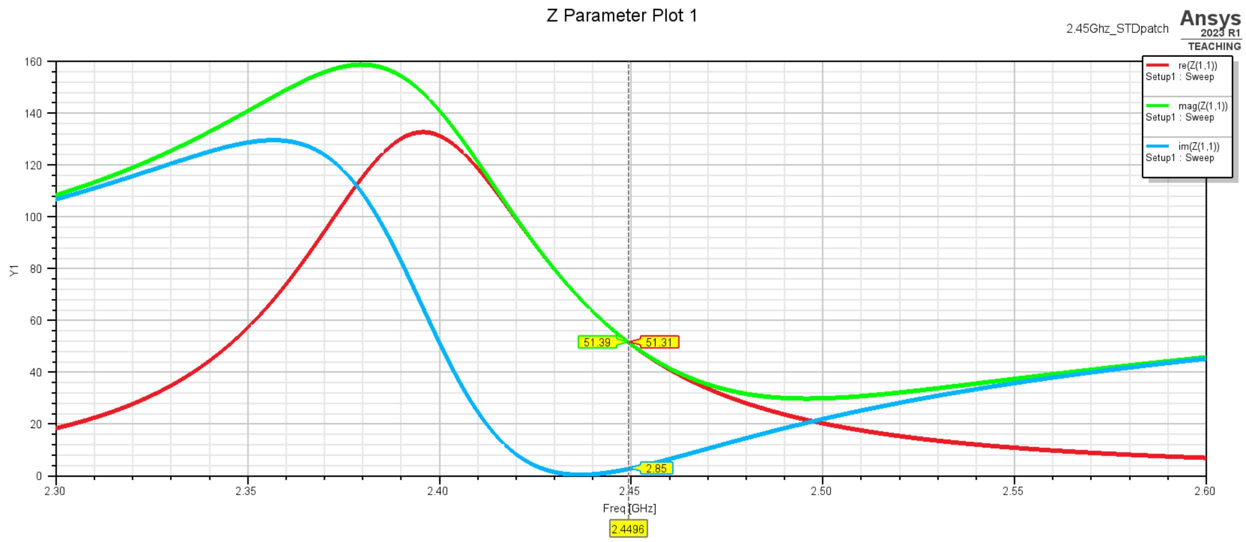

Figure 25: Rectangular Patch Z Antenna

The directivity radiation patterns help illustrate the differences in radiation behavior between the two antennas and show how the unique shape of the L-shaped patch could be useful in applications where a less directional antenna is desired. The L-shaped antenna produces two main lobes approximately 90 degrees apart and away from the origin, about 45 degrees, whereas the rectangular patch antenna exhibits a single, well-defined main lobe radiating perpendicularly from the center of the patch. This is expected due to the constructive interference created by the two symmetrical current paths, like a half-wavelength array, resulting in strong central radiation and reduced radiation elsewhere. In contrast, the L-shaped patch behaves more like a two-dimensional array, with its geometry influencing the field distribution in multiple directions. This multidirectional behavior is particularly interesting and could be leveraged in scenarios requiring broader coverage or diversity in radiation direction.

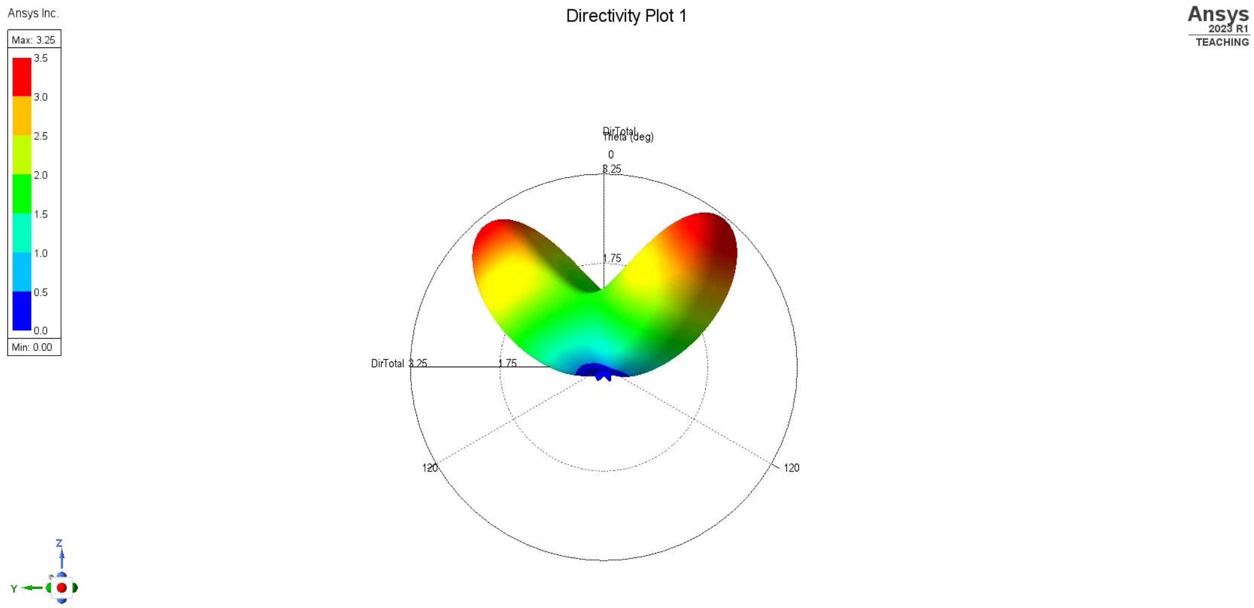

Figure 26: L-Shaped Patch Antenna directivity radiation pattern at 2.45 GHz.

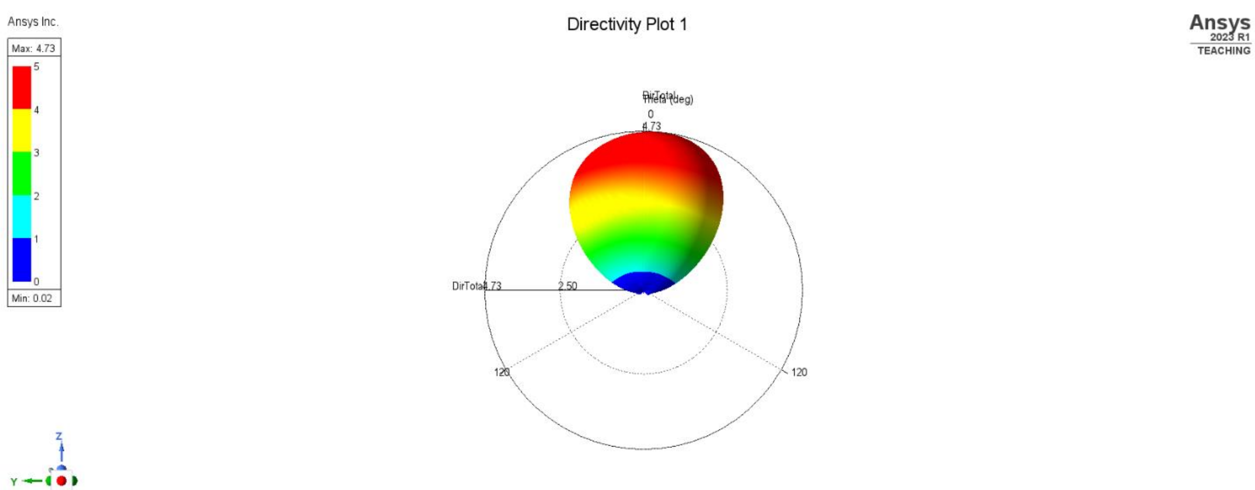

Figure 27: Rectangular Patch Antenna Directivity Radiation pattern at 2.45 GHz

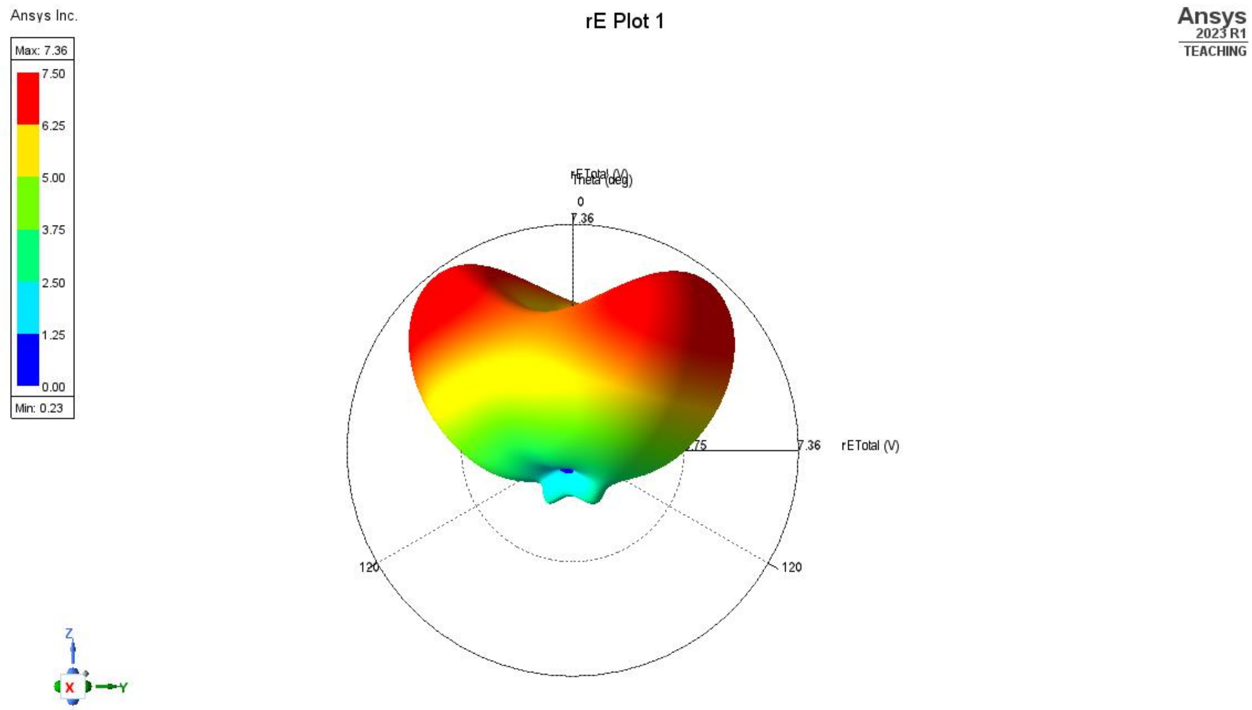

Figure 28: 3d Radiation pattern for L shaped patch antenna (realized gain)

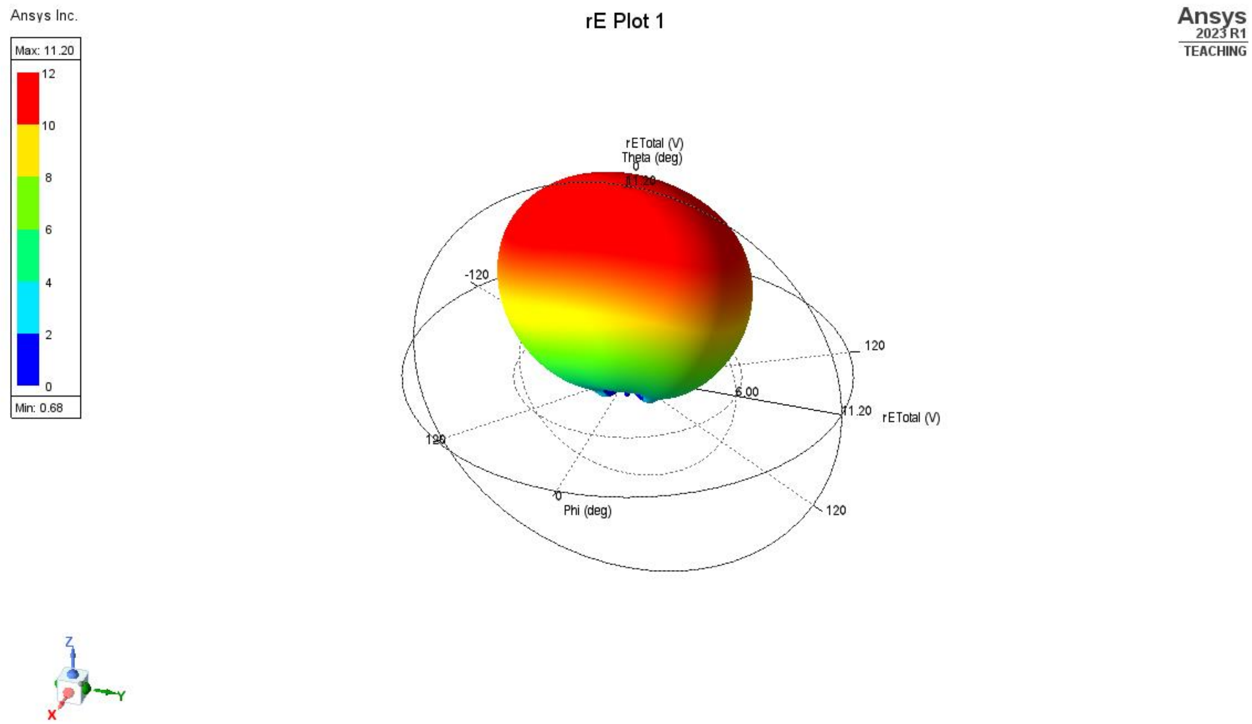

Figure 29: 3d Radiation pater for Rectangular shaped patch antenna (realized gain)

The final parameter of comparison is the half-power bandwidth. For a standard rectangular patch antenna, the radiation pattern is roughly circular, with the highest power at the center and decreasing as you move outward. In contrast, the L-shaped patch produces a similar pattern but can be thought of as two rectangular patches placed side by side. This results in two separate lobes, each resembling a smaller version of the original circular pattern. However, the key difference is that the maximum power for each lobe in the L-shaped design is only about half of what is seen in the single rectangular patch.

Conclusion

This project focused on the design, simulation, and testing of a patch antenna operating at a center frequency of 2.45 GHz. Two antenna types were explored: a standard rectangular patch and a custom L-shaped patch. Starting with basic microstrip patch design equations, the rectangular antenna served as a foundation to understand core properties such as gain, impedance, and bandwidth.

The L-shaped antenna was then developed through iterative parametric sweeps, adjusting leg lengths and feed position to improve resonance and impedance matching.

HFSS was used extensively to simulate the antenna performance, including S-parameters, impedance, radiation patterns, and gain. The simulations guided the physical design, which was later fabricated and tested. Real-world measurements showed a slight frequency shift from the simulated results, likely due to small defects introduced during manual fabrication and soldering.

Despite this, the measured data stayed within an acceptable range of the target frequency. Comparison between the L-shaped and rectangular designs showed that the L-shaped antenna had lower gain and directivity but offered a slightly better impedance match near 50 ohms. The custom shape also created a dual-lobe radiation pattern, which may be useful for applications requiring broader angular coverage rather than focused directional performance. The rectangular patch, in contrast, provided higher gain and efficiency with a more traditional single-lobe pattern.

Overall, this project demonstrated how patch geometry, feed location, and careful tuning can influence antenna behavior. It highlighted the trade-offs involved in customizing antenna shape and showed how even small design choices can affect real-world performance. While tools like HFSS are valuable for predicting results, physical testing remains essential to account for manufacturing variation and unexpected interactions.

References

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[2] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, 2nd ed. Hoboken, NJ: Wiley, 1997

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Acknowledgment

NA

Appendix A: Problems encountered

Problem statement:

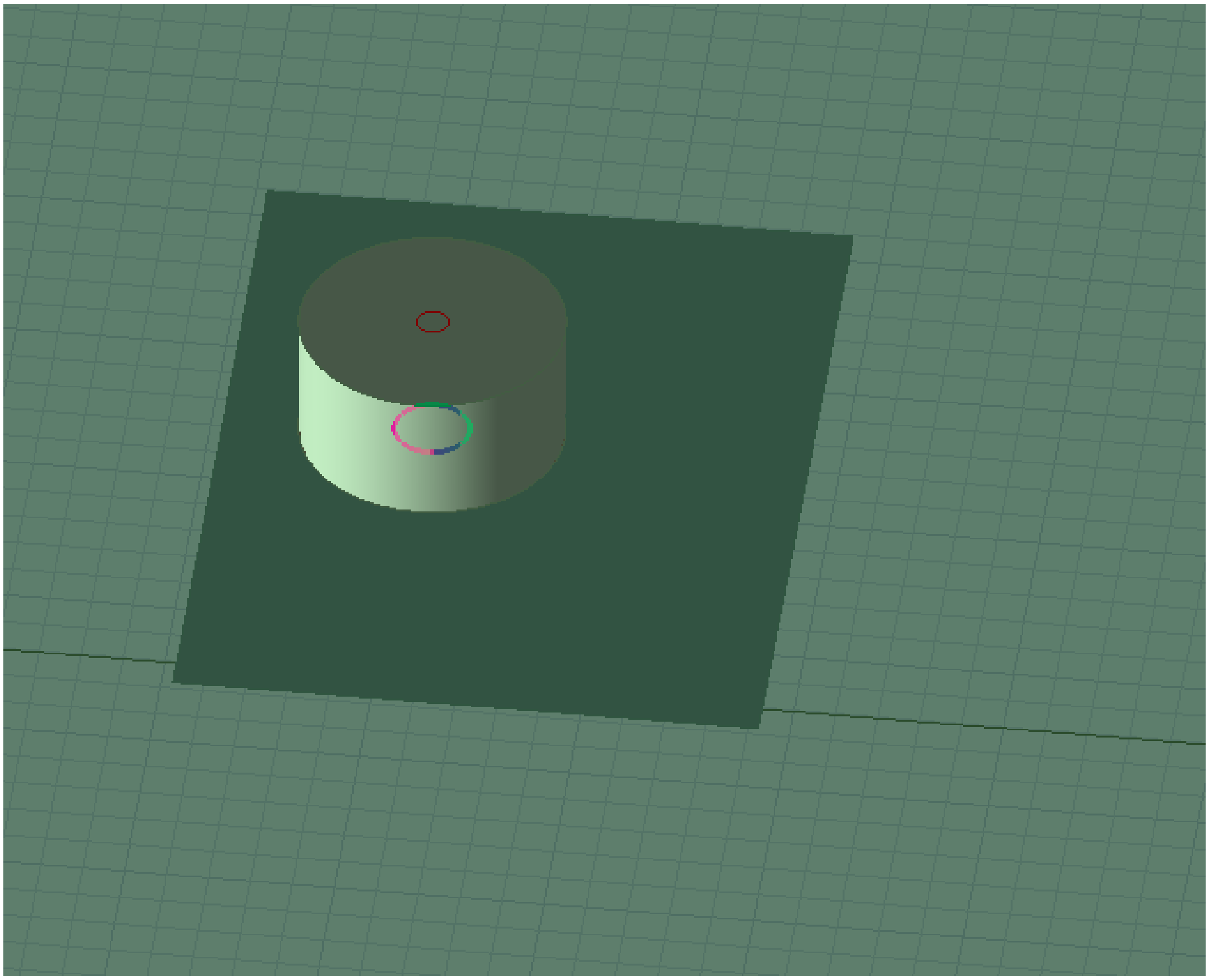
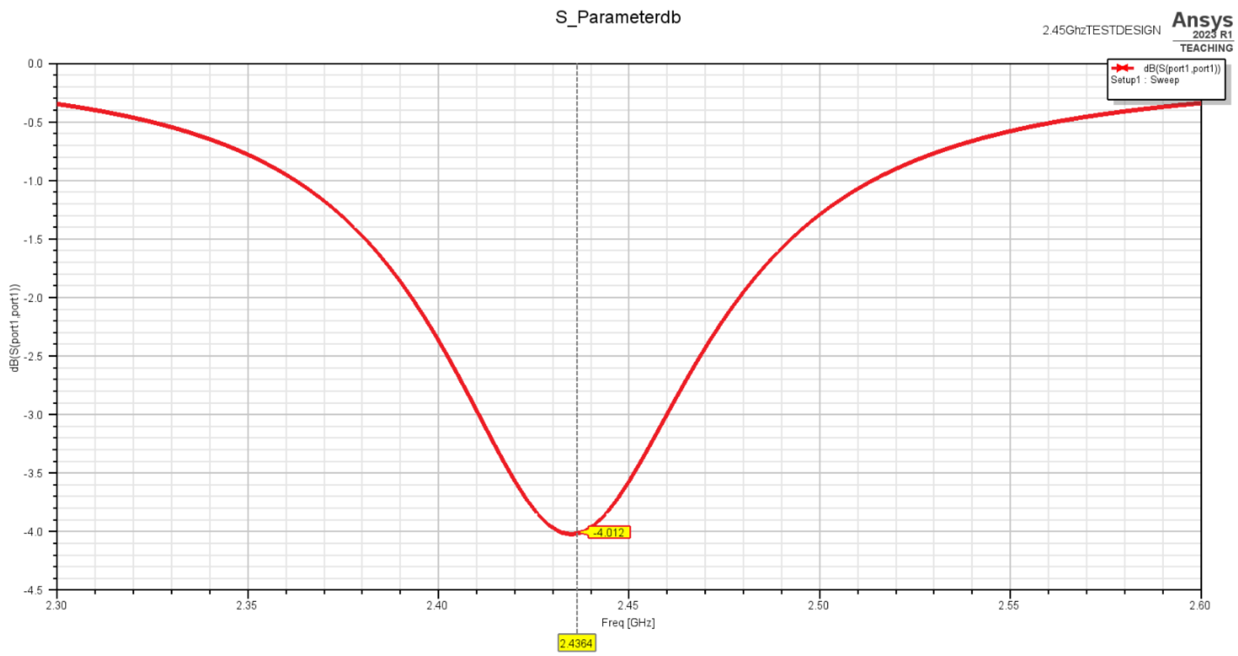


Diagram Description:

- **Port Appearance:** The image shows the current setup of the port.

- **GND Hole Radius:** 1.525 mm
- **Probe Radius:** 0.762 mm
- **Excitation Port Diameter:** 6.35 mm
- **Sheathing Radius:** 6.35 mm



S-Parameter Plot (in dB):

Configuration with coaxial sheath diameter of **1/4 inch (6.35 mm)**

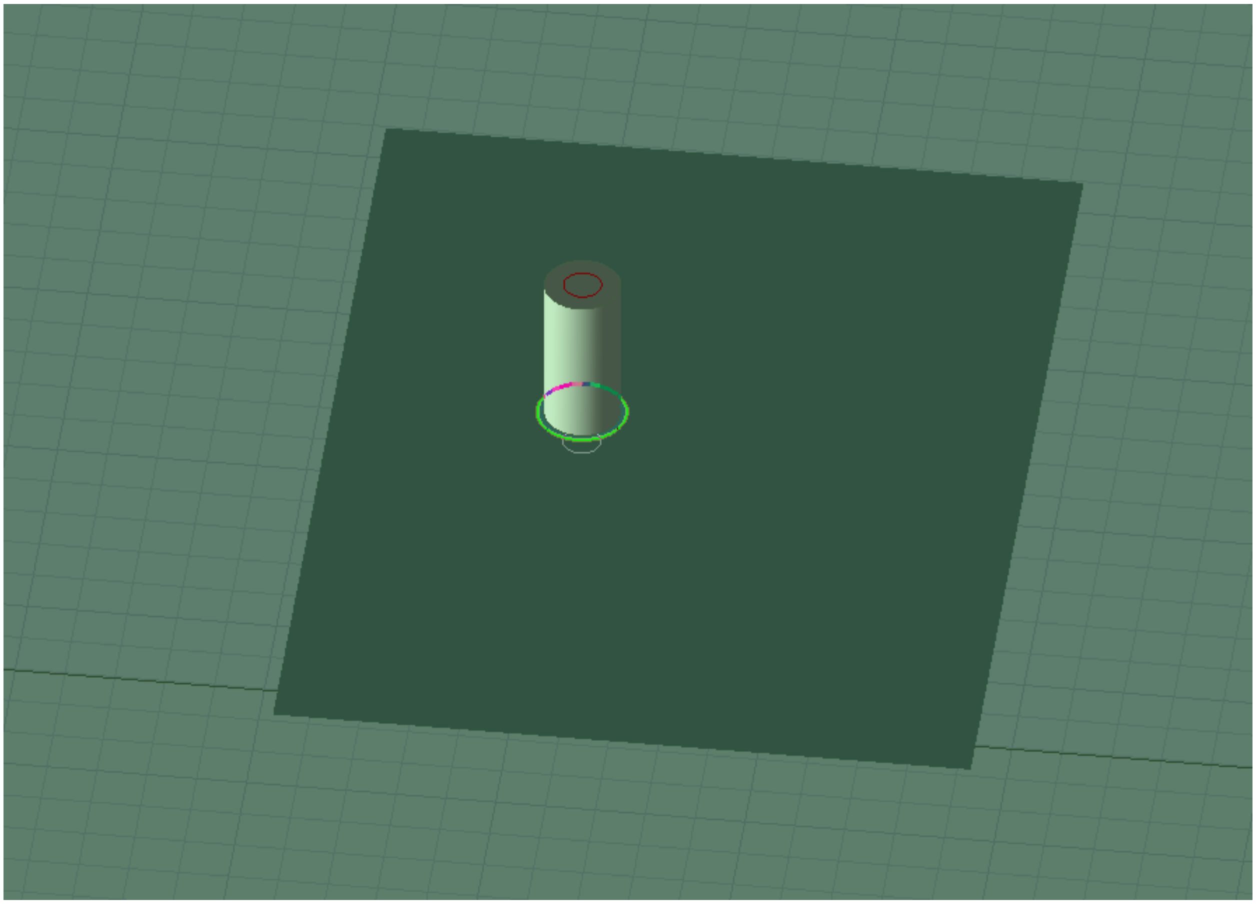
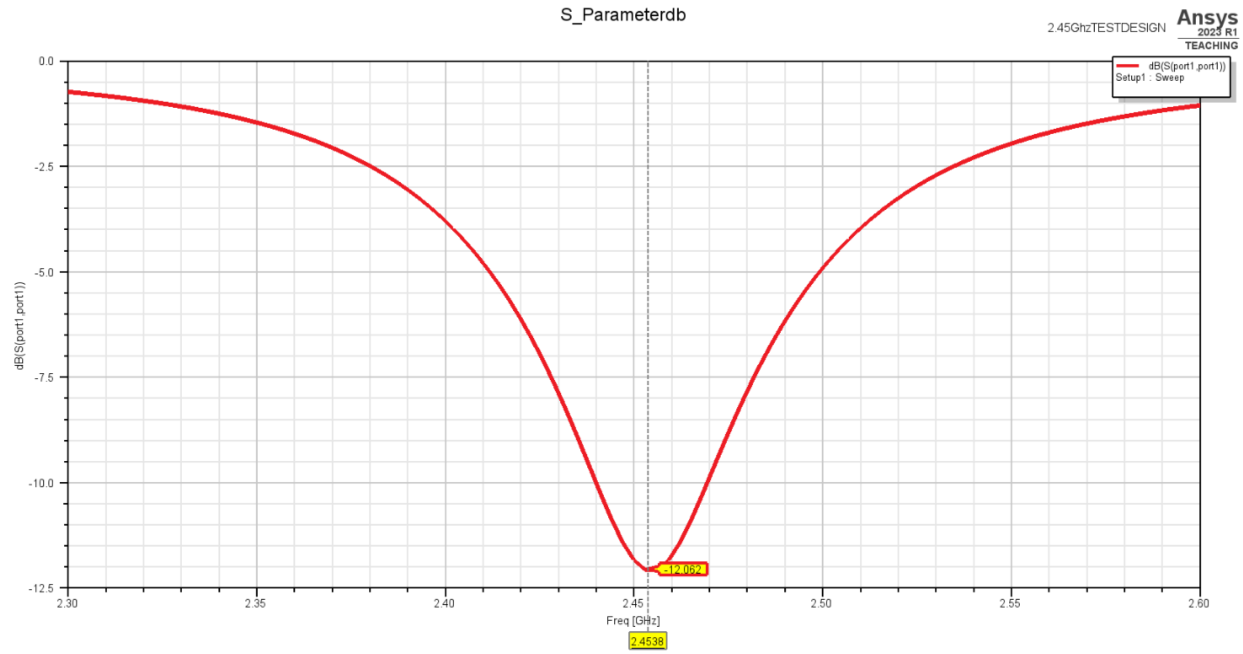


Diagram Description:

- **Port Appearance:** The image shows the current setup of the port.
- **GND Hole Radius:** 1.525 mm
- **Probe Radius:** 0.762 mm
- **Excitation Port Diameter:** 1.525 mm
- **Sheathing Radius:** 1.525 mm



S-Parameter Plot (in dB):

Configuration with coaxial sheath diameter of **1.525 mm**, which is **twice the radius of the probe**.

Problem:

I've encountered an unexpected issue in my simulations that I'd appreciate your insight on.

Specifically, increasing the dielectric sheath radius of the coaxial feed seems to significantly affect the input impedance of the patch antenna. From what I understand, the standard analytical models for patch antennas typically don't account for the dielectric width of the coax feed, so I initially assumed changes in sheath size wouldn't have a substantial impact on matching. However, in my simulations, even small changes to the sheath radius lead to large variations in the S-parameters, far more than I would expect.

This has made me question whether the issue lies in how I'm modeling the feed in my simulation. Is it possible that I'm missing a key parameter or incorrectly assuming the coax feed has negligible influence? At this point, I’m unsure whether this is a flaw in my setup or if such sensitivity is to be expected.

Solution/Answer:

While going through HFSS simulations and some design examples, the student noticed that even small changes in the size of the coax pin could cause big changes in how the antenna matched. One case showed that increasing the probe diameter from 1.2 mm to 2.0 mm moved the resonance on the Smith chart and made the VSWR bandwidth wider. It turns out that a thicker pin has less inductance, which shifts the resonant frequency higher and throws off the S_{11}.

The thought process for the probe is that it was acting like a little inductor inside the patch. When the pin is thin, it doesn't really get in the way. But when it gets too thick, it starts changing the impedance like an unwanted matching circuit. The main takeaway was that keeping the pin small helps the antenna behave the way it’s supposed to.

Another thing that stood out was that at higher frequencies, like above a few GHz, the vertical length of the pin also matters. The feed starts acting like a stub, adding extra reactance that shifts the impedance. So the student made it a rule to keep both the pin size and length as short and small as possible to avoid problems.

Appendix B: L-shaped patch antenna width variation

An interesting idea that came up during the design process was using multiple widths in the L-shaped patch antenna. The reasoning was that the width of the patch affects its resonant frequency, so by combining two patches with different widths in the same layout, it could be possible to make the antenna resonate at two separate frequencies. This concept was explored by varying the width in the final design. The results from the parametric analysis are shown below.

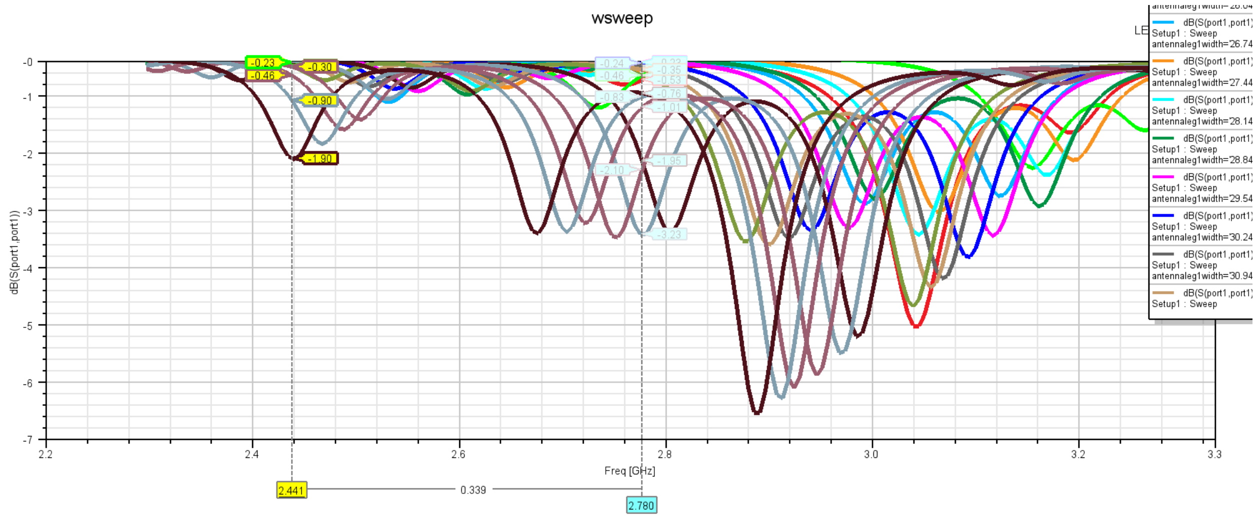


Figure 30: L-shaped Patch Antenna with lopsided leg width parametric sweep

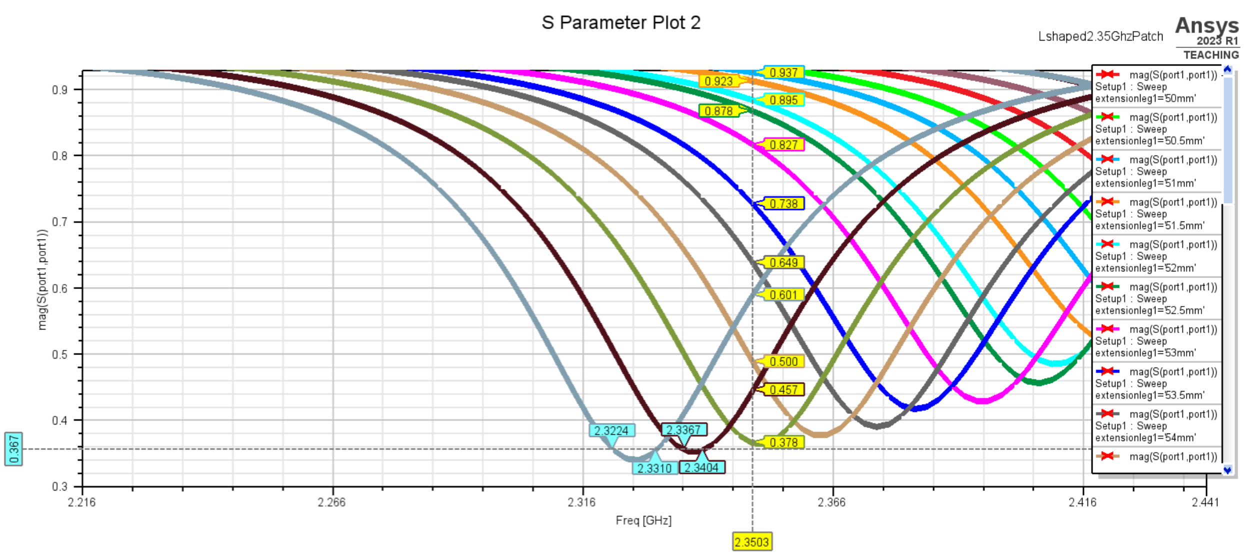


Figure 31: L-shaped Patch Antenna leg length parametric sweep

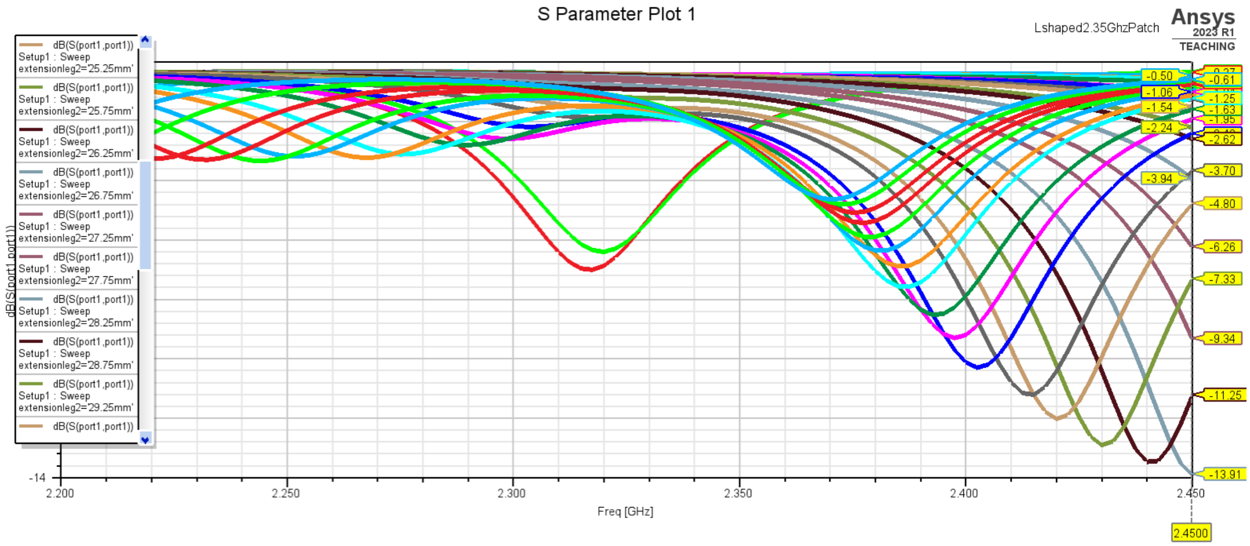


Figure 32: L-shaped Patch Antenna coax pin parametric position sweep

By following a straightforward approach first varying the width, then the length, and finally adjusting the coax pin it became clear that with more thorough analysis, it might be possible to design a patch antenna that is matched at two different frequencies. However, this proved to be tricky, as one frequency always seemed to match better than the other. It was also observed that changing the length mainly controls the resonant frequency (f_0), while the width influences how well the antenna resonates or how strong the match is.

Appendix C: Rectangular-shaped patch antenna data

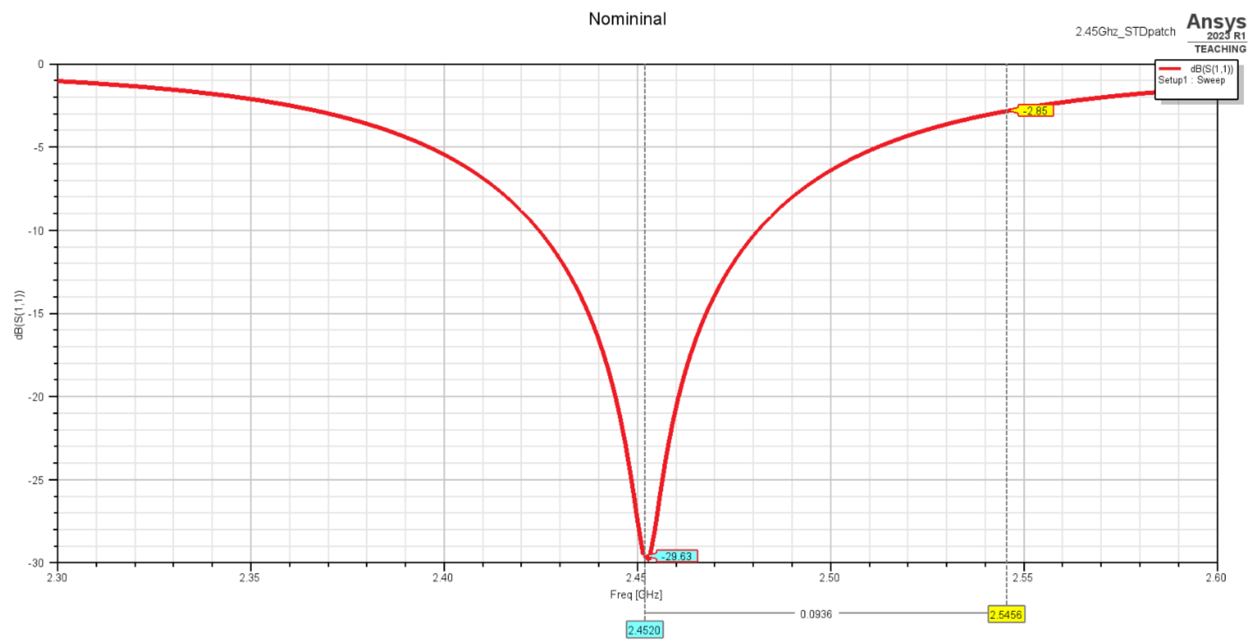


Figure 33: Standard Patch Antenna at 2.45 GHz

Note: The bandwidth between the -10 dB points is 0.0564 GHz

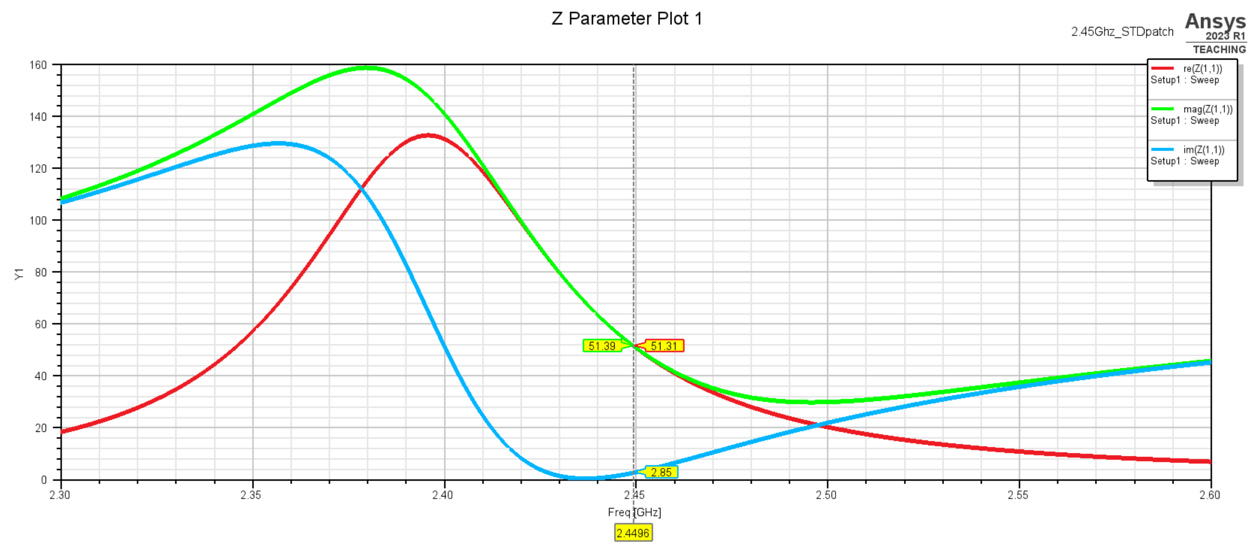


Figure 34: Standard Patch Z Antenna

Note: impedance is 51.31ohms real and 2.85ohms imaginary

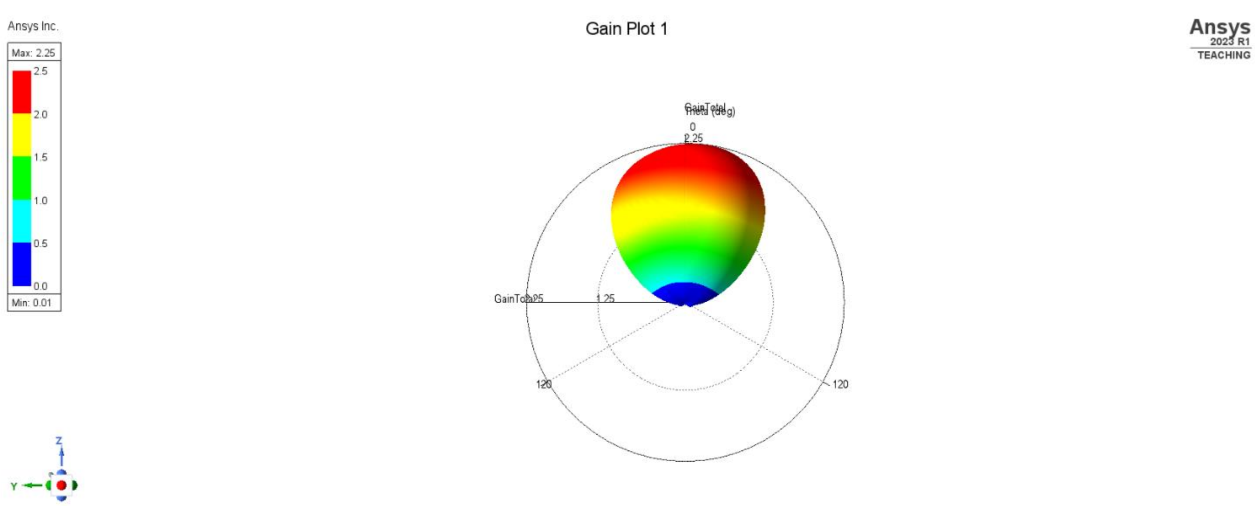


Figure 35: Standard Patch Antenna Gain Radiation Pattern at 2.45 GHz

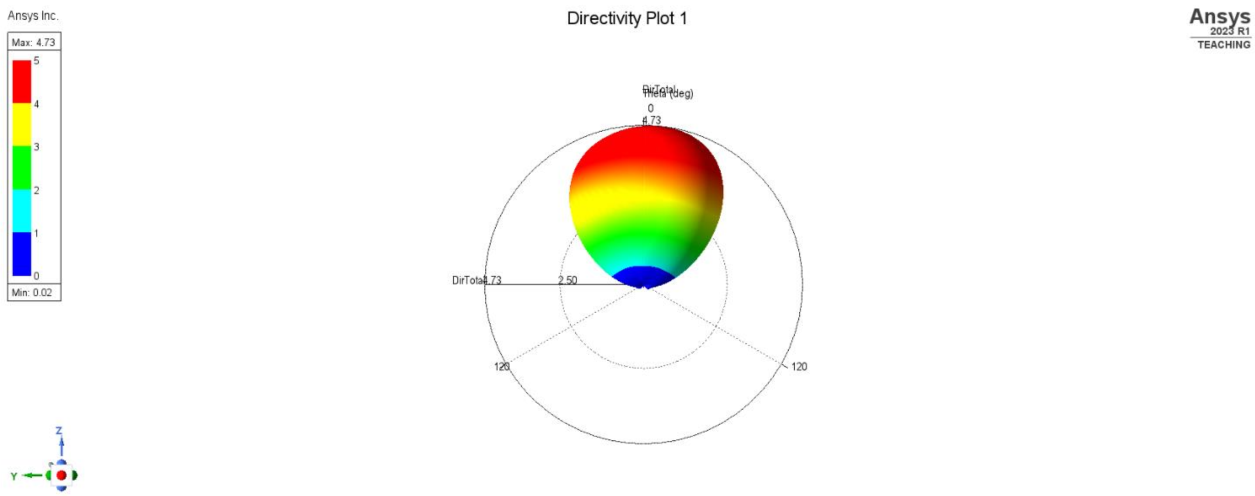


Figure 36: Rectangular Patch Antenna Directivity Radiation pattern at 2.45 GHz

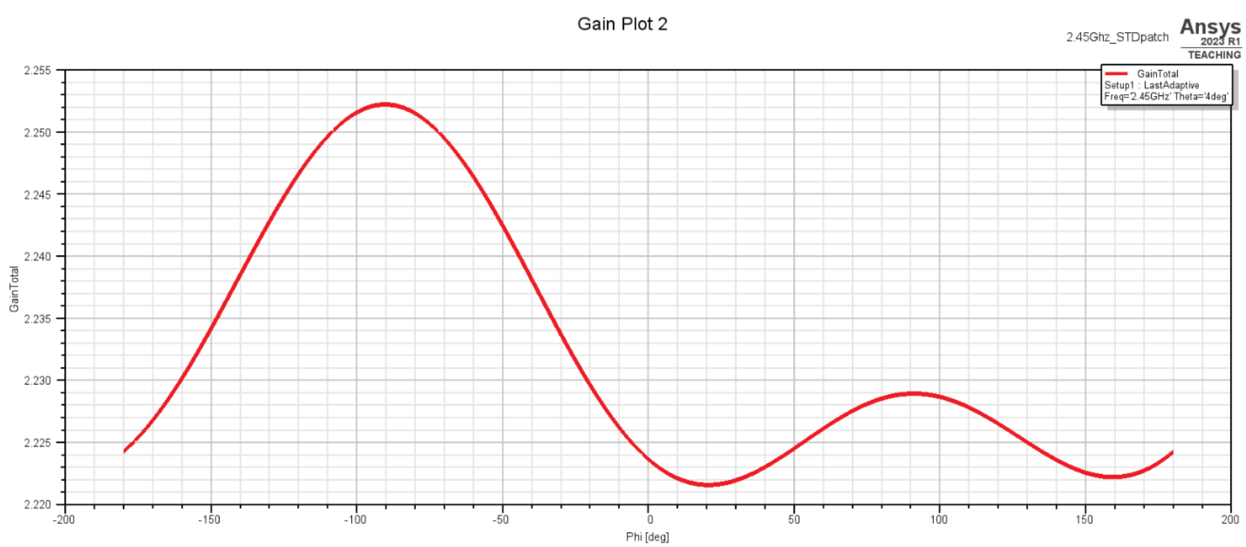


Figure 37: Rectangular Patch 2D Gain at 2.45 GHz

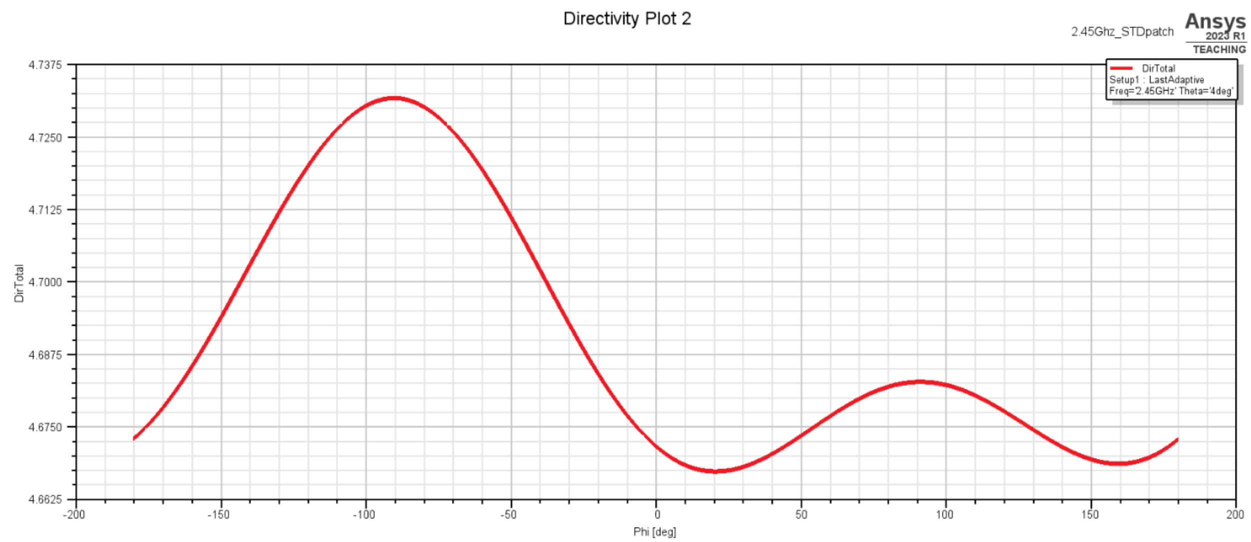


Figure 38: Rectangular Patch 2D Directivity at 2.45 GHz

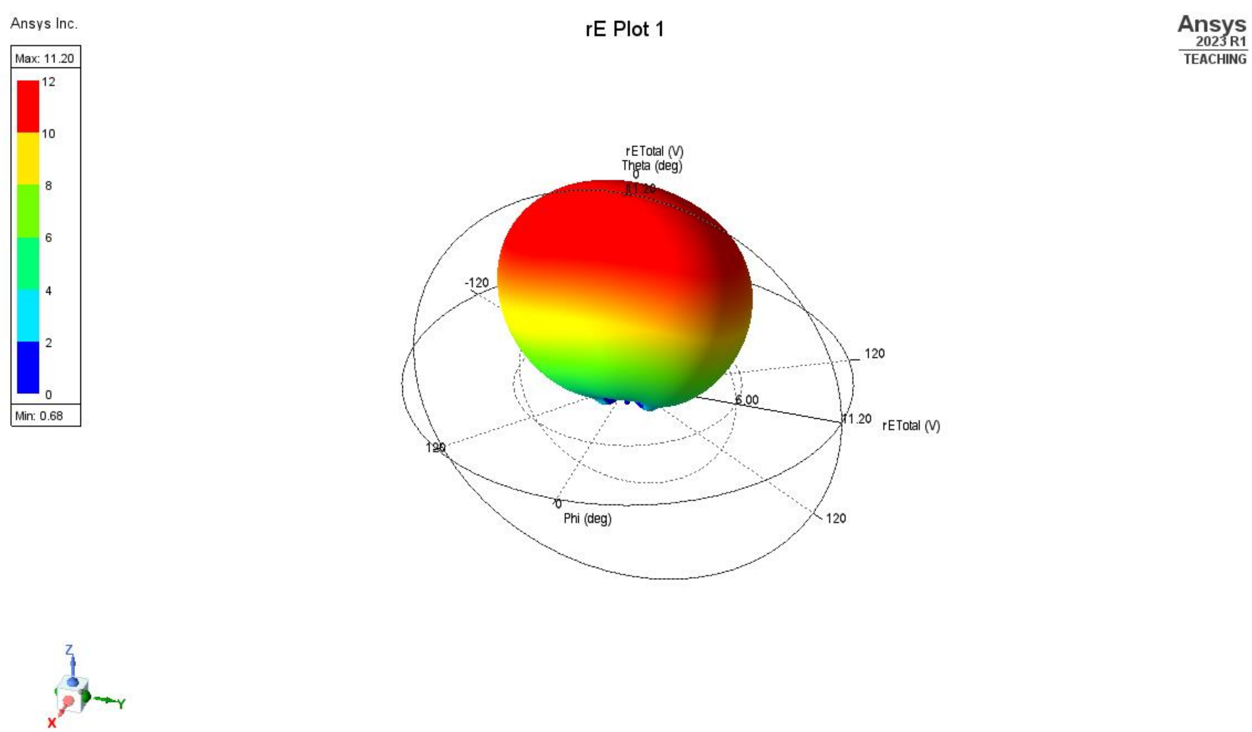


Figure 39: Rectangular Patch 3D radiation pattern at 2.45 GHz

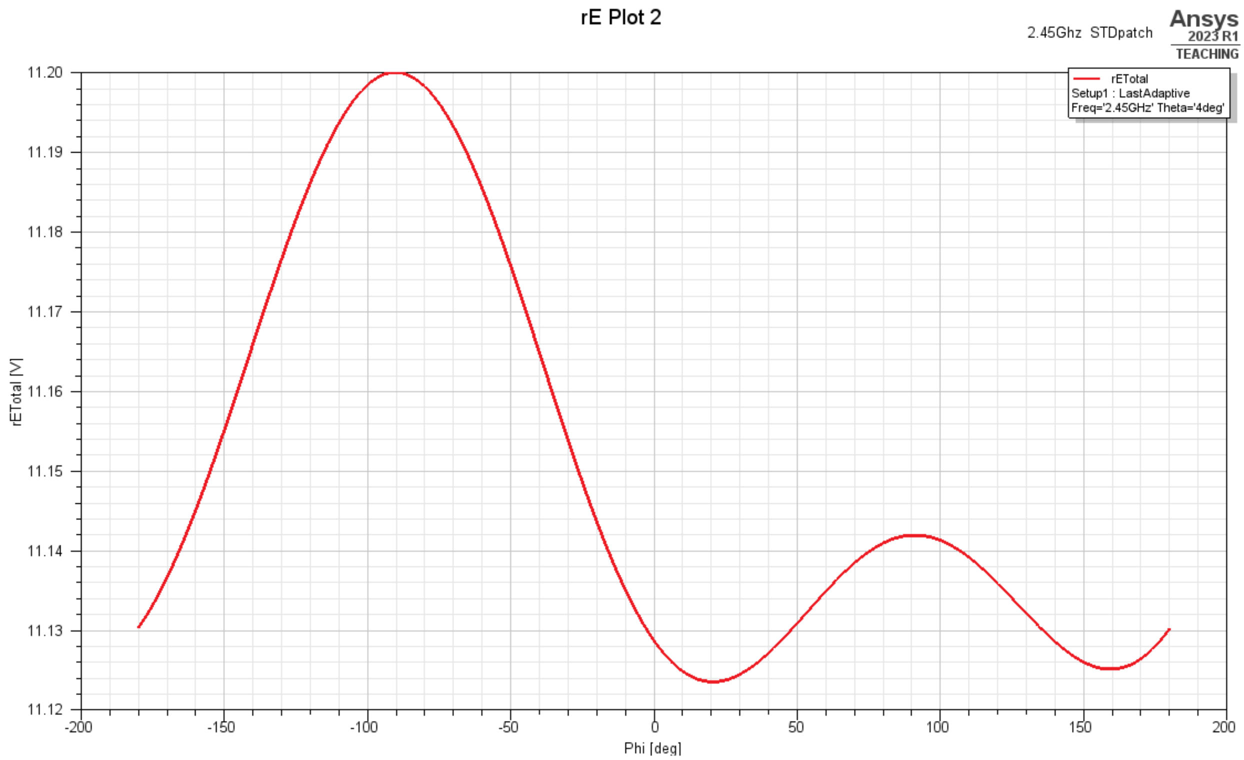


Figure 40: Rectangular Patch 2D radiation pattern at 2.45 GHz