

BEng Embedded
Electronic Systems
Advanced Radio
Frequency Systems
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1 Introduction

This assignment explores the simulation of five different antennas using industry standard software packages MATLAB [1] and Ansys Electronics Desktop High Frequency Simulation Software (Ansys HFSS) [2]. Ansys HFSS is used to simulate a microstrip patch antenna and MATLAB is used to simulate a cylindrical dipole, folded dipole, horn antenna and helix antenna. Post-simulation, the results are analysed and compared to expected phenomena and real-world applications.

2 Task 1 – Rectangular microstrip patch antenna

2.1 Background research and literature review

2.1.1 Radar and communication systems

Due to the low profile of microstrip patch antennas, they are desirable in systems where the use of a traditional antenna that occupies significant space in 3 dimensions would adversely affect the performance of the system. One such example is in CubeSats [3] (a type of small satellite) where volume is extremely limited. These CubeSats use antennas operating in the S and X band at frequencies of 2.4GHz and 8-12GHz respectively.



Figure 1: Ant Dev. Corp: Medium Gain X-band Patch Array Antenna [3]

Other radar and communication systems use phased array microstrip antennas to achieve a reduction in interference and increase in range [4]. Antennas in an array configuration are able to achieve high directionality, an example of this is shown in section 3.3.3.1.

2.1.2 ESP32 uses an inverted F microstrip [5]

Microcontrollers with WiFi capabilities use a different type of microstrip, called the inverted F microstrip, these are used in applications where volume is even more limited. These antennas are often found in “smart” / “IoT” devices to connect them to the internet or a local network.

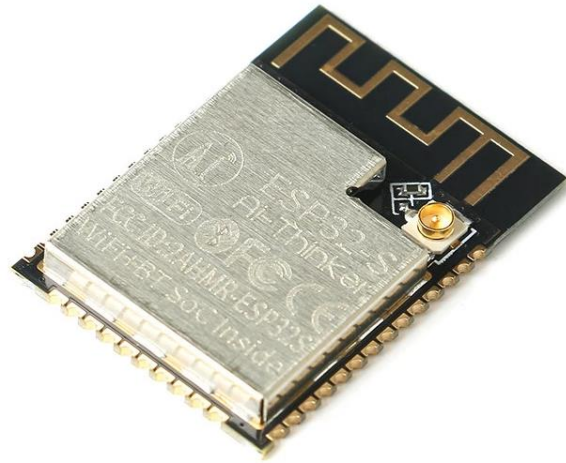


Figure 2: Inverted-F microstrip antenna on the ESP32 Ai-Thinker module [5]

2.1.3 Quarter wave transformer vs inset feed

Quarter wave transformers and inset feeds are both elements that can be applied to a patch antenna to match the impedance of the transmission line. A quarter wave transformer is generally easier to design as its length is fixed at one quarter of the effective wavelength. The main disadvantage of the quarter wave transformer is the additional physical space it requires. A quarter wave transformer was not used for this assignment as it would have required a larger substrate area than 70mm by 70mm.

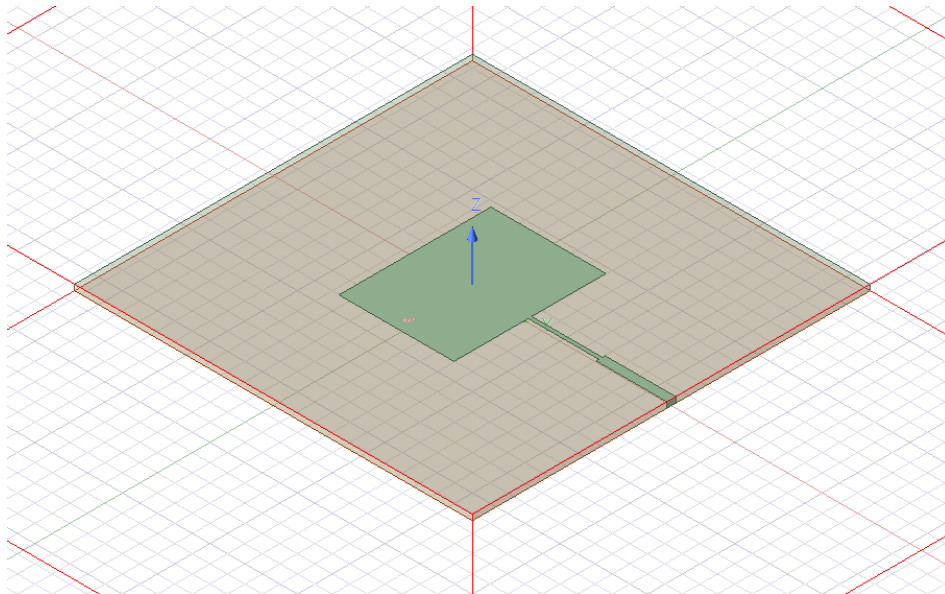


Figure 3: A quarter wave transformer added to a microstrip patch antenna

2.1.4 Inset feed

An inset feed requires significantly less space as below shown in Figure 4. The final numbers for the inset feed were arrived at by sweeping through variables using Ansys HFSS's optimetrics after setting an initial length of half the radius of the patch antenna. These values are detailed in Table 1.

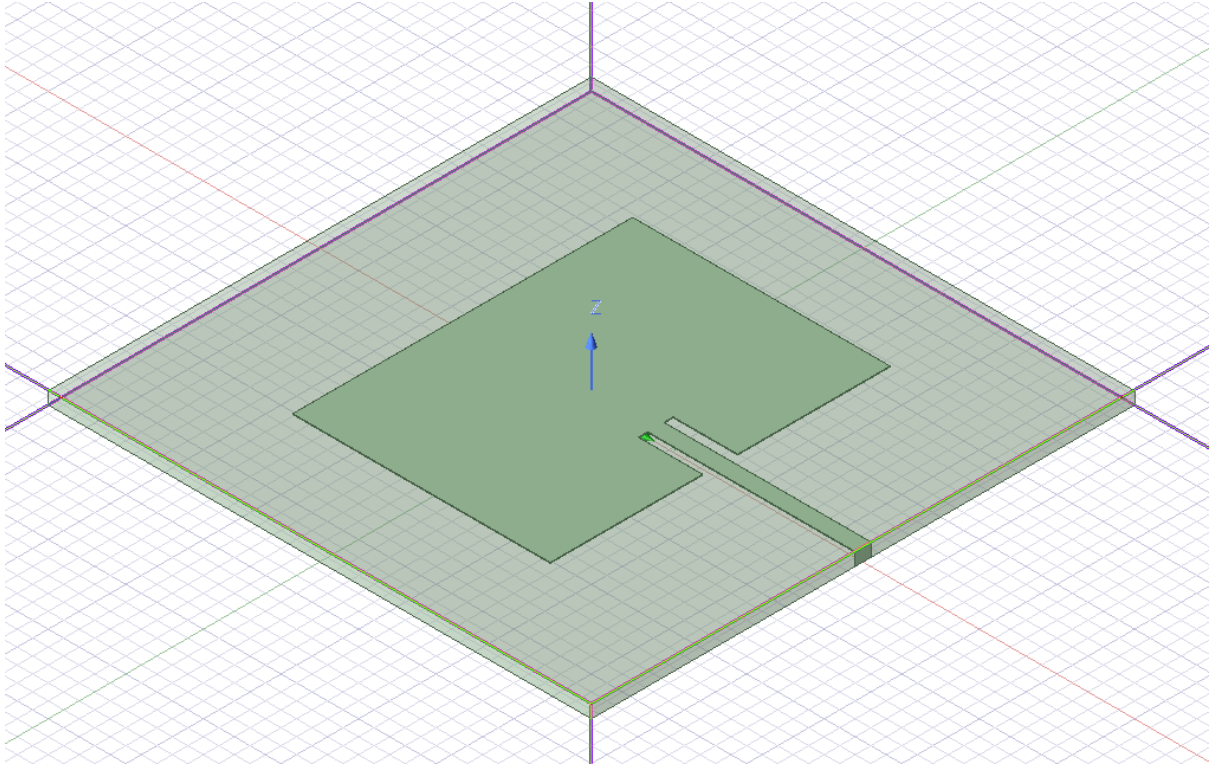


Figure 4: Microstrip patch antenna with an inset feed

2.2 Patch dimension calculations

The operating frequency, f_r , of this microstrip patch antenna is specified to be 2.1GHz. Equation 1 below shows the formula used to calculate the width of the patch antenna.

$$W = \frac{c}{2f_r \sqrt{\frac{\epsilon_r + 1}{2}}} [6]$$

Equation 1

$$= \frac{3 * 10^8}{2 * 2.1 * 10^9 \sqrt{\frac{4.4 + 1}{2}}}$$

$$= 43.7mm$$

Next, the effective relative permittivity, ϵ_{reff} , must be calculated using Equation 2.

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(\frac{1}{\sqrt{1 + 12 \left(\frac{h}{w} \right)}} \right) [6]$$

Equation 2

$$= \frac{4.4 + 1}{2} + \frac{4.4 - 1}{2} \left(\frac{1}{\sqrt{1 + 12 \left(\frac{1.6 * 10^{-2}}{43.7 * 10^{-2}} \right)}} \right)$$

$$= 4.117$$

The effective relative permittivity can now be used to calculate the effective length of the patch using Equation 3.

$$L_{eff} = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} [6]$$

Equation 3

$$= \frac{3 * 10^8}{2 * 2.1 * 10^9 \sqrt{4.117}}$$

$$= 35.2mm$$

The length extension, ΔL , is calculated using Equation 4

$$\Delta L = 0.412h \left[\frac{(\epsilon_{reff} + 0.3)(\frac{w}{h} + 0.264)}{(\epsilon_{reff} - 0.258)(\frac{w}{h} + 0.8)} \right]$$

Equation 4

$$= 0.412 * 1.6 * 10^{-2} \left[\frac{(4.117 + 0.3)(\frac{43.7 * 10^{-2}}{1.6 * 10^{-2}} + 0.264)}{(4.117 - 0.258)(\frac{43.7 * 10^{-2}}{1.6 * 10^{-2}} + 0.8)} \right]$$

$$= 0.74mm$$

The actual length is calculated using Equation 5

$$L = L_{eff} - 2\Delta L [6]$$

Equation 5

$$= 35.2 * 10^{-2} - 2 * 0.74 * 10^{-2}$$

$$= 33.76mm$$

2.3 Simulation results

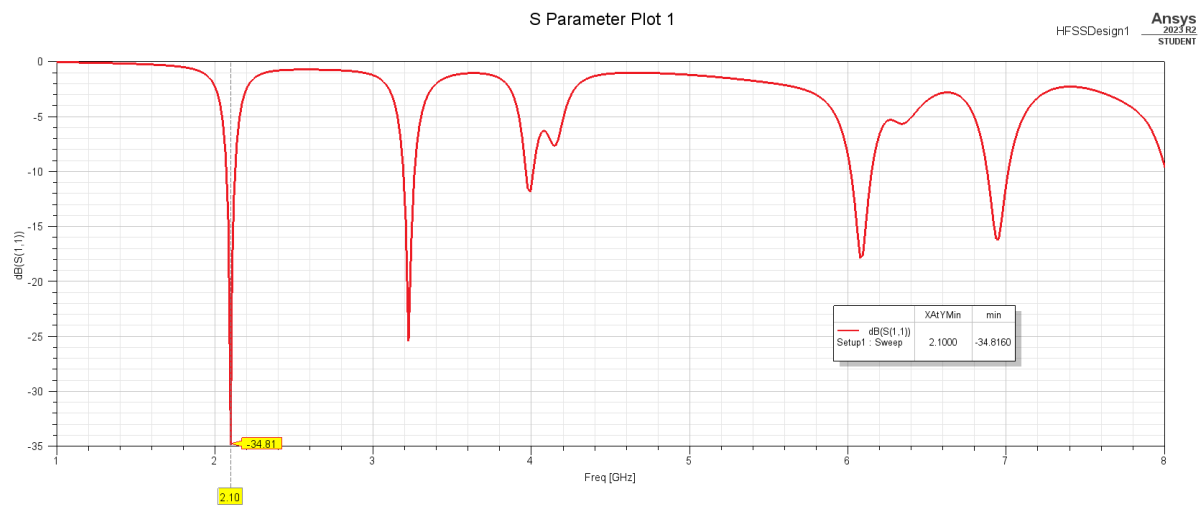


Figure 5: S-Parameter plot of the patch antenna in dB from 1 to 8GHz

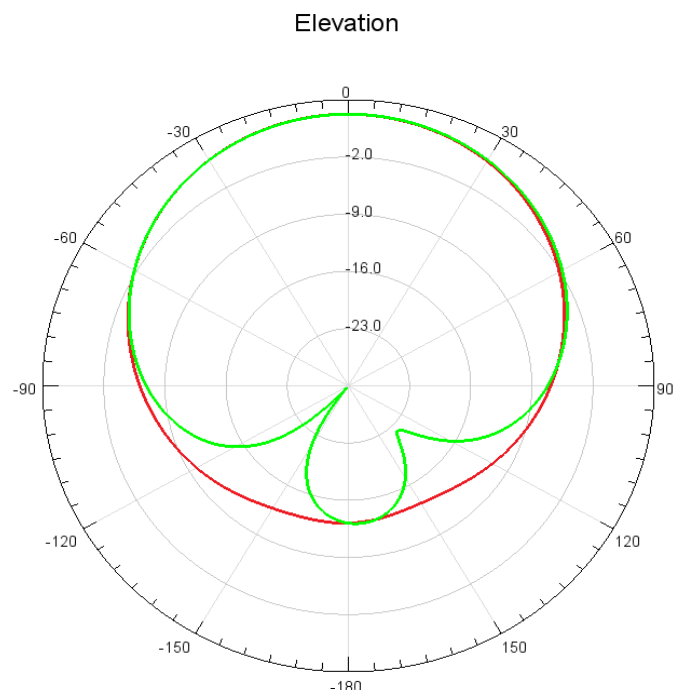


Figure 6: 2D polar plot of the gain in dB of the simulated patch antenna in elevation at $\Phi = 0^\circ$ and 90°

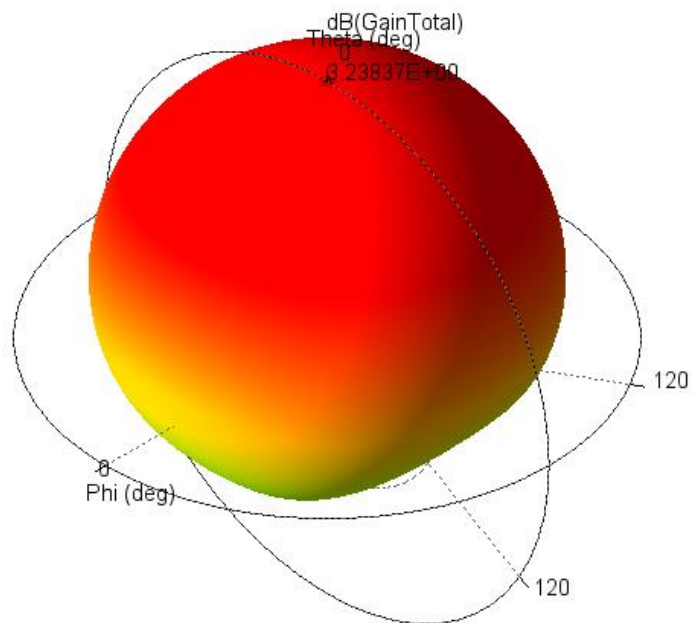


Figure 7: 3D polar plot of the gain in dB of the simulated patch antenna

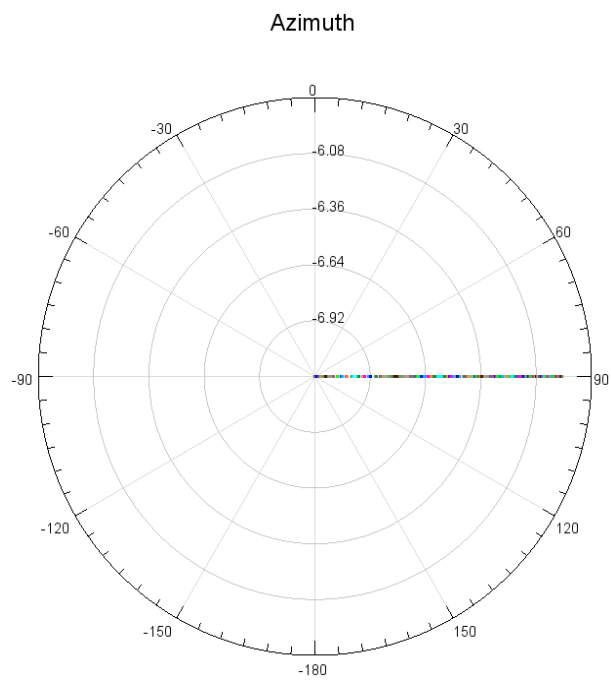


Figure 8: 2D polar plot of the gain in dB of the simulated patch antenna in azimuth

2.4 Simulation analysis and evaluation

The simulations were used to tune the dimensions of the patch antenna to centre the operating frequency on 2.1GHz as shown in the previous section in Figure 5. The patch final patch had the properties shown below in Table 1.

Table 1: Patch antenna parameters

Patch width	43.8mm
Patch length	33.19mm
Inset feed length	8.2975mm
Inset feed width	2.09mm
Copper thickness	0.1mm

The S-Parameter results displayed above in Figure 5 shows the patch antenna has an operating frequency of 2.10 GHz @ -34.816 dBi. The bandwidth here makes this patch antenna good at rejecting radiation in other nearby frequencies. There are several higher frequencies at which have high gain. These greater frequencies could be a result of other dimensions of the antenna having their own respective resonant frequencies.

A possible use for this antenna is in radar systems where the received frequency is very close to 2.1GHz with a minimal doppler shift.

The elevation plot for this antenna, show above in Figure 6, shows that this is a directional antenna at both $\Phi = 0^\circ$ and 90° . At $\Phi = 0^\circ$, the antenna has a main lobe and a side lobe, whereas at $\Phi = 90^\circ$, the main and back lobes overlap with each other.

The azimuth plot for this patch antenna is show in Figure 8 at $\Phi = 180^\circ$ to $\Phi = -180^\circ$. This plot shows that there is very little gain in the azimuth plane which, when taking into consideration the original design, is expected as the antenna only has a 0.1mm length in this dimension.

3 Task 2

3.1 Cylindrical Dipole

3.1.1 Design

The specified operating frequency of 1.0GHz was input into the Antenna Designer App in MATLAB.

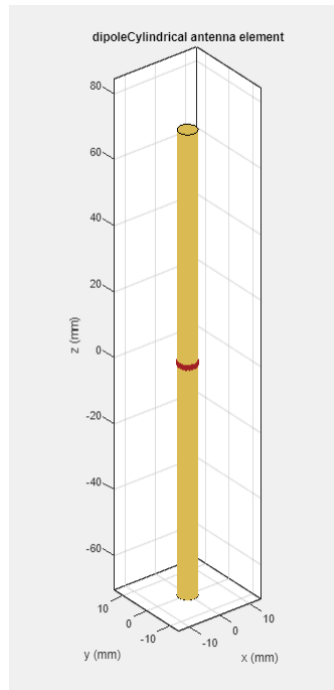


Figure 9: A cylindrical antenna designed for operation at 1GHz in MATLAB

3.1.2 Results

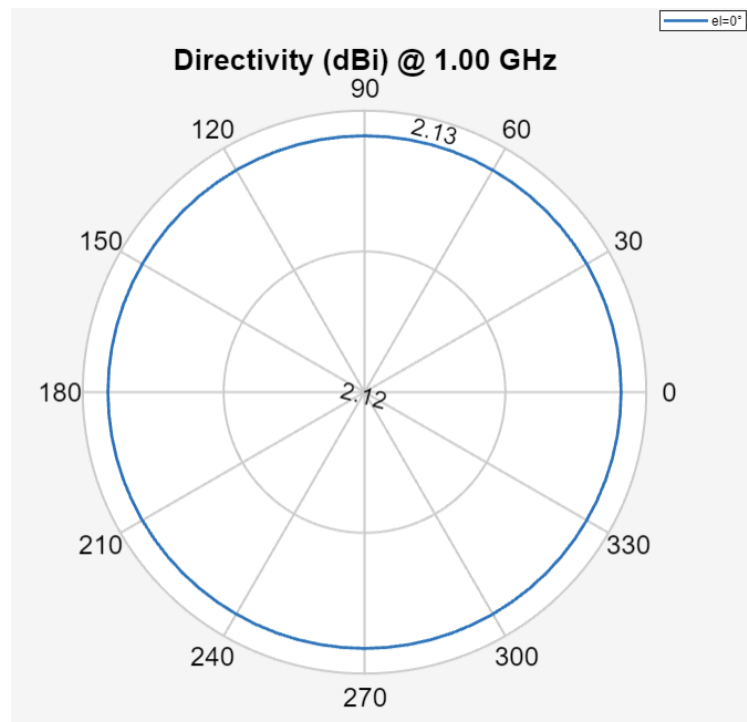


Figure 10: Directivity in Azimuth of the cylindrical antenna

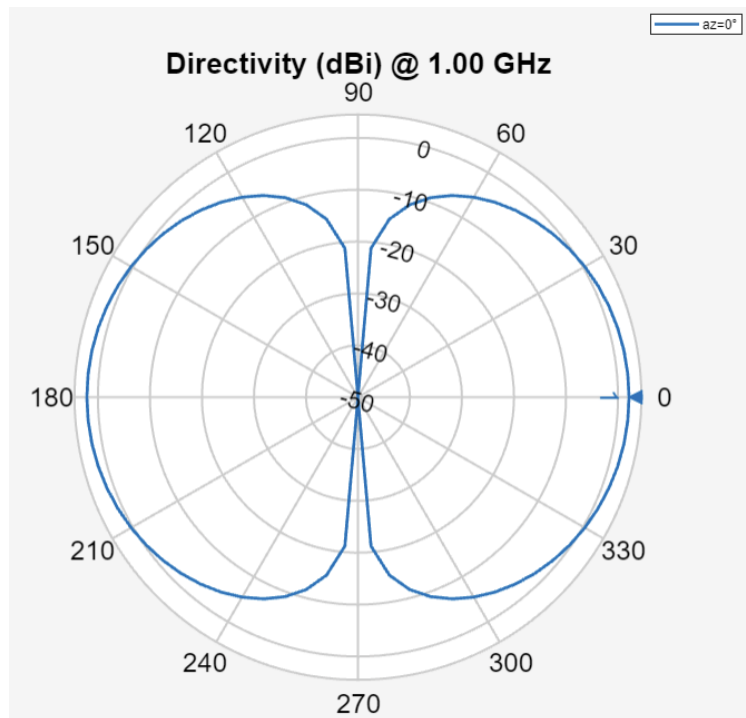


Figure 11: Directivity in elevation of the cylindrical antenna

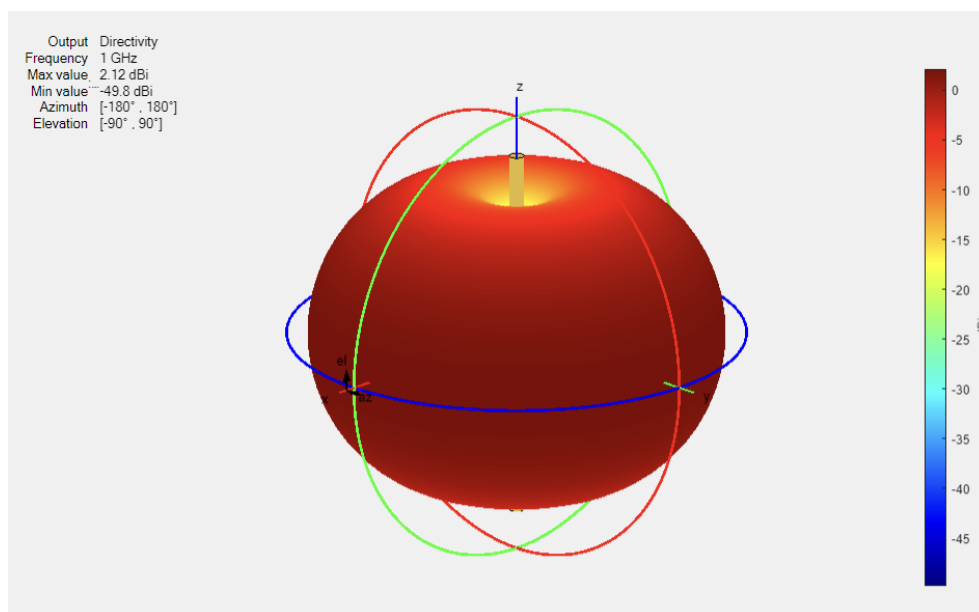


Figure 12: Gain displayed on a 3D polar plot of the cylindrical antenna

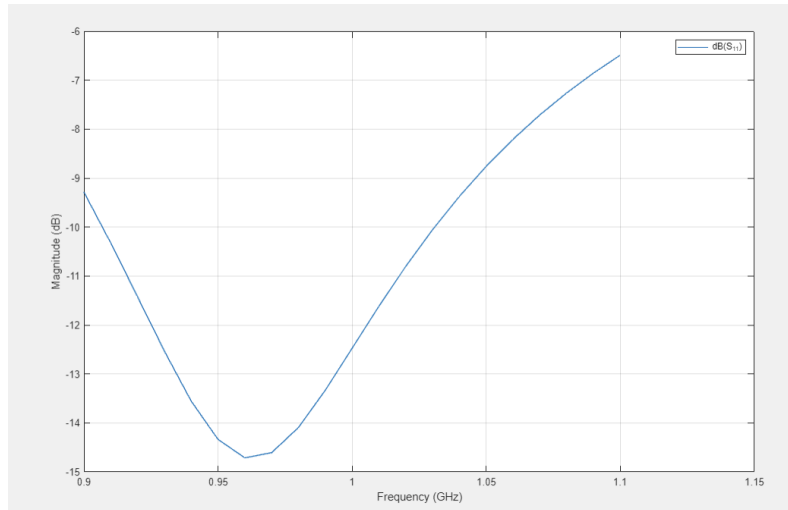


Figure 13: The S11 S-Parameter of the cylindrical antenna

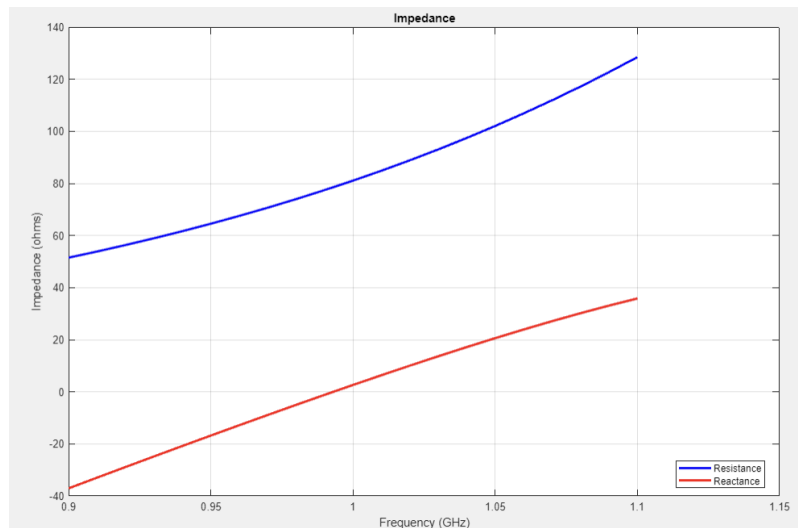


Figure 14: Impedance of the cylindrical antenna

3.1.3 Analysis

3.1.3.1 Antenna parameters

This antenna has a length of 14.09cm with a radius of 2.8018mm.

3.1.3.2 Directionality

This cylindrical dipole antenna is omnidirectional in its azimuth, shown in the 2D polar plot in Figure 10 and the 3D polar plot in Figure 12. The 2D polar plot in elevation, shown in Figure 11, has a radiation pattern with two main lobes, at points 180° from one another. This is a property of a bidirectional antenna.

3.1.3.3 Operating frequency

This antenna has an operating frequency that is below the frequency specified by the design, at 0.96GHz instead of 1GHz. Going forwards, this antenna would need to be tuned by adjusting the lengths so that they match the desired frequency. This could be achieved by either shortening the dipole, as the operating frequency increases as the length decreases, or by adjusting the impedance (via the reactance) such that it is 0 at 1GHz, compare to 3Ω as shown above in Figure 14.

3.2 Folded Dipole

3.2.1 Design

The specified operating frequency of 105.5MHz was input into the Antenna Designer App in MATLAB.

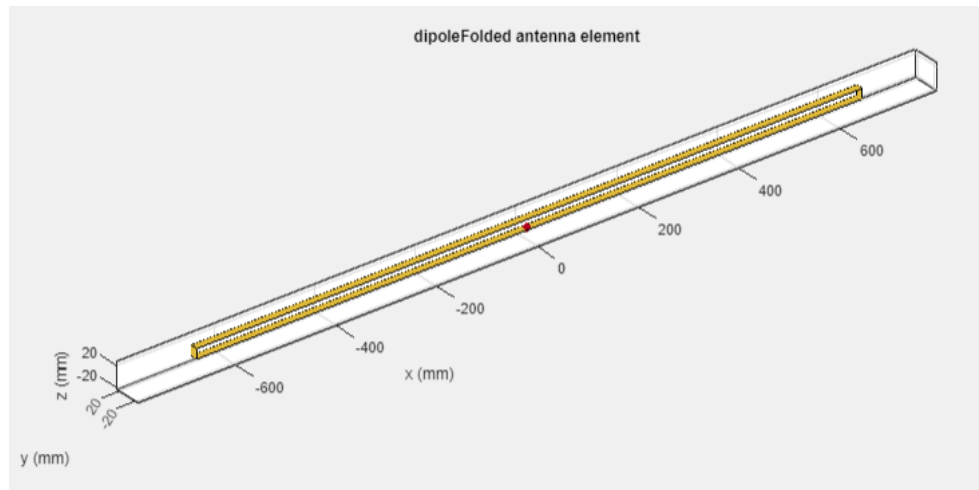


Figure 15: A folded antenna designed for operation at 1GHz in MATLAB

3.2.2 Results

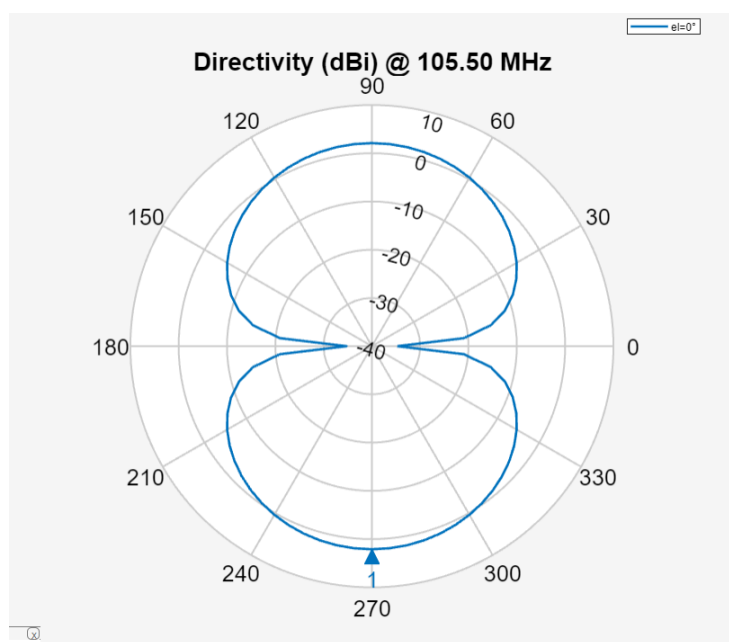


Figure 16: Directivity in azimuth of the folded dipole antenna

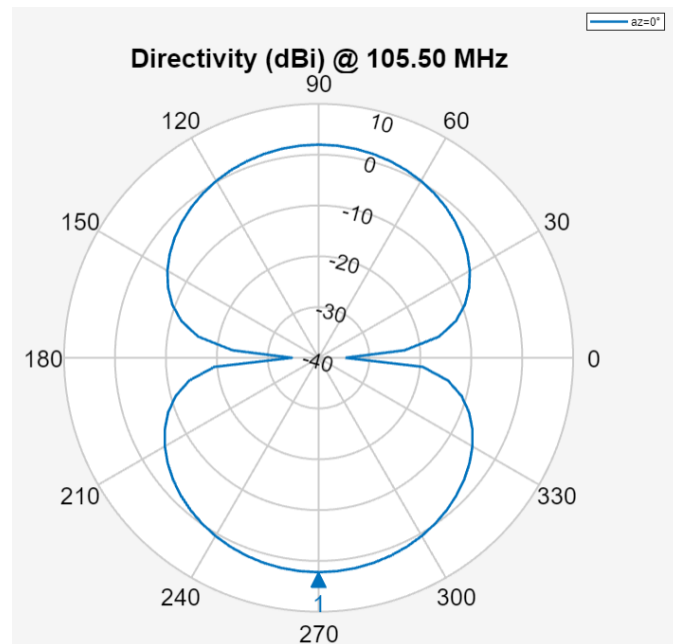


Figure 17: Directivity in elevation of the folded dipole antenna

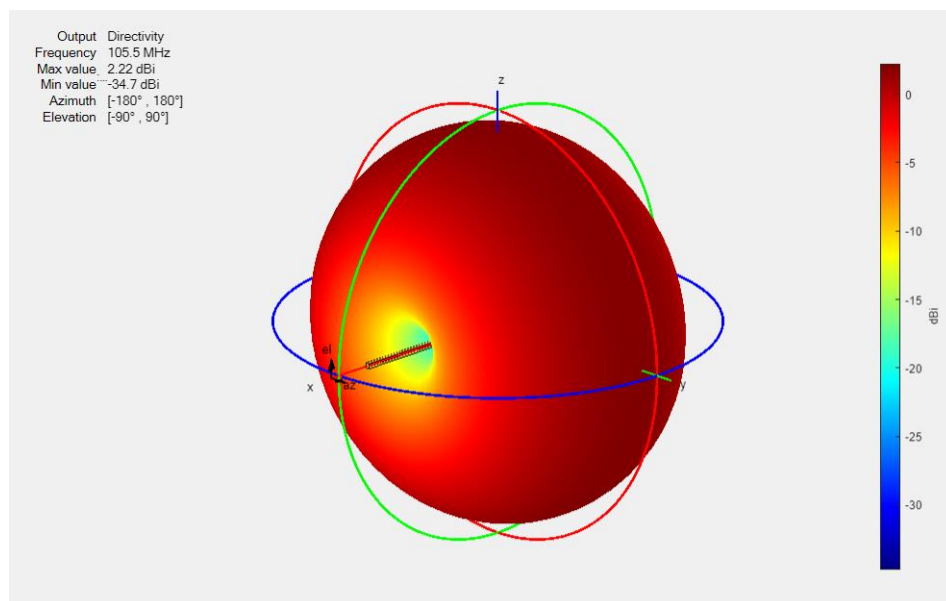


Figure 18: Gain displayed on a 3D polar in dBi of the folded dipole antenna

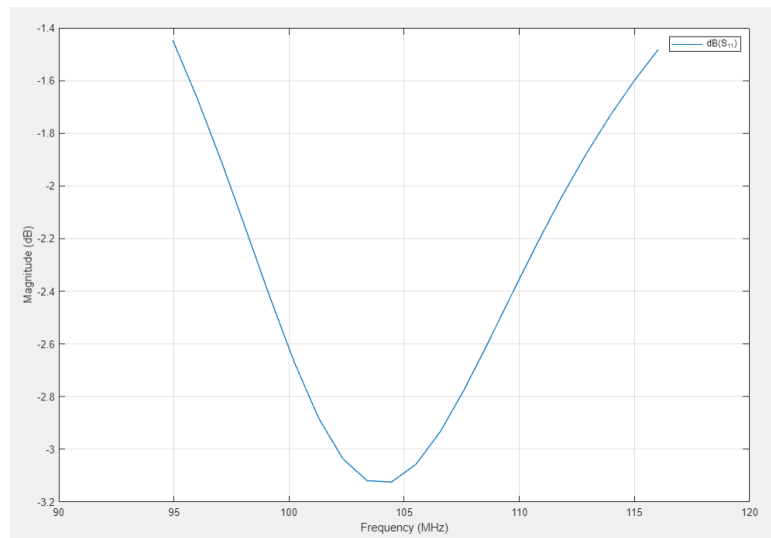


Figure 19: The S11 S-Parameter of the folded dipole antenna

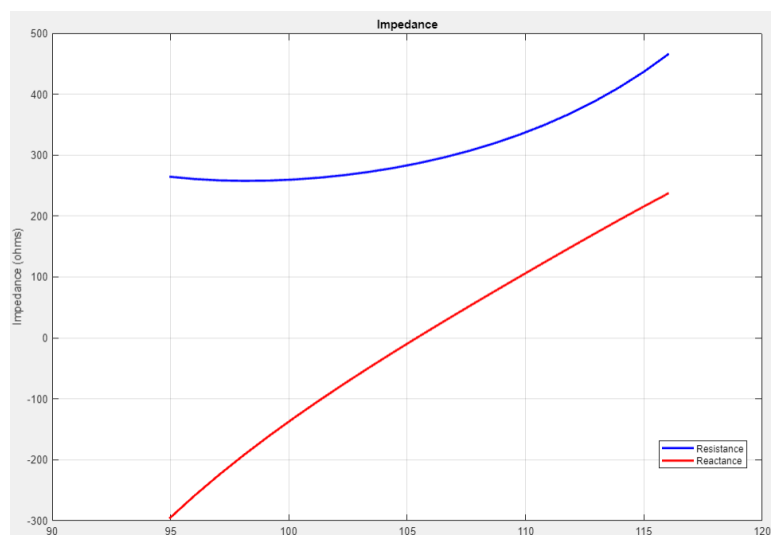


Figure 20: Impedance of the folded dipole antenna

3.2.3 Analysis

3.2.3.1 Antenna parameters

The simulated folded dipole antenna has a length of 1.3214m, a width of 1.4208cm, and a spacing of 1.8944cm.

3.2.3.2 Directionality

This antenna is bidirectional in both azimuth and elevation, shown in Figure 16 and Figure 17 respectively, which produces a torus in the 3D polar plot of the radiation pattern, shown in Figure 18.

3.2.3.3 Operating frequency

Similar to the cylindrical dipole antenna, the operating frequency of this antenna is slightly out from the specified frequency, at 104.5MHz instead of 105.5MHz. Similar tuning would be required for the operating frequency of this antenna to become centred on 105.5MHz.

3.2.3.4 *Application suitability*

This antenna would be suitable in applications where broadcasting in every direction is desirable, such as in WiFi applications where a single access point is responsible for communication with many devices at varying values of Φ .

3.3 Horn antenna

3.3.1 Design

The specified operating frequency of 11.0GHz was input into the Antenna Designer App in MATLAB.

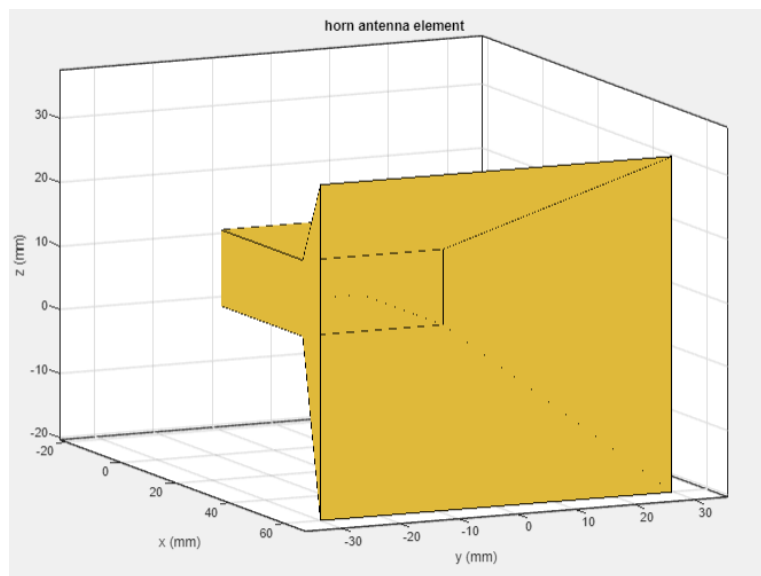


Figure 21: A Horn Antenna designed for operation at 11GHz in MATLAB

3.3.2 Results

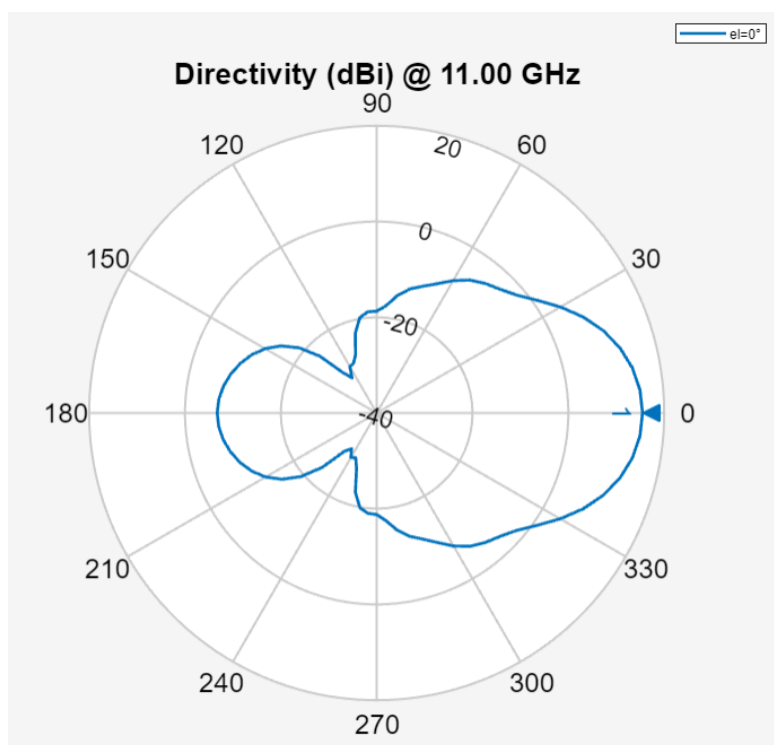


Figure 22: Directivity in azimuth of the horn antenna

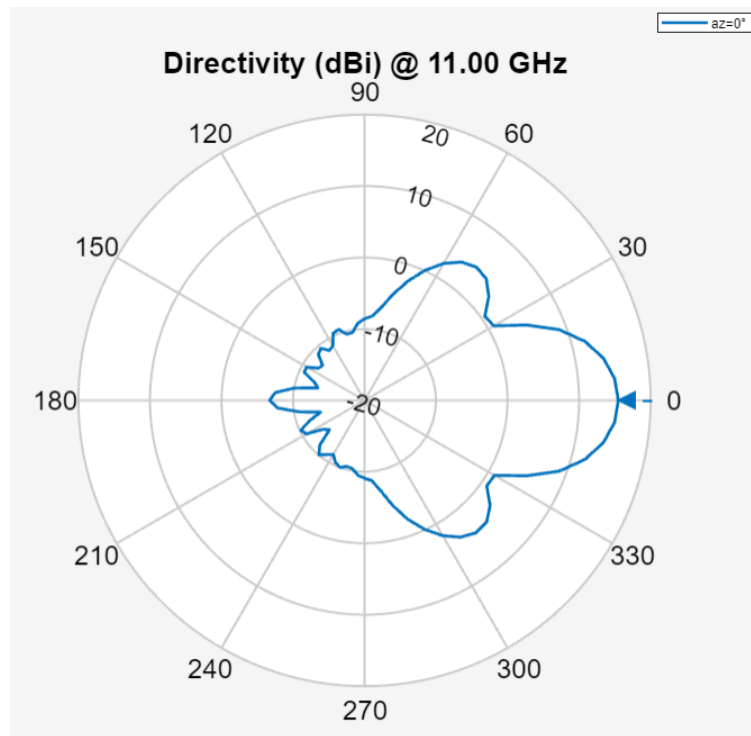


Figure 23: Directivity in elevation of the horn antenna

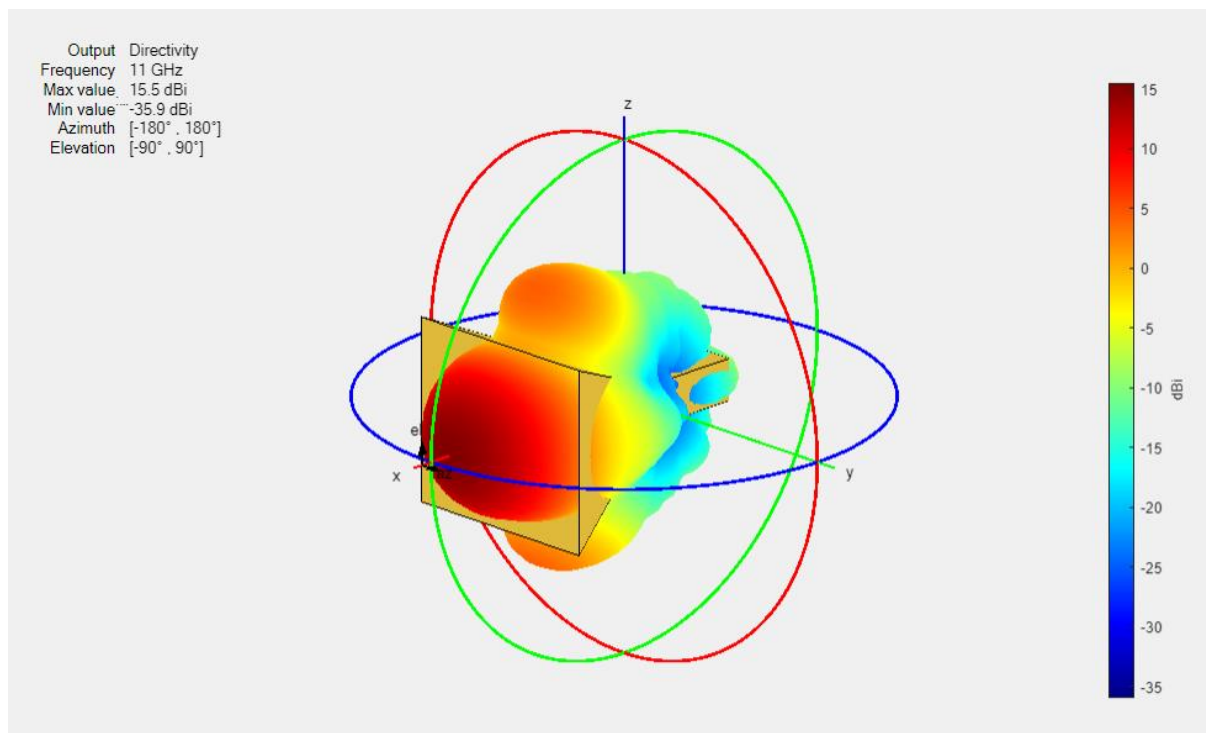


Figure 24: Gain displayed on a 3D polar in dBi of the horn antenna

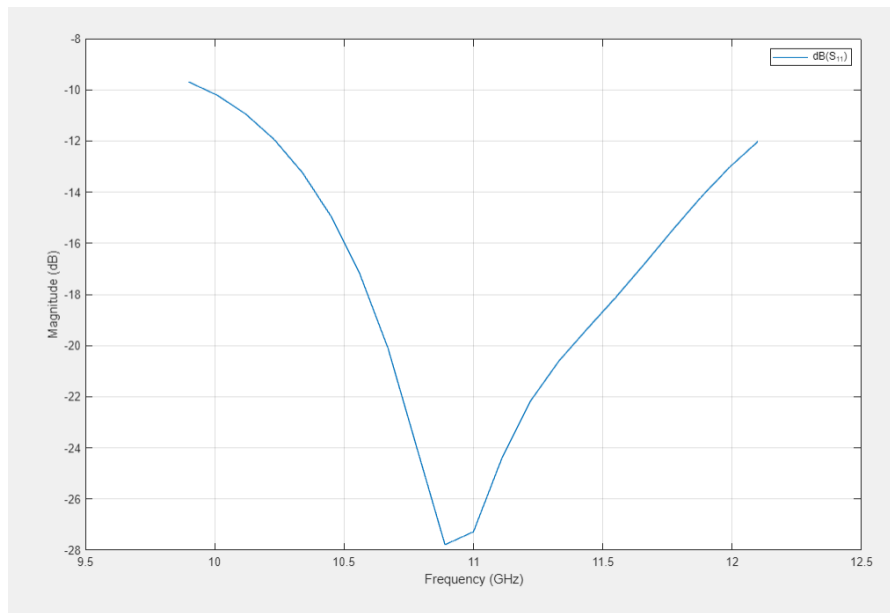


Figure 25: The S₁₁ S-Parameter of the horn antenna

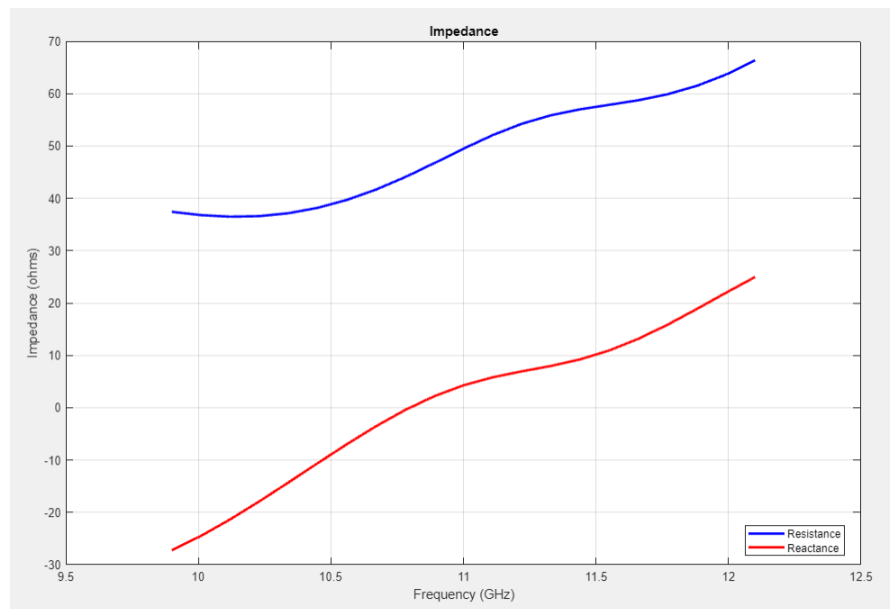


Figure 26: Impedance of the horn antenna

3.3.3 Analysis

3.3.3.1 Antenna parameters

FlareLength (m)	0.044946
FlareWidth (m)	0.059748
FlareHeight (m)	0.052659
Length (m)	0.029814
Width (m)	0.023848
Height (m)	0.011922
FeedWidth (m)	0.0007636
FeedHeight (m)	0.0063592
FeedOffset (m)	[-0.00875 0]

Figure 27: Parameters for the horn antenna generated in MATLAB

3.3.3.2 Directionality

The azimuth and elevation plots, Figure 22 and Figure 23 respectively, show that this horn antenna is highly directional. The azimuth plot shows a main lobe accompanied by a back lobe at -10dBi. The elevation plot also has a back lobe at -10dBi, but some side lobes at $\Phi = 45^\circ$ and 315° . This is undesirable for highly directional communication systems as the antenna is subject to noise from sources in additional directions.

3.3.3.3 Operating frequency

The operating frequency of this antenna is 10.95GHz. The 50Ω resistance is perfectly centred on 11GHz but the reactance is 0 further off at 10.8GHz. the dimensions for this horn antenna would need to be adjusted by making the length and width smaller to increase the frequency at which this antenna operates at.

3.3.3.4 Application suitability

This horn antenna would be suitable for a point-to-point communication system where external interference would ideally be minimised. The high directionality of this antenna supports this and the small back lobe serves to reduce the impact of local interference from close by.

3.4 Helix array antenna

3.4.1 Design

The specified operating frequency of 11.0GHz was input into the Antenna Array Designer App in MATLAB.

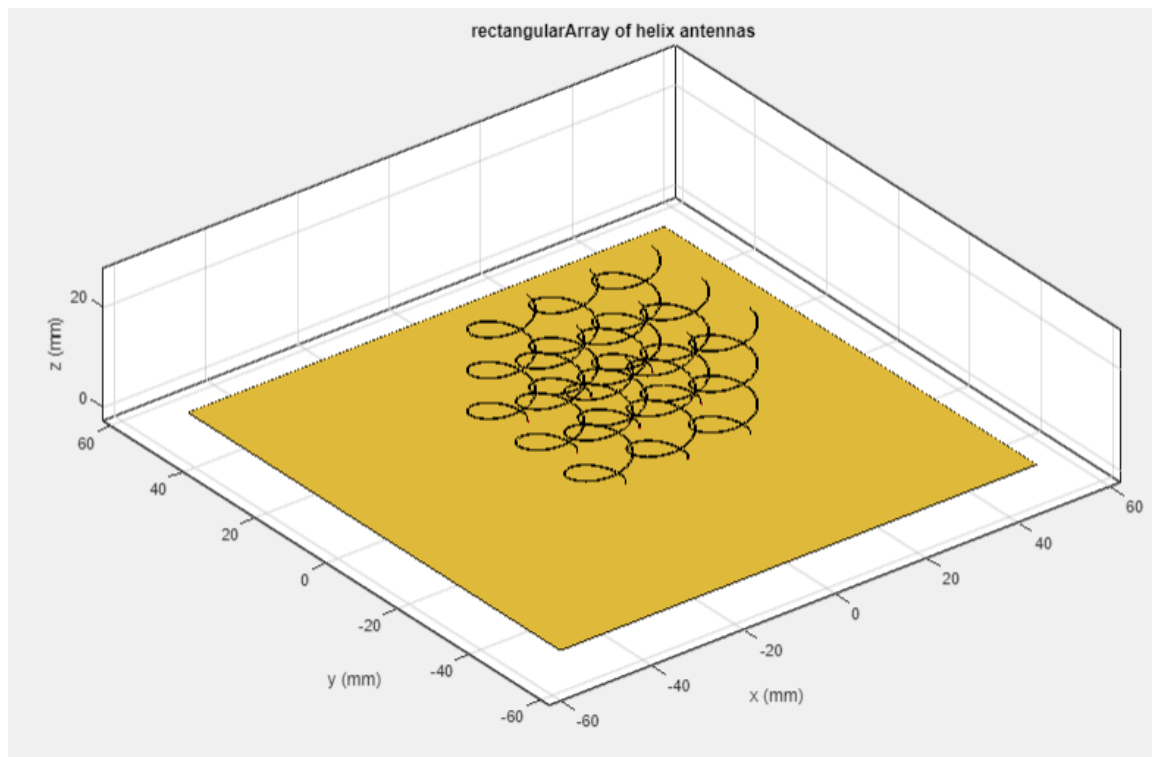


Figure 28: Arrangement of helix antennas in the array

3.4.2 Results

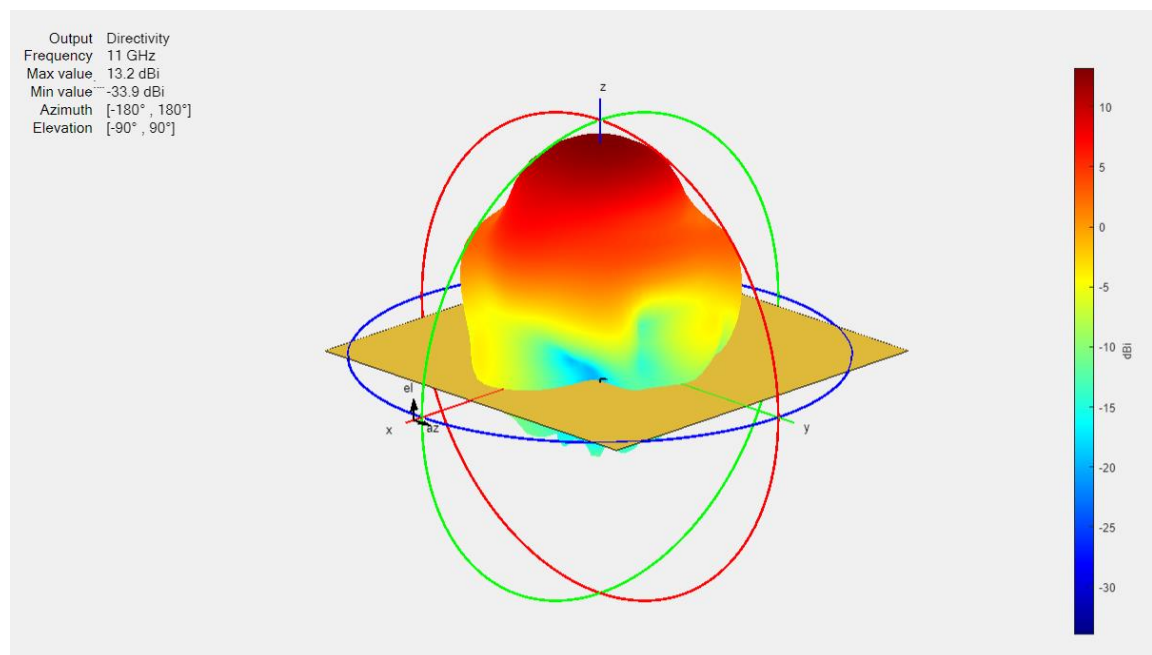


Figure 29: Gain displayed on a 3D polar in dBi of the helix antenna array

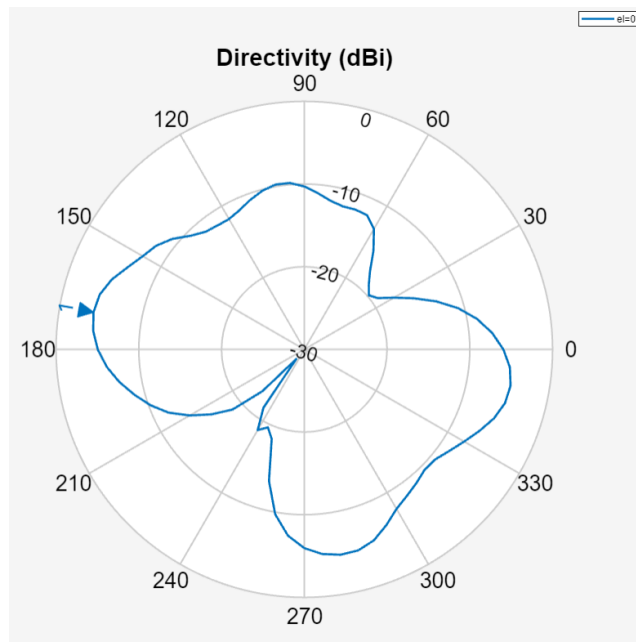


Figure 30: Directivity in azimuth of the helix antenna array

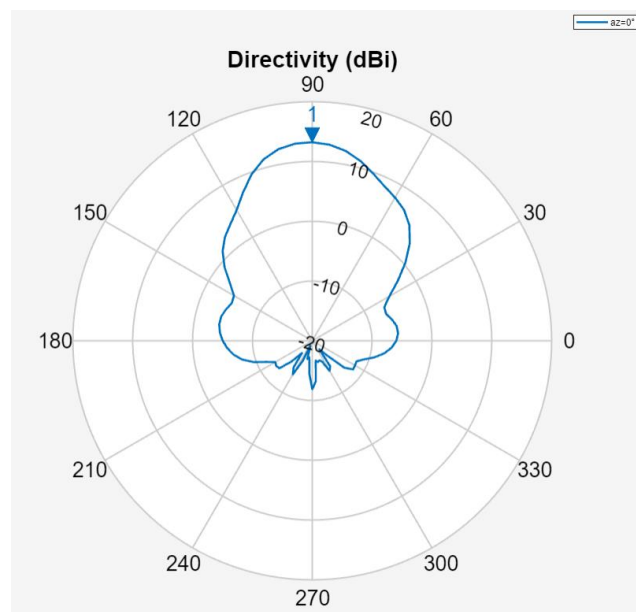


Figure 31: Directivity in elevation of the helix antenna array

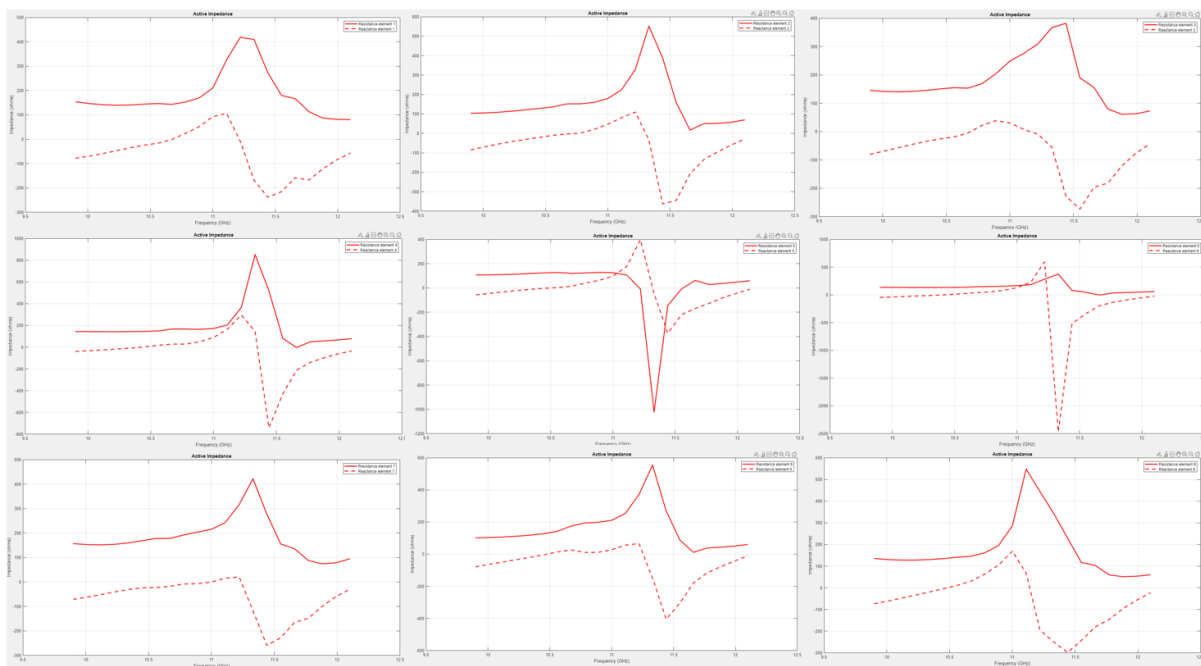


Figure 32: Impedances across each of the 9 helix antenna array elements

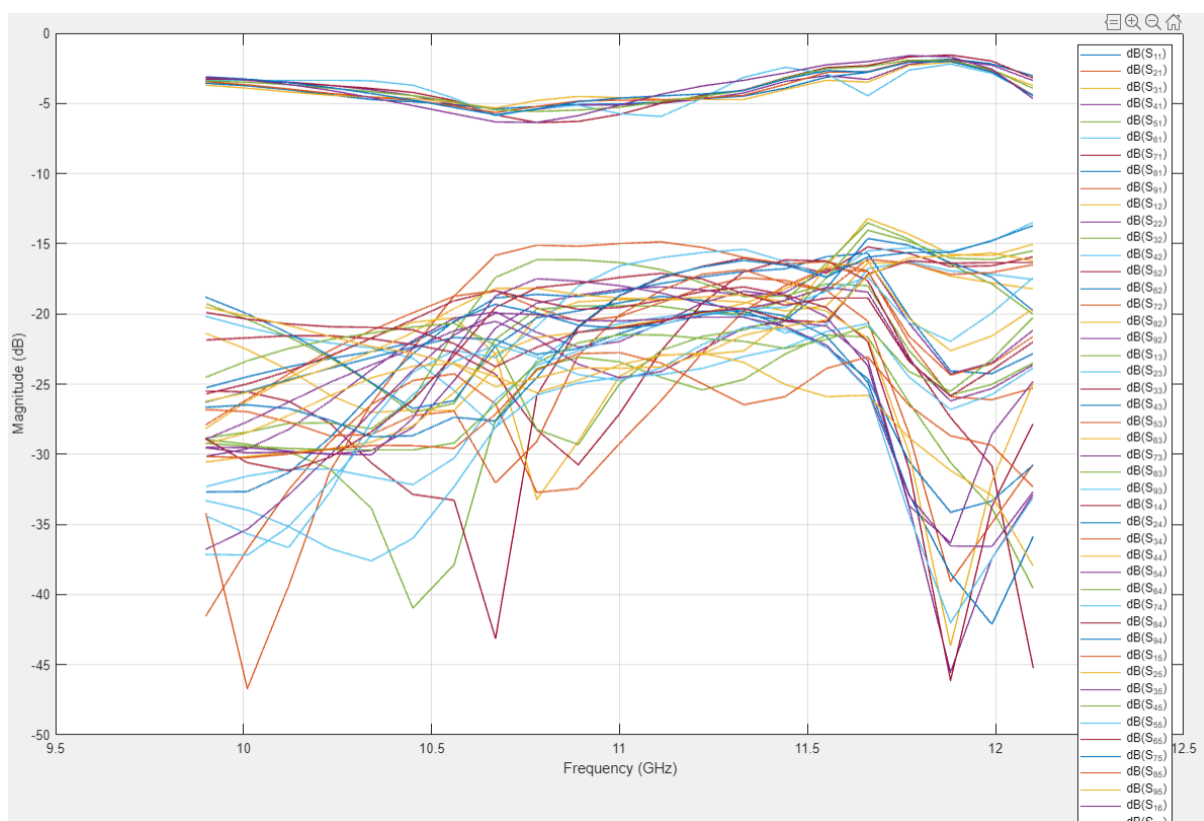


Figure 33: The S-Parameters for the helix antenna array

3.4.3 Analysis

3.4.3.1 Antenna parameters

▼ rectangularArray - Element - helix	
Radius (m)	0.0057805
Width (m)	0.00023125
Turns	3
Spacing (m)	0.0080944
WindingDirection	CCW
FeedStubHeight (m)	0.001
GroundPlaneRadius (m)	0.017345

Figure 34: Parameters for each element of the helix antenna array

▼ rectangularArray	
Size	[3 3]
RowSpacing (m)	0.013627
ColumnSpacing (m)	0.013627
Lattice	Rectangular
AmplitudeTaper (V)	1

Figure 35: Parameters for the spacing of the array elements

3.4.3.2 Directionality

This array of antennas is the most directional of those explored in this assignment.

3.4.3.3 Operating frequency

The operating frequency of this antenna is across a range of frequencies from 10-12GHz, as shown by the impedance and reactance plots for each element in Figure 32. Importantly, the Azimuth and elevation plots taken at 11GHz show this antenna is still highly directional at the desired frequency. The elevation plot, Figure 31, shows a main lobe with two wide side lobes, with a small and narrow back lobe accompanied by two nulls and two side lobes.

3.4.3.4 Application suitability

This helix antenna arrays would be suitable for broadcasting to a satellite, but may struggle when receiving due to the wide range of acceptance.

4 Conclusion

This assignment has explored the simulation of different types of antennae in Ansys HFSS and MATLAB and it is clear that without further tuning, MATLAB cannot produce an antenna that has an operating frequency as specified by the designer. An understanding of the equations that are used to produce these dimensions is essential to adjust the correct parameters.

5 Recommendations

Further tuning of the dimensions of the patch antenna can result in an antenna with higher gain, but potentially at the cost of bandwidth. Considerations of the bandwidth the antenna should operate across should be taken into mind when tuning an antenna. Using real-world values for the

thicknesses and precision of copper that is etched away on a printed circuit board should also be considered as these theoretical designs may not be practical for the real world as very tight tolerances on the width of a line may be outside of the specifications a manufacturer can produce on a circuit board.

6 Bibliography

- [1] MathWorks, "MATLAB," [Online]. Available: <https://uk.mathworks.com/products/matlab.html>. [Accessed 22 May 2024].
- [2] Ansys, "Ansys HFSS | 3D High Frequency Simulation Software," [Online]. Available: <https://uk.mathworks.com/products/simulink.html>. [Accessed 22 May 2024].
- [3] S. Schaire, "Small Satellite Conference 2017 - Lunar and Lagrangian Point L1/L2 CubeSat Communication and Navigation Considerations," 10 August 2017. [Online]. Available: <https://ntrs.nasa.gov/api/citations/20170007444/downloads/20170007444.pdf>. [Accessed 22 May 2024].
- [4] Keysight, "How to Design and Test a Phased Array Antenna," 26 April 2024. [Online]. Available: <https://www.keysight.com/us/en/assets/7123-1103/ebooks/How-to-Design-and-Test-a-Phased-Array-Antenna.pdf>. [Accessed 22 May 2024].
- [5] Z. Peterson, "Microstrip Patch Antenna Calculator for RF Designers," 21 November 2021. [Online]. Available: <https://resources.altium.com/p/microstrip-patch-antenna-calculator-rf-designers>. [Accessed 22 May 2024].
- [6] S. Jacob, "Advanced Radio Frequency Systems (ACDA6019) Lecture -9," 17 April 2024. [Online]. Available: <https://moodle.uwtsd.ac.uk/mod/resource/view.php?id=572373>. [Accessed 22 May 2024].
- [7] R. Hill, "A Practical Guide to the Design of Microstrip Antenna Arrays," 1 February 2001. [Online]. Available: <https://www.microwavejournal.com/articles/3144-a-practical-guide-to-the-designof-microstrip-antenna-arrays>. [Accessed 22 May 2024].
- [8] Nikolova, "Nikolova 2019 1," 2019. [Online]. Available: https://www.ece.mcmaster.ca/faculty/nikolova/antenna_dload/current_lectures/L20_Mstrip1.pdf. [Accessed 22 May 2024].
- [9] NASA, "Radio Science Subsystem (RSS) - NASA Science," NASA, [Online]. Available: <https://science.nasa.gov/mission/cassini/spacecraft/cassini-orbiter/radio-science-subsystem/>. [Accessed 22 May 2024].
- [10] K. M, "A microstrip patch antenna as a standard transmitting and receiving antenna," *IEEE Transactions on Electromagnetic Compatibility*, vol. 32, no. 1, pp. 5-8, 1990.
- [11] antenna-theory.com, "Microstrip Antennas: The Patch Antenna," [Online]. Available: <https://www.antenna-theory.com/antennas/patches/antenna.php>. [Accessed 22 May 2024].

- [12 Q. Z. X. & L. Y. Zhang, "Tuning rectangular microstrip antenna through scan and zoom
] algorithm," *EURASIP Journal on Wireless Communications and Networking*, vol. 67, 2018.
- [13 S. S. Y. Y. J. X. a. J. H. Y. Lu, "Wideband Dual Linearly Polarized Hollow- Waveguide Septum
] Antenna Array for Ku-Band Satellite Communications," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 3, pp. 2433-2442, 2023.