

Cerys Versey Advanced RF systems

by Cerys Versey

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DESIGN AND ANALYSIS OF RF ANTENNAS



Cerys Versey (2217178)
11/05/2024 [Company address]

Abstract

Antennas can take a variety of shapes and sizes which all possess different features. This report hopes to teach the reader not only the difference between different antennas, different antenna modelling software but also key use cases and design parameters for each antenna. The report will introduce each antenna type before explaining the methodology, simulation results and use for each antenna giving a comprehensive review of each antenna type.

Task 1 – rectangular microstrip antenna

Introduction

A microstrip antenna is an antenna made from a conductive material that is placed within a PCB, it can take a variety of shapes and sizes [1]. They can be printed onto circuit boards for a low-cost low profile with patch antennas printed in a row allowing for increased directivity and gain.

The below antenna is designed for an operating frequency of 2.2 GHz, with a substrate of FR4 and a patch and ground plane made out of PEC also known as perfect electrical conductor. PEC has a relative permittivity of 4.3. relative permittivity can be thought of as a materials ability to sort electrical energy in an electric field often also thought of as the dielectric constant [2].

To be able to create the design in CST. Firstly, the dimensions of the antenna need to be calculated. Firstly, the width of the patch is calculated as the length requires the width and length to be calculated prior.

$$W = \frac{c}{2fr\sqrt{\epsilon_r+1}/2} = \frac{3 \times 10^8}{2 \times (2.2 \times 10^9) \times \sqrt{4.3+1}/2} = 0.041883757797 = 0.0419 \text{ m} \quad d.p = 41.9 \text{ mm}$$

W = width

fr = resonant frequency

er = relative permittivity

c = speed of light

Once the width is calculated the length can be calculated. Actual length is calculated using length extension (ΔL) and effective length (L_{eff}). length extension is comprised of effective relative permittivity (ϵ_{reff}), width and height.

$$H = 1.6 \text{ mm} = 0.0016 \text{ m}$$

$$\text{Actual length} = L_{eff} - 2\Delta L = \frac{c}{2fr\sqrt{\epsilon_{reff}}} - 0.824h \left[\frac{(\epsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{\epsilon_{reff}-0.258)(\frac{W}{h}+0.8)} \right] = 0.0326816 \text{ m} = 32.6816 \text{ mm}$$

$$L_{eff} = \frac{c}{2fr\sqrt{\epsilon_{reff}}} = \frac{3 \times 10^8}{2 \times 2.2 \times 10^9 \times \sqrt{4.0164}} = 0.0340$$

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \left(\frac{1}{\sqrt{1+12(\frac{h}{W})}} \right) = \frac{4.3+1}{2} + \frac{4.3-1}{2} \times \left(\frac{1}{\sqrt{1+12(\frac{0.0016}{0.0419})}} \right) = 4.016376395$$

$$\Delta L = 0.412 h \left(\frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{\epsilon_{eff} - 0.258 \left(\frac{W}{h} + 0.8 \right)} \right) = 6.592 \times 10^{-4}$$

Once the dimensions were calculated the antenna was drawn this was initially done by setting up the vacuum this gives the software the required size and material of which the antenna is operating in. once this was done the bottom layer of the antenna was set up this was done by drawing a square made from FR4. FR4 is a common material used in PCB made antennas this is due to FR4's light weight but durable nature. It is an epoxy fibreglass material [3, 4] which means it can be exposed to high temperatures. However, FR4 is not recommended for high frequency applications due to its dielectric constant and loss tangent which are amplified at high frequencies leading to signal degradation [5]. However, for simple prototyping FR4 can be a highly useful due to its cheaper cost compared to other high frequency antenna materials like copper [6].

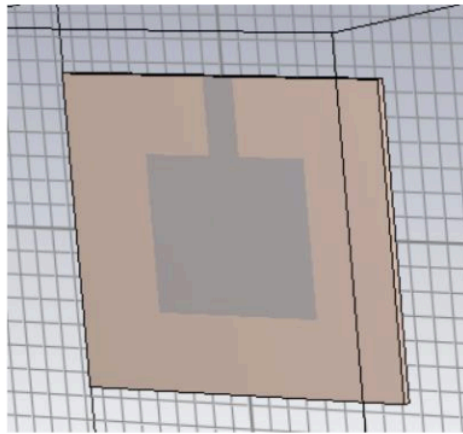


Figure 1 - square made out of FR4 sat in a vacuum

Once this was done the radiating element was created this was made from PEC also known as a perfect electrical conductor. This material only exists in simulations but allows for antenna designers to create perfect antennas to later be used as best case for working out the best possible performance of a RF system.

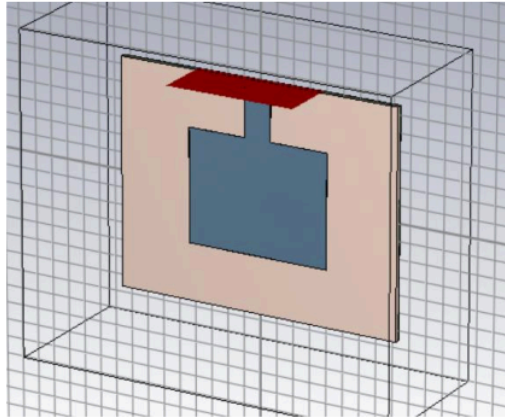


Figure 2 - PEC radiating element

Once this was done a face was set up for radiating the antenna was then simulated. A 3d radiation plot was taken as well as an impedance plot and VSWR plot. The VSWR plot shows that the antenna has minimal reflections at 2.2 GHz this is expected as this is the frequency the antenna is designed to work at.

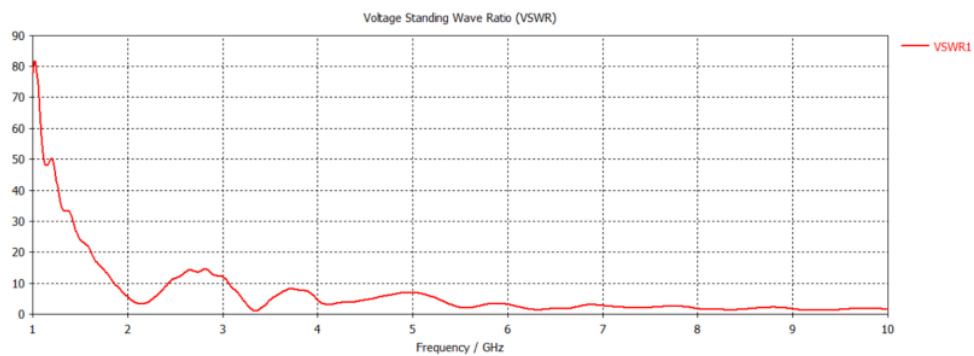


Figure 3 - VSWR Plot for a 2 GHz patch antenna

The S parameter plot shows the antenna has some VSWR at 2.2 GHz this shows the antennas shape could be optimised to decrease the loss caused by standing wave ratios in the antenna. The radiation pattern shows that the antenna possesses some directivity but also suffers from a large back lobe this not only reduces the antennas directivity but also effects the gain and power output in the main lobe.

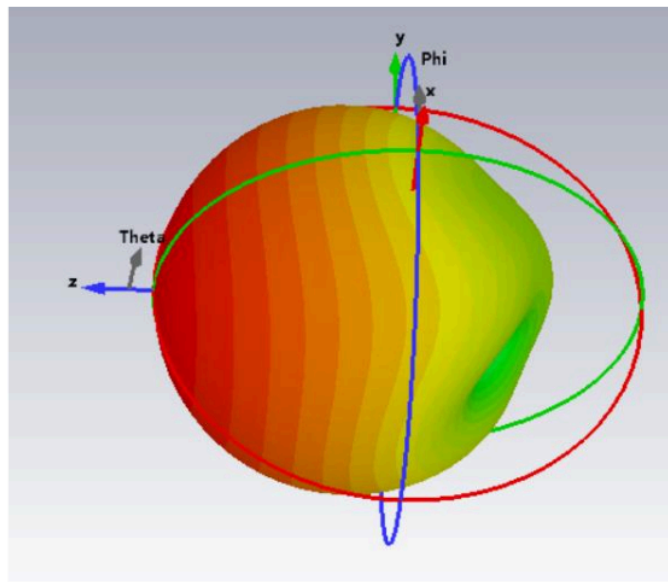


Figure 4 - Patch antenna radiation pattern

The S parameter further backs up this idea of loss in the main lobe.

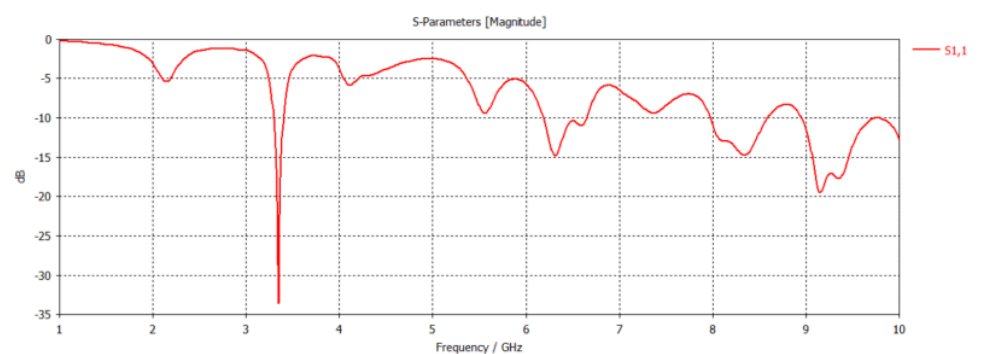


Figure 5 - S parameter plot for patch antenna

To be able to increase the gain in the main lobe the reader could consider changing the material used, dimensions or adding further elements to create an array. However, the reader should be aware that changing these parameters could also change the radiation pattern, gain and frequency of the antenna. It is recommended that the used using optimization tools to focus on improving the different aspects their user requirements require.

Task 2

MathWorks Simulink software was used for the following antenna designs. Its built-in antenna design toolbox allows for efficient optimise and design changes.

Cylindrical Dipole antenna

A cylindrical dipole antenna is comprised of a dipole antenna in a cylindrical shape with a central feed. The antenna was designed to have a centre frequency of 2GHz. In the below image the yellow is made of PEC also know as a perfect electrical conductor and the red is the feed elements. Two cylindrical antenna were created, one simply designed for 2 GHz and then another designed at 2 GHz which is optimised to have maximum gain. This can be changed based on the builder that was selected, MathWorks toolboxes allow for the user to pick from greater gain, directivity or maximum bandwidth. In order too achieve this the user must choose the parameters that will be optimized in the example below the offset feed distance was chosen for maximum gain optimisation.

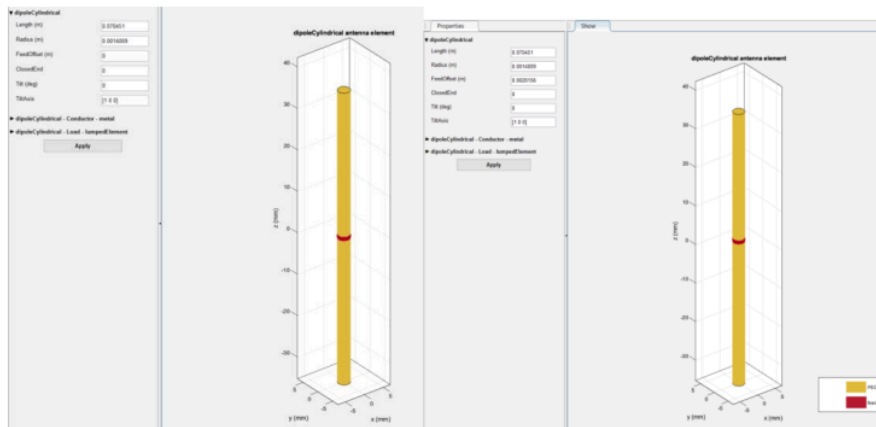


Figure 6- none - Optimised cylindrical antenna

Figure 7 – optimised cylindrical dipole antenna

MATLAB's antenna design toolbox allows for the user to review key aspects of the antenna design such as the antennas impedance plot. Impedance is defined as a measure of the opposition of flow of current when a voltage is applied. Impedance has both a magnitude and a phase [7].

$$Z = \sqrt{R^2 + X^2}$$

Where R is equal to resistance and X is reactance. The real part of the impedance states the power that will either be absorbed or radiated away from the antenna [8]. This means that this energy will be lost and can cause a lack of efficiency in the antenna. To be able to reduce this affect the antenna

should have minimal impedance at the frequency of desired use. This can be seen below the plot shows if the impedance is more resistive or reactance.

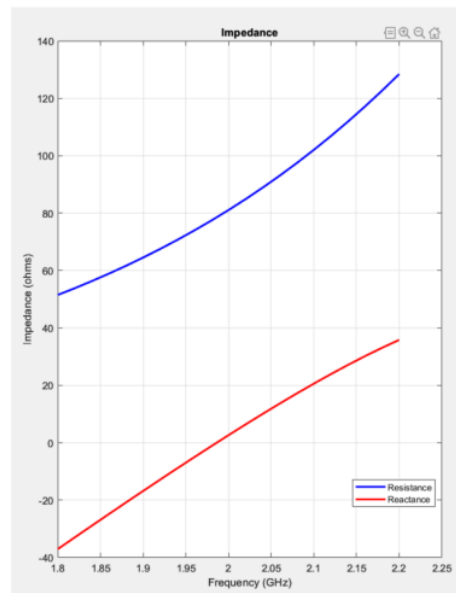


Figure 8 - Impedance VS frequency plot for Cylindrical dipole antenna

The antenna toolbox also allows for the user to view the antenna radiation pattern. The user can view the radiation pattern in 3d, azimuth or elevation. An azimuth antenna pattern can be thought of as the top down view of an antenna [9]. The Elevation plot shows the antenna in the vertical plane [10]. The radiation patterns show the directivity of the antenna. This is a measure of how directional an antennas radiation pattern is [11]. The design of the antenna can affect its directionality, traditionally an omnidirectional antenna has no directionality this is due to its radiation pattern being a circle. This means it radiates equally in all directions. However, in practice an omnidirectional antenna cannot be made as there will be nulls or interference causing dips in the pattern [12].

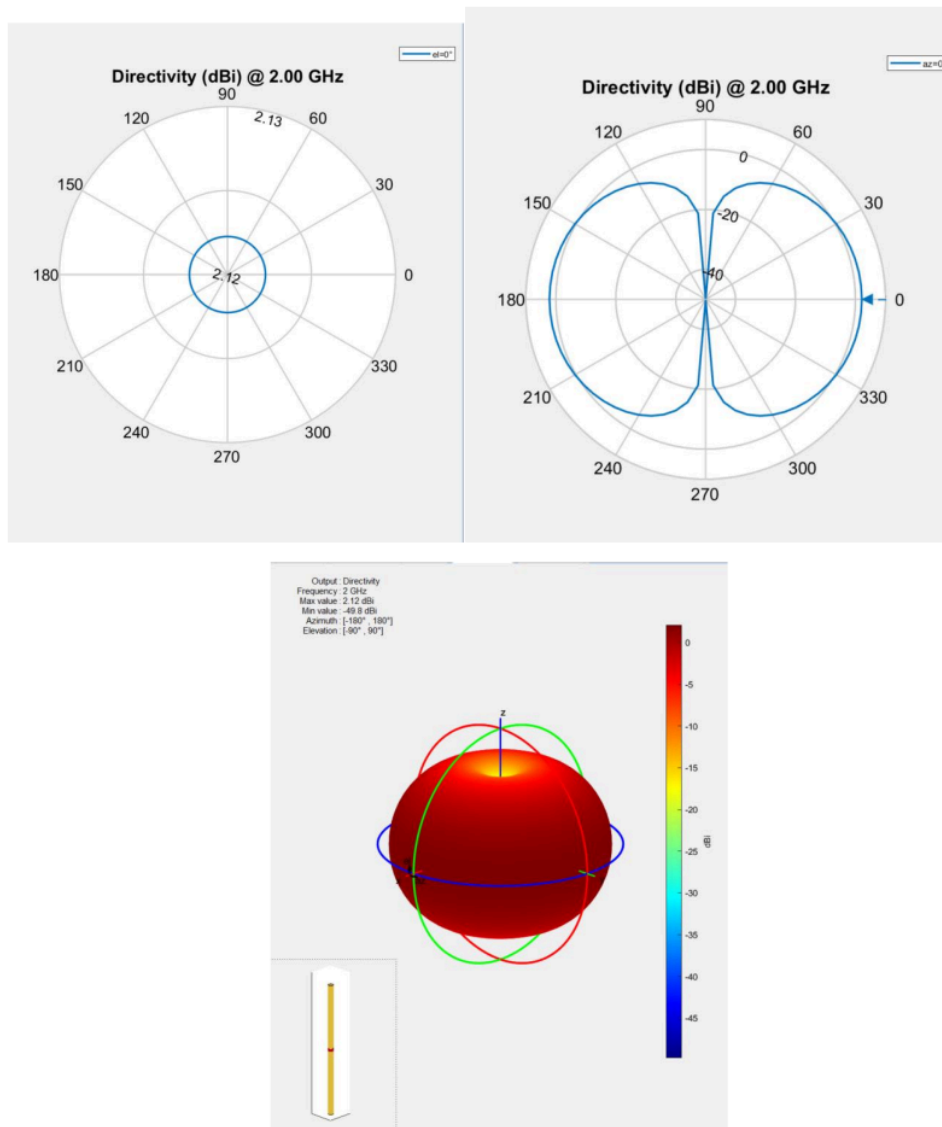


Figure 9 - Azimuth plot for a cylindrical dipole antenna

Figure 10 - Elevation plot for a cylindrical antenna

Figure 11 - 3d radiation pattern cylindrical antenna plot

The antenna toolbox allows for the user to see a S parameter plot of the antenna, specifically S11. S11 states the reflection coefficient of the antenna. It states how much input power is reflected back into port 1. This is essential as this needs to be as low as possible to avoid standing wave ratios and increased loss at the desired operation frequency [13]. This can be seen below in the S parameter plot for a 2 GHz cylindrical dipole antenna which has -12.5 Db of reflected energy at port 1 [14].

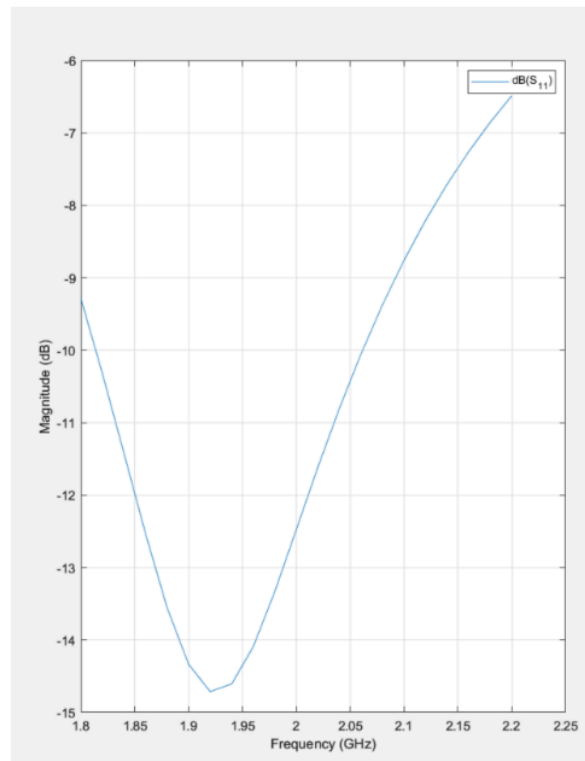


Figure 12 - s parameter plot for a cylindrical antenna

Analysis of cylindrical antenna plots and features

As can be seen from the above impedance plot at 2 GHz the antenna impedance is almost entirely resistive. This data allows for the user to be able to impedance match the antenna with other items such as filters, amplifiers and splitters to create more complex RF chains.

The S parameter plot shows that at 2 GHz the reflection is -12.5 this means around 88 % of the antenna energy is effectively given to the feed. The ideal S11 value is 0 Db this means 100 % of the energy is radiated and not reflected back. However, in practice this is almost impossible to achieve due to impedance mismatch between cables, elements connectors or imperfection in the materials [15].

The azimuth plot shows the antenna has large nulls at 90 and 270 degrees respectively. This shows that at 90 and 270 degrees no energy is radiated. Maximum radiation occurs at 0 and 180 degrees and has a radiated power of 2.12 dB .

Cylindrical antennas are often used in radio communication systems this is due to two reasons A due to its ability to support 3 different transmission modes and B due to its easy ability in the commercial market [16].

Cylindrical antennas use in communication greatly impacts its design; as different telecoms standards have come into service 3G (2001), 4G (210) it has led to a change in requirement for different frequencies this has forced the cylindrical antennas to become smaller and smaller as antenna length has an inverse relationship to frequency.

Folded dipole

A folded dipole is one of the simplest designs to make. It takes a simple dipole antenna and folds it back on itself creating a loop.

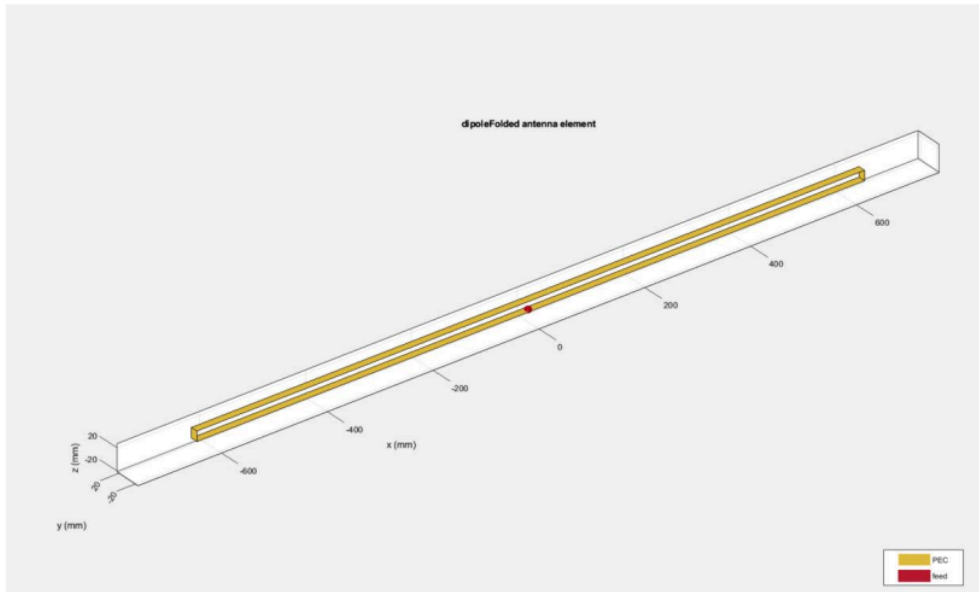


Figure 13 - Folded dipole antenna

Folded dipoles produce a similar antenna pattern to that of a cylindrical antenna but simply shifted 180 degrees in the azimuth plane. The pattern radiates along the antenna element rather than out of the element this can be seen in the 3d radiation pattern below.

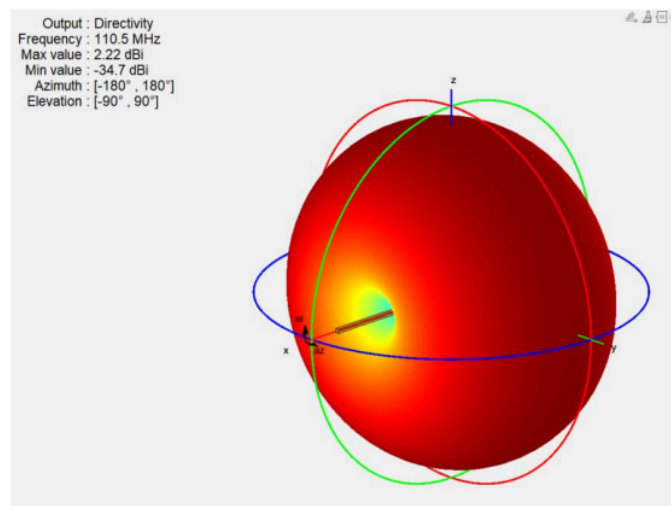


Figure 14 - 3D radiation pattern

The pattern experience nulls at 0 and 180 degrees in the azimuth and elevation plane. The elevation plane is in contrast to that of the omni directional radiation pattern that the cylindrical dipole antenna has. This means that the antenna has greater directivity than that of the cylindrical dipole.

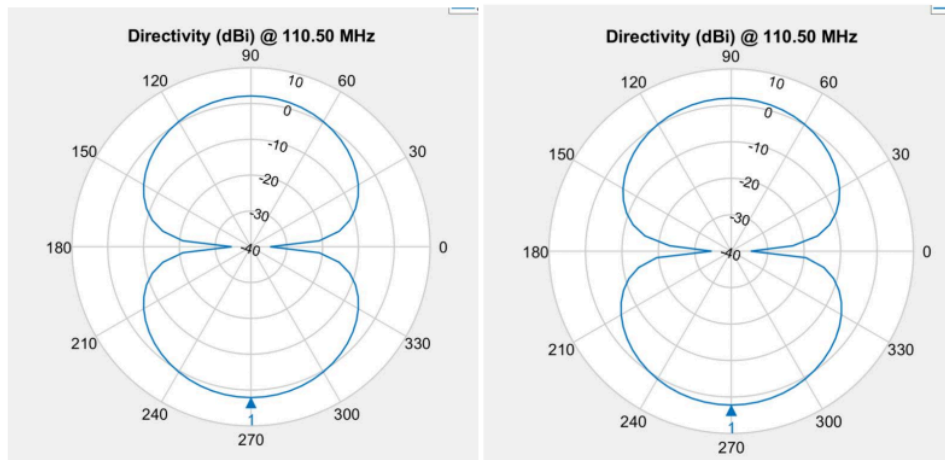
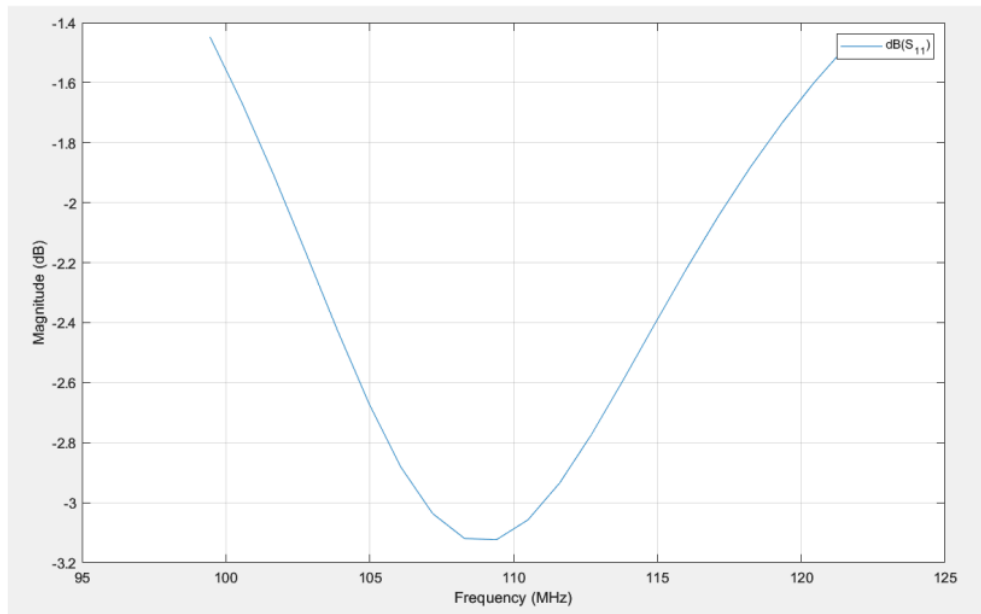


Figure 15 - Azimuth and elevation plots of the folded dipole

The S-parameter plot for a folded dipole has a similar shape plot to that of the cylindrical dipole antenna this is due to the antenna being designed for specific frequencies. However, the folded dipole experiences far less reflection of that than the cylindrical dipole.



As can be seen from the above plot the antenna only experiences -3.1 Db of reflection compared to the -12 dB of the cylindrical antenna.

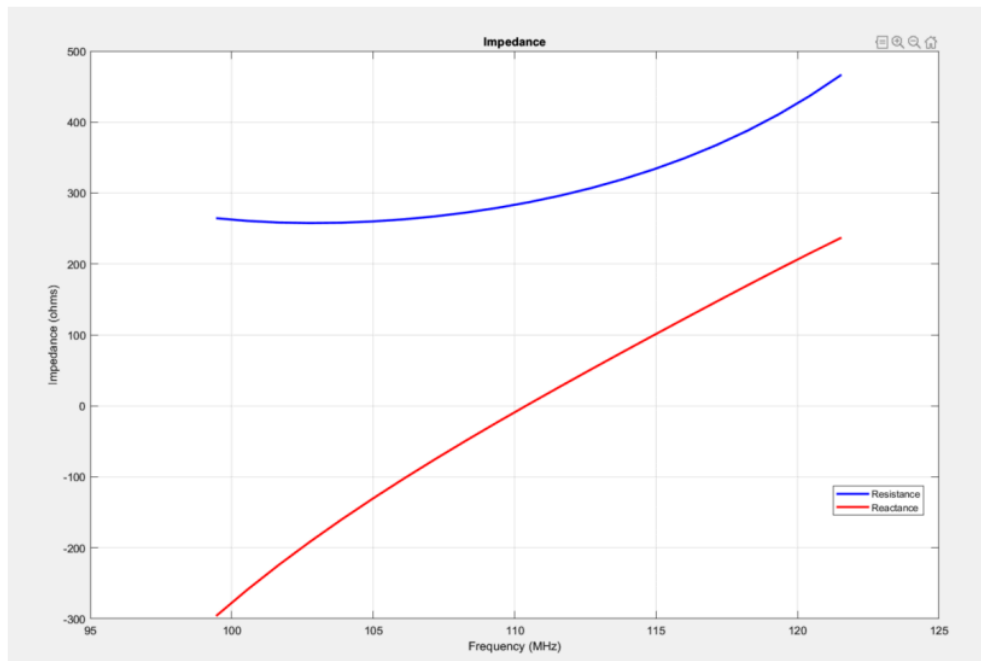


Figure 16 - cylindrical antenna impedance plot

The impedance graph shows no reactance at the resonant frequency this means the impedance is solely comprised of resistance. The resistance is around 300 ohms.

Folded dipoles are often used in conjunction with other antennas such as being used as a feeder for parabolic antennas or used with reflectors to increase the directivity of an array.

Folded dipoles ability to be added in conjunction with other antennas makes them very popular. They are often used in radio receivers or in TV receivers.

Overall the folded dipole has low directivity but does have high gain making it perfect for long distance applications.

Horn antenna

A horn antenna is also known as an aperture antenna due to the aperture at one end of the antenna [13]. A horn antenna is the most directive of the antennas assessed so far.

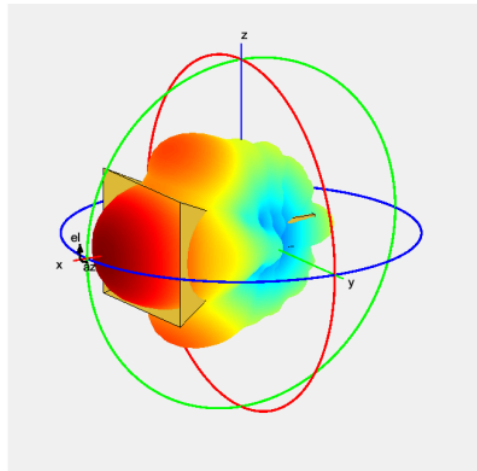


Figure 17 - 3D antenna pattern Horn

It has a main lobe directed towards the 0-degree point in elevation. There is a small back lobe which reduces the power in the main beam. A back lobe is a lobe 180 degrees away from the main lobe; it is smaller in size and is often caused by constructive interference, impedance mismatch or imperfections in the antenna material. The horn antenna also has two side lobes which reduce the antenna's overall directivity.

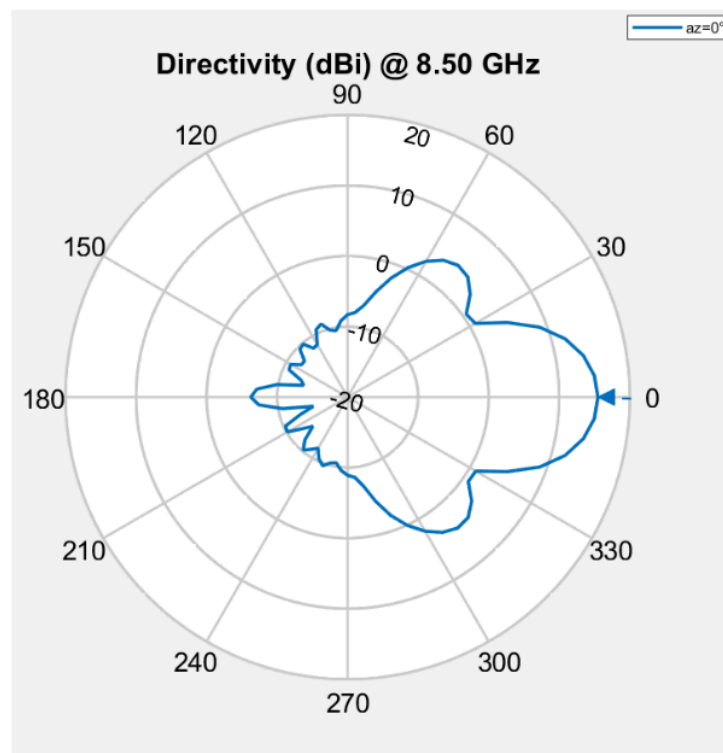


Figure 18 - horn antenna elevation plot

The horn antenna experiences a significant back lobe in azimuth with large nulls either side. However, the main lobe has no side lobes allowing for greater directivity.

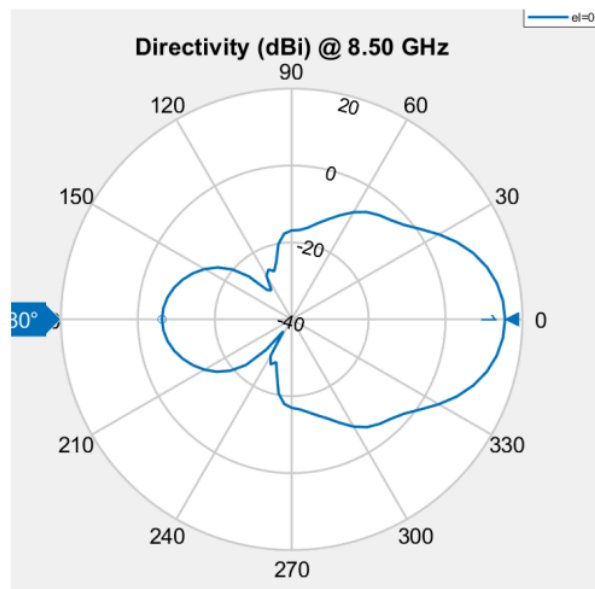


Figure 19 - Horn antenna azimuth plot

The s parameter plot shows that horn antenna has the least VSWR at 8.5 GHz this is where the antenna experiences the least loss.

Horn antennas have a wide bandwidth, high gain and experience low sidelobe levels, this makes it perfect for a number of uses from radar to satellite comms. Due to horn antennas flexibility to work in a number of places they are often adapted or used in conjunction with other antennas. One example of this is the introduction of the sectoral horn in 1897[17]. The introduction of the sectoral allows for extremely high directivity often being used in point to point communication [18].

Helix antenna (21 GHz)

A helix antenna is considered one of the simplest antennas to make this is due to its elongated spring shape, its simple design means it can be made from thin wire if required. Helix antennas are often used in very high frequency applications [16]. Helix antennas are often mounted to ground plane this is commonplace in most helix antenna design with the only exception being omnidirectional helix antennas [19].

The antenna 3d radiation pattern shows that main radiation occurs in the Y direction with 2 main side lobes in the x direction as well as a back lobe.

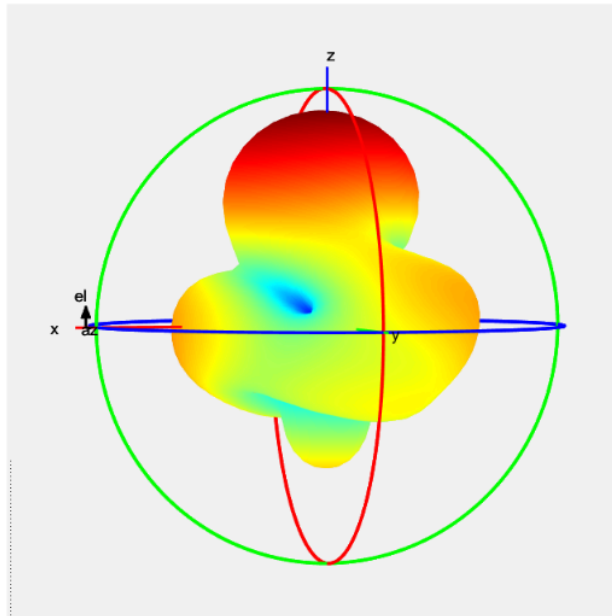


Figure 20 - Radiation pattern of a Helix antenna

This is increasingly obvious in the azimuth plane; the radiation occurs in two directions one at 330 degrees and another at 170 degrees. This shows that the antenna has low directivity as the antenna radiates in a number of directions. The antenna at its max has a directivity of 1.275 Db.

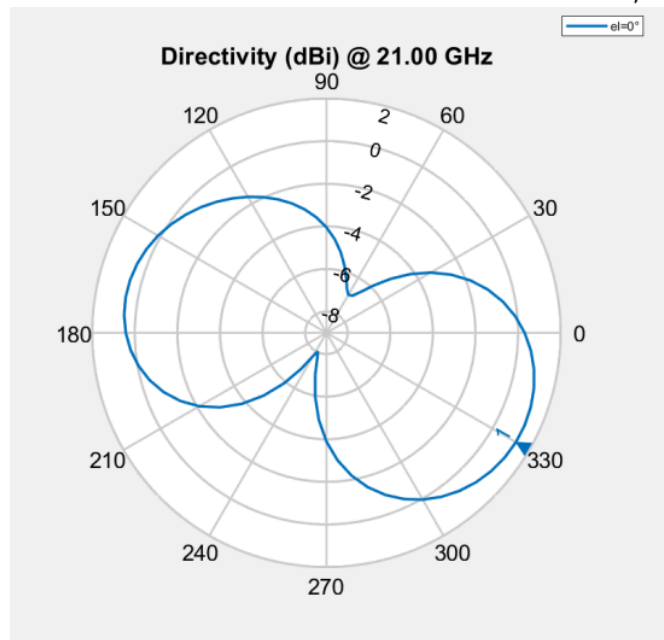


Figure 21 - azimuth plot helix antenna

The reader can greater see the back lobe and side lobes in the elevation plot. The back lobe consists of a lobe with -1.03 Db which are accompanied with two side lobes with 0.31 Db with the main lobe sitting at 10.46 Db.

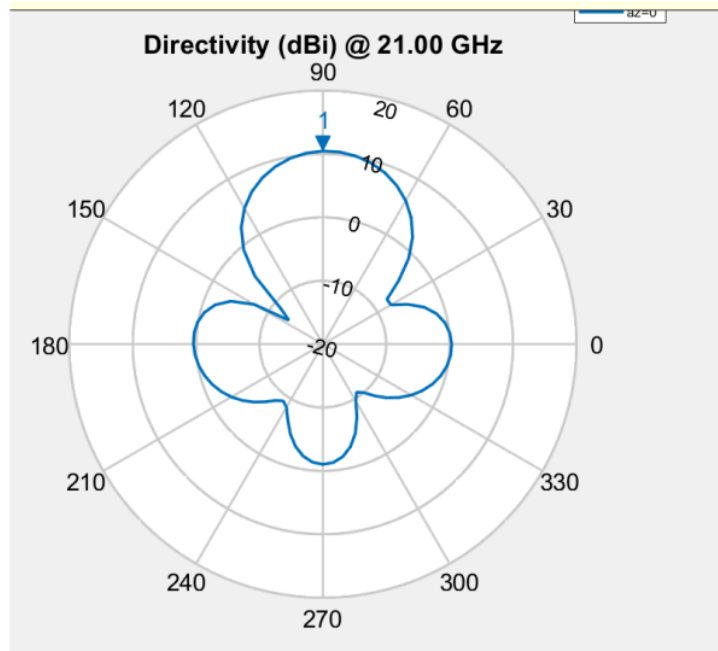


Figure 22 - Helix antenna elevation plot

The S parameter plot shows that the antenna most affectively reduces SWR at 20.25 GHz not the 21 GHz the antenna is designed for. This shows how different antenna parameters can affect each other for example having maximum directivity can cause bigger SWR effects.

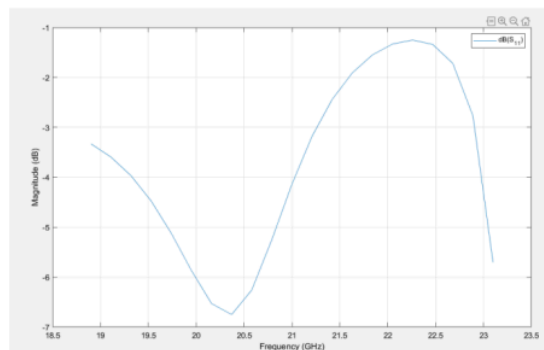


Figure 23 - S parameter Helix antenna plot

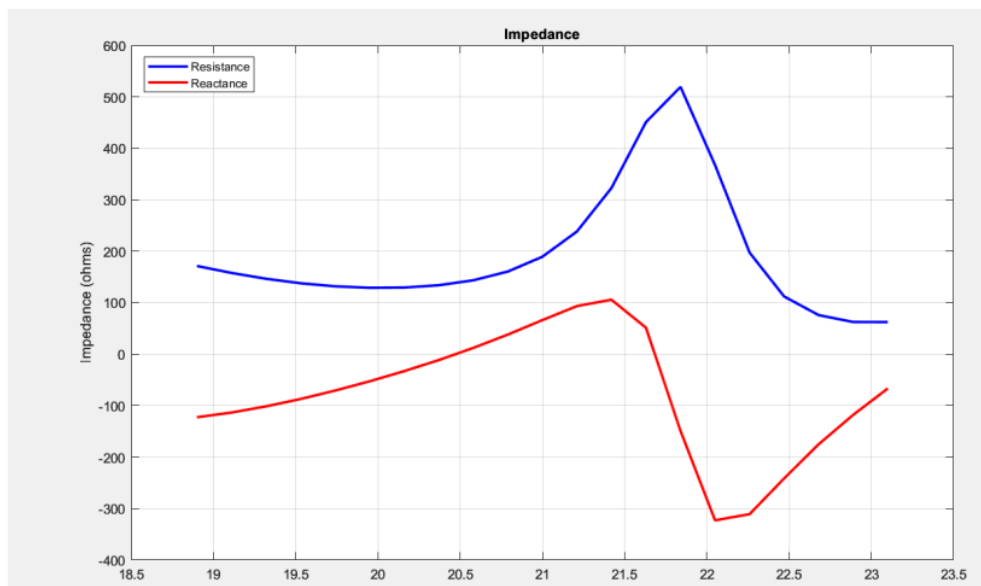


Figure 24 - Impedance graph for a helix antenna

The above impedance graph shows what ratio of resistance and reactance that the impedance is made from. As can be seen from the plot at 21 GHz the antenna has 100 ohms of reactance and 510 ohms worth of resistance.

Helix antennas are used for long distance communications such as satellite relays. Most helix antennas operate between 300 MHz and 3 GHz, this is why the operation of the above antenna is reduced compared to the same antenna designed for 3GHz.

Task 3

Antennas can be placed together to form arrays. These arrays allow for greater angular coverage, increased directivity or even greater gain. In the below example an antenna array is created with 9 elements made from helix antennas. The central element is at the centre of the ground plane. The array is designed to work at 21 GHz.

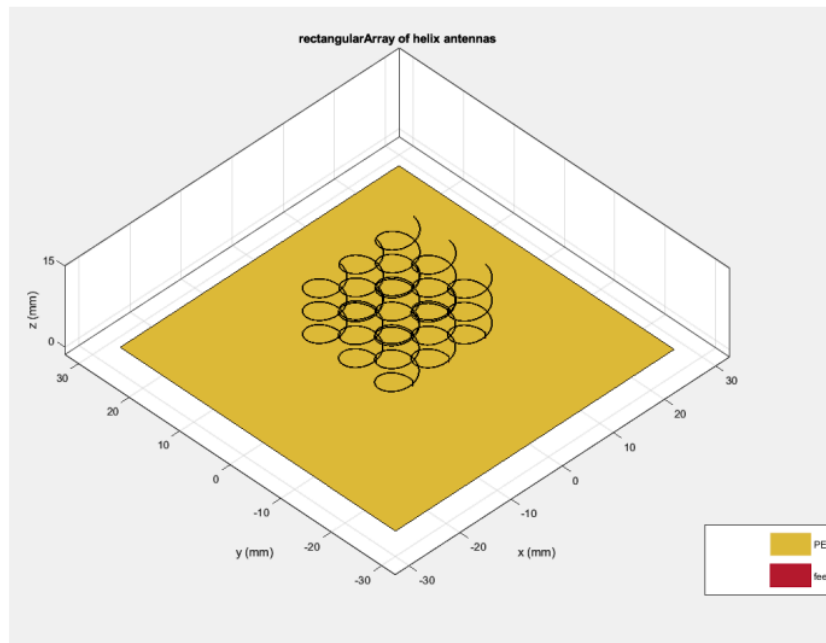


Figure 25 - antenna array

The antenna's radiation pattern was plotted in 3d, Azimuth and elevation. It is clear from the antenna's elevation plot that the array dramatically increases the directivity compared to the singular helix, the array also reduces the side and back lobes which are more prominent in the single helix array.

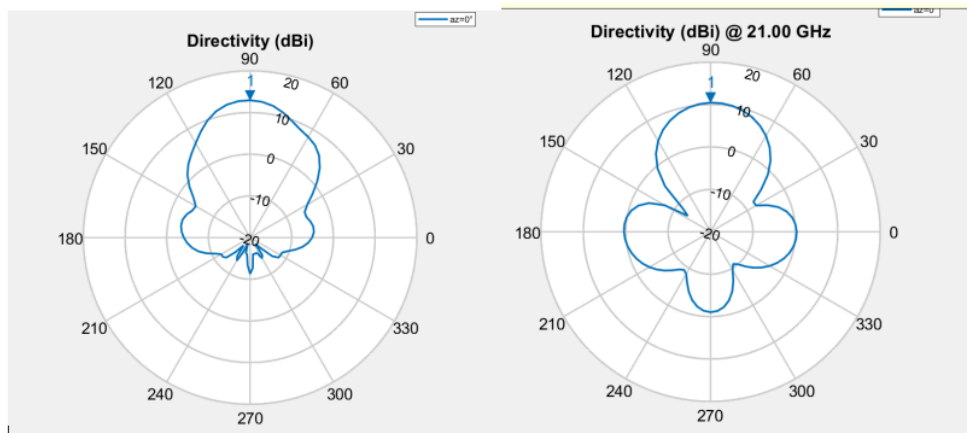


Figure 26 – Helix array antenna elevation plot

Figure 27 - Helix antenna elevation plot

In azimuth the helix array also shows less overall directivity but in the main lobe does have more power.

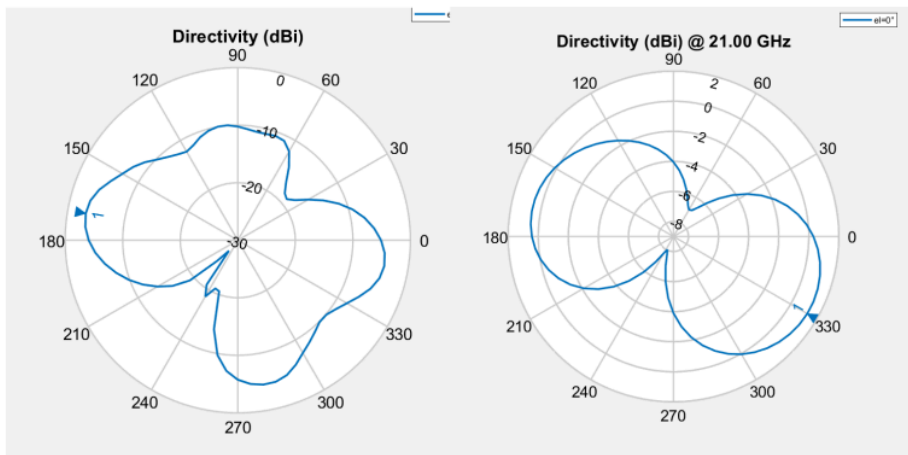


Figure 28 - azimuth antenna array plot

Figure 29 – Antenna azimuth plot

The impedance plot for the array is done by analysing each element individually. The first element has the same impedance as the singular helix antenna showing at resonant frequency the antenna impedance is almost entirely resistive. However, this greatly changes with element 5 (the most central element). The impedance plot for element 5 shows the antenna impedance is almost equal parts reactive and resistive. This shows that the same antenna can possess different parameters when placed in an array allowing for different outputs.

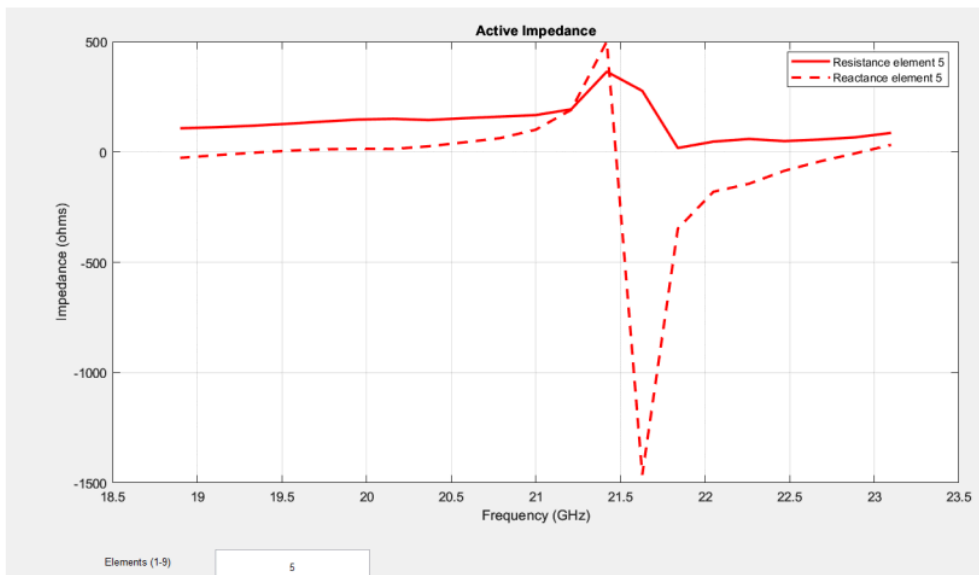


Figure 30 - impedance plot for Helix antenna 5

This can further be seen in the antenna array S parameter plot each antenna has different values at different ports showing just how important spacing can be in arrays.

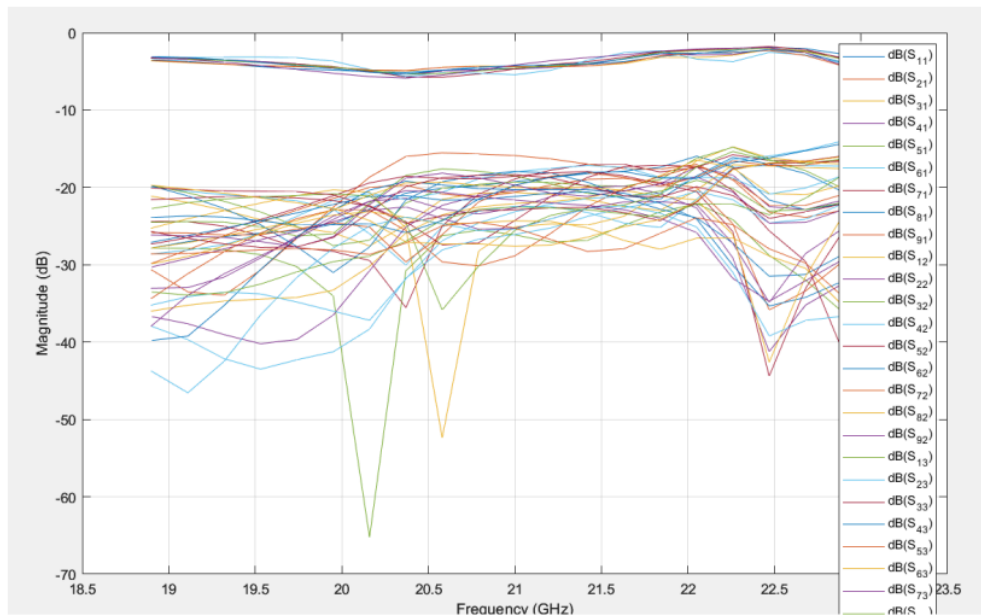


Figure 31 - helix antenna array s parameter plot

Antenna arrays allow the user to improve certain features such as increase gain, allow for greater directivity, certain arrays can be electronically steered for even greater directivity and better signal to noise ratio [20] [21]. These key attributes mean they are used in a variety of places from wireless communication, military or satellite communications [22]. Due to the diverse areas array antennas are found they can take many shapes and sizes; these shapes and sizes are often defined by the use case and the policies that underpin the different industry's they sit in.

In conclusion the reader should now have not only a strong understanding of different antenna types, modelling software but also a thorough understanding of different analysis tools which can be used to determine key features such as directivity, gain or loss in an antenna.

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GRADING FORM: ADV. RF SYSTEMS

CERY'S VERSEY

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ENGAGEMENT WITH LITERATURE

The report should demonstrate the use of relevant, high-quality academic and professional sources. Comprehensive research incorporating recent journal articles, textbooks, and reliable sources should be evident. The credibility of each source should be evaluated, favouring peer-reviewed materials. All references must follow IEEE format, with consistent in-text citations.



Demonstrates strong ability to select and evaluate technical literature. Effectively incorporates relevant academic and professional sources, including textbooks, peer-reviewed journals, and technical articles. Citations are well-integrated to support theoretical explanations and justify design decisions. It would have been better with more peer reviewed journals.

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KNOWLEDGE AND UNDERSTANDING

The report must exhibit sound knowledge of RF principles, and antenna theories. Theoretical concepts such as impedance matching, array antenna, resonance frequency, and antenna applications should be clearly explained. Concepts should be related meaningfully to practical contexts. The report should demonstrate how this knowledge informed the design decision and the application of core knowledge in mathematics, engineering, and natural sciences to solve broadly defined problems and analyse real-world RF systems.



Demonstrates a good understanding of antenna theory, electromagnetic behaviour, and RF design principles, with correct application of formulas and meaningful interpretation. Material choices reflect awareness of relevant electromagnetic properties. While some mathematical derivations are included, clearer links between theory and practical outcomes would enhance the analysis. Consideration of societal and regulatory needs is limited. Overall, the work shows strong foundational knowledge in antenna theory.

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COGNITIVE AND INTELLECTUAL

The report should present a critical analysis of simulation results and theoretical data. Findings must be discussed with evidence, leading to logical and valid conclusions. Comparisons between theoretical and simulation results should be presented. Discussions should include implications, limitations, and alternative solutions



Demonstrates effective use of first principles and computational techniques to analyse antenna performance. Critically interprets discrepancies in

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S-parameters and impedance, offering reasoned insights into behaviours such as VSWR, side lobes, and nulls. Simulation results are well discussed, the analysis would benefit from deeper quantitative comparison with theoretical expectations, such as percentage deviations or efficiency loss, to enhance the analytical skill.

PRACTICAL SKILLS

Marks for practical skills will be provided based on the Practical application of engineering principles and skills in designing, simulating, or conducting experiments. Appropriate engineering software and methodologies should be applied to design antennas. The simulation process and parameters should be documented clearly, with justifications for methods used. Results should be presented with a neat plots and visuals. Problem-solving skills should be demonstrated through analysis and design refinements.. Proficiency with tools, and software to support your solutions.



Demonstrates strong proficiency in applying computational and analytical techniques using CST Studio and MATLAB's Antenna Toolbox to model a range of antenna types. Simulations are clearly presented with relevant visuals, including S-parameters and radiation plots, and the step-by-step methodology is well documented. Practical use of simulation tools reflects solid engineering skills. Minor improvements could be made by standardising simulation parameters and providing more detail on solver settings and simulation constraints to enhance technical clarity and reproducibility.

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The report should be clear and well-structured for technical and non-technical readers. Complex ideas must be communicated effectively, with appropriate terminology and visual aids. A logical flow from introduction to conclusion should be maintained. Professional presentation elements such as clear headings, subheadings, and a well-organised reference list should be included.



The report is well-structured and clearly presented, with effective use of visuals and language suited to a technical audience. It demonstrates awareness such as VSWR limits and material sustainability. Stronger engagement with professional standards and explicit references to relevant guidelines would enhance the depth and credibility of the analysis.

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