

Design and Analysis of Electromagnetic Systems Part 1.

Electromagnetic Radiation

ACDC5009

**BEng Embedded
Electronic Systems**

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1 Introduction

This document presents the development and analysis of several simulation models using Ansys' software suite. These simulations include the modelling of a waveguide and an antenna, accompanied by the theoretical background that supports the results. This include a demonstration of how the theory compounds the credibility of the simulation through calculating and comparing the values outputted from the information given in the specification.

NOTE: Part 2 (TASK 3) IS PAST THE APPENDIX OF THIS DOCUMENT

2 Waveguide (Task 1)

2.1 Vacuum filled waveguide (Task 1A)

2.1.1 Simulation creation

To simulate the waveguide, Ansys' high frequency simulation software (HFSS) in driven modal solution mode. Within HFSS, a cuboid was drawn and the dimensions amended to conform with the specification. As such, the length would be $50mm$, width would be $23mm$ and the height $8mm$. The full calculations for which can be found in appendix A. The materials were then sets, as it was vacuum this step was omitted due to it already being vacuum. The excitations were then set, by selecting the relevant faces and assigning a wave port excitation. Next the number of modes on the port was set to three, simulating the three main modes. Then, a simulation setup on advanced mode was created to make an broadband analysis between $2GHz$ and $30GHz$, as per the specification. Note the save fields (at basis frequencies) should be ticked. The analysis can then be validated and ran.

The port fields were created after the waveguide had been analysed through viewing the port field display made by default during analysis on each end of the waveguide and selecting the 3 modes that should be outputted.

2.1.2 Dominant mode & port field diplays

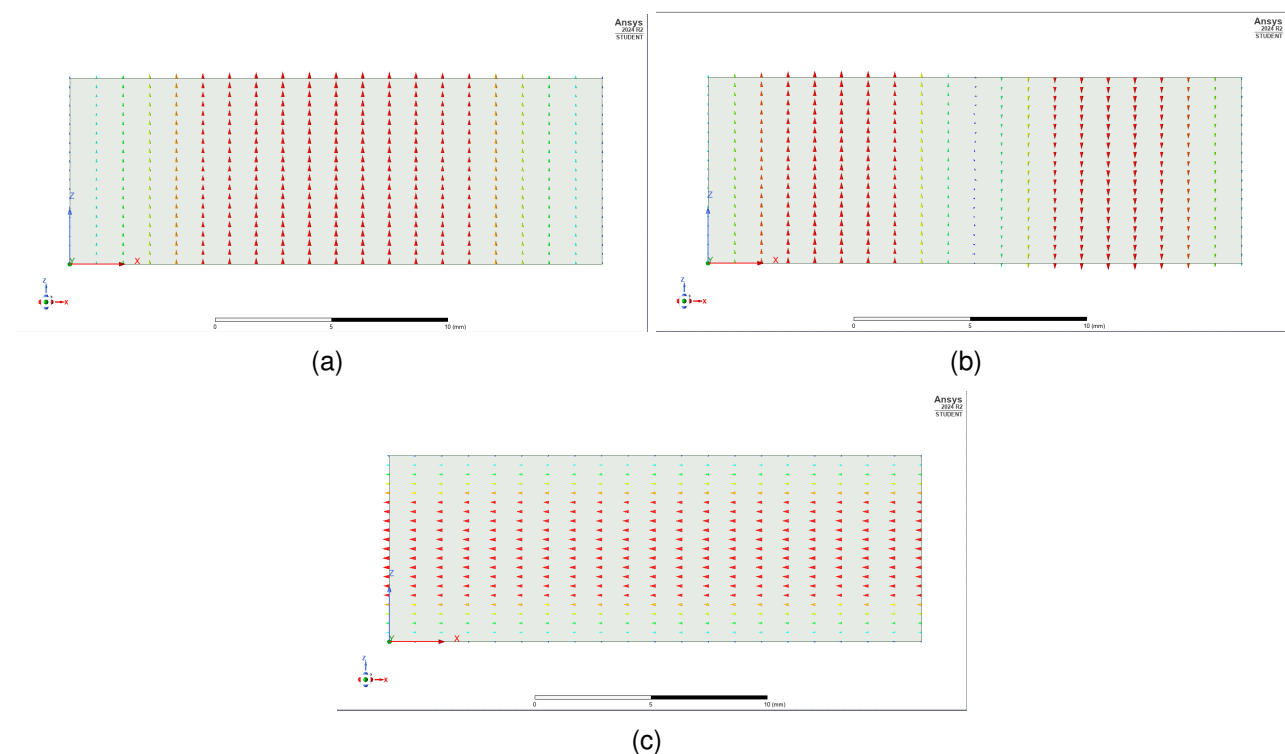


Figure 1: Task 1A port 1 field displays

Figure 1 shows the three dominant ports simulated, which will be referred to as mode 1, mode 2 & mode 3 hereafter. Of which, it can be observed that a is transverse electric wave, where $m = 1$ and $n = 0$ as such, it can be said that the dominant mode is TE_{10} . Similarly, c show TE_{01} . Both of which can be differentiated from TM , as they cannot exist in a rectangular waveguide [1]. In b, it can be observed that there's two occurrences points in the horizontal plain. Furthermore, due to the distribution, it's not TM . As such, it is likely TE_{20} .

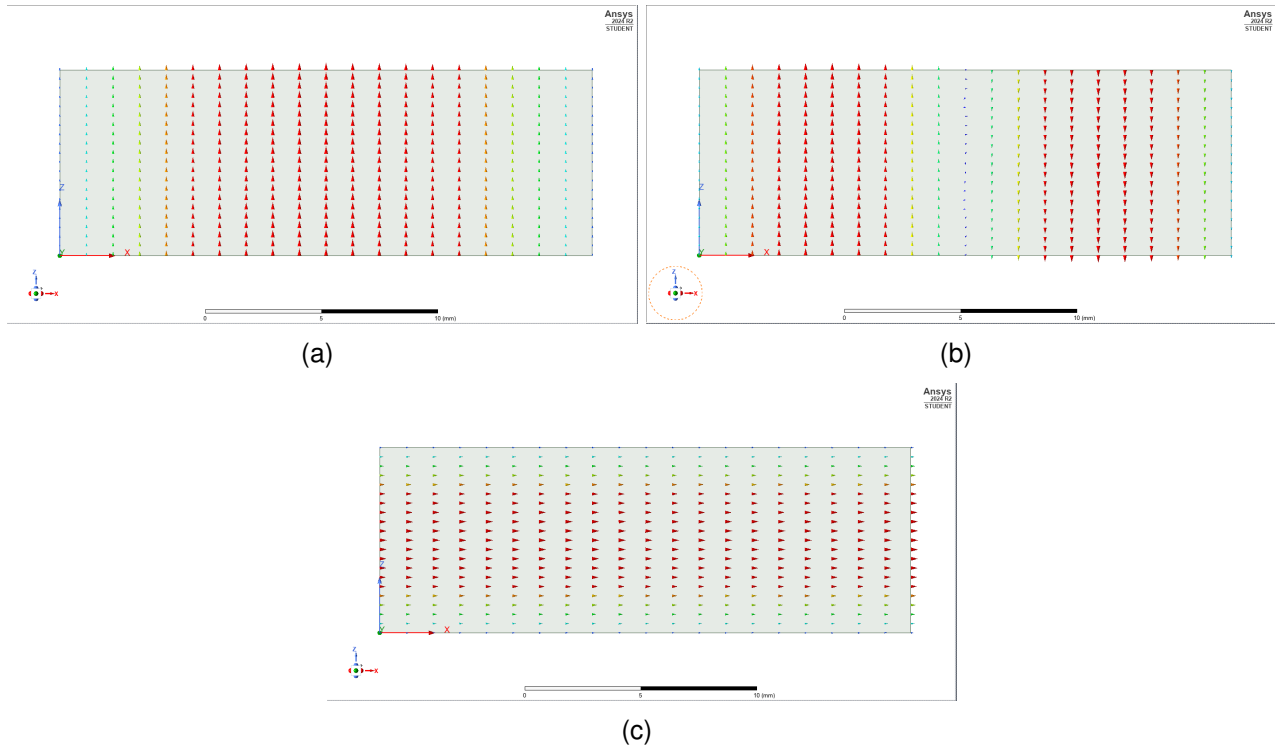


Figure 2: Task 1A port 2 field displays

2.1.3 Magnitude and vectors

The magnitude and vector diagrams were gained through adding plot fields on the object. This was set to the magnitude and vector plots, which can be done for both electric and magnetic fields independently.

Figure 3 and figure 4 shows the magnitude and vectors for the vacuum and perfect conductors. They show the direction of propagation for the respective wave within the waveguide. As such, it can be observed that the dominant mode is TE_{01} due to the lack of the electric field in the direction of propagation. This is in direct contrast to the magnetic field, which does have elements in the direction of propagation.

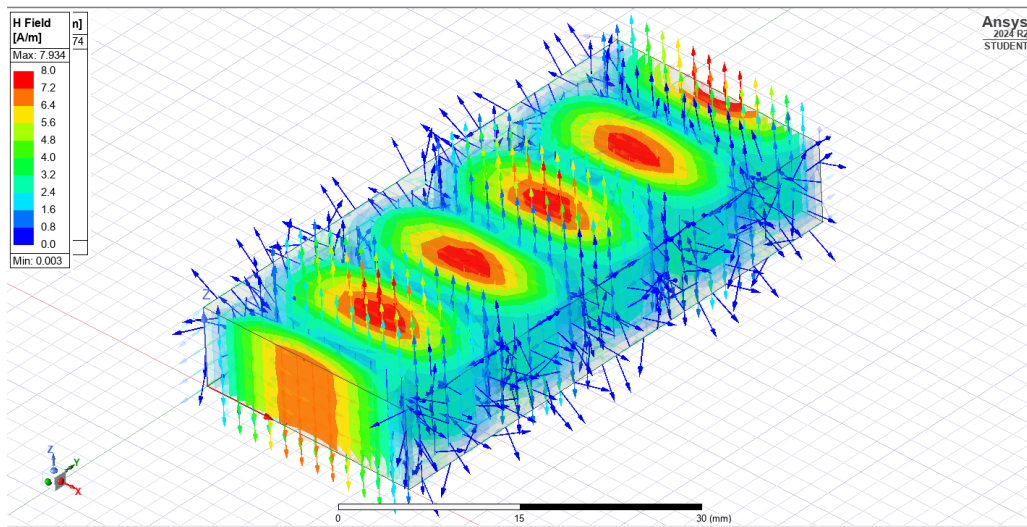


Figure 3: Task 1A Electric field magnitude and vectors

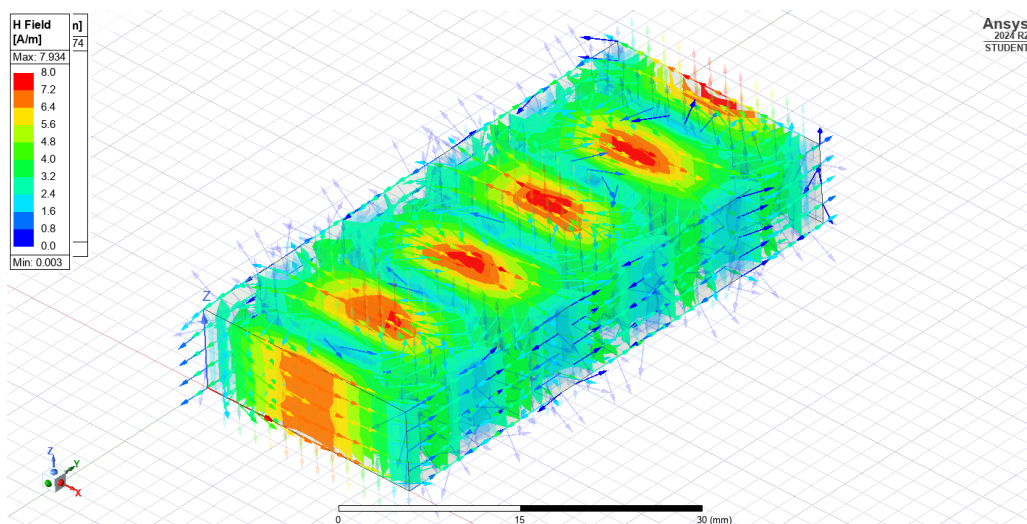


Figure 4: Task 1A Magnetic field magnitude and vectors

2.1.4 Cut off frequencies

The cut off points for the modes were gained through adding an analysis to the results tab, which would capture the gamma to a rectangular graph. Then, all 3 ports can be selected to ensure that they were all plotted. The data from which can be exported for use in this document. As can be seen in Figure 5 mode 1 starts at approximately 6.5GHz from figure 5 and was measured to 6.48GHz in Ansys. Mode 2 was read to approximately 13GHz and was measured to 12.99GHz in Ansys. Mode 3 was read to 19GHz and measured to 18.73GHz . This means that the minimum and henceforth dominant mode is Mode 1, hence, the cutoff frequency will also be just below 6.48GHz , where any signals will be attenuated.

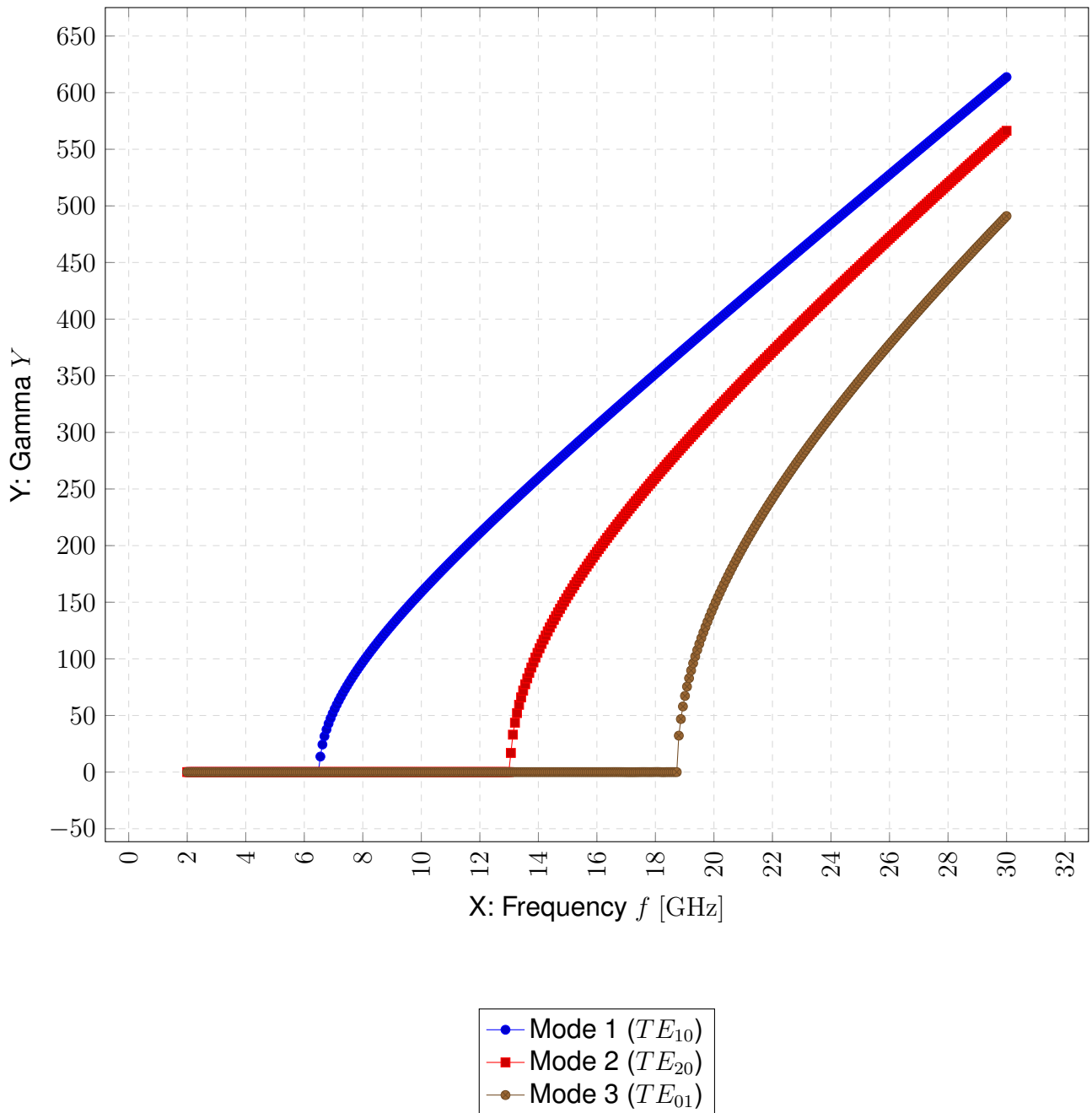


Figure 5: Gamma with respect to frequency.

2.1.5 Cut off calculations

In this case, waveguide dimensions (a & b) will stay constant, in this case being $23mm$ and $8mm$ respectively.

The speed of light (c) can be calculated using:

$$\begin{aligned}c &= \frac{1}{\sqrt{\epsilon\mu}} \\ \epsilon &= \epsilon_0\epsilon_r \\ \mu &= \mu_0\mu_r\end{aligned}$$

$$\begin{aligned}\epsilon_0 &= 8.854 \times 10^{-12} F/m, \epsilon_r = 1 \text{ in vacuum} \\ \mu_0 &= 4\pi \times 10^{-7} H/m, \mu_r = 1 \text{ in vacuum}\end{aligned}$$

$$\begin{aligned}c &= \frac{1}{\sqrt{(8.854 \times 10^{-12} \times 1)(4\pi \times 10^{-7} \times 1)}} \\ &= 299,795,637.7 m/s \\ &\approx 3.00 \times 10^8 m/s\end{aligned}$$

The cut off frequency can be given by the size and mode of the waveguide. As such:

$$f_c = \frac{c}{2} \left(\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \right)$$

For mode 1, $m = 1$, $n = 0$, giving:

$$\begin{aligned}f_c &= \frac{3 \times 10^8}{2} \left(\sqrt{\left(\frac{1}{23}\right)^2 + \left(\frac{0}{8}\right)^2} \right) \\ &= 6,521,739,130 Hz \\ &\approx 6.53 GHz\end{aligned}$$

For mode 2, $m = 2$, $n = 0$, giving:

$$\begin{aligned}f_c &= \frac{3 \times 10^8}{2} \left(\sqrt{\left(\frac{2}{23}\right)^2 + \left(\frac{0}{8}\right)^2} \right) \\ &= 13,043,478,260 Hz \\ &\approx 13.04 GHz\end{aligned}$$

For mode 3, $m = 0$, $n = 1$, giving:

$$\begin{aligned}f_c &= \frac{3 \times 10^8}{2} \left(\sqrt{\left(\frac{0}{23}\right)^2 + \left(\frac{1}{8}\right)^2} \right) \\ &= 18,750,000,000 Hz \\ &\approx 18.75 GHz\end{aligned}$$

2.2 Teflon filled waveguide (Task 1B)

2.2.1 Simulation creation

Similar to the details within section 2.1.1, a rectangular waveguide can be created. However, the step omitted previously to add a materials is required now. As such, a Teflon material fitting the brief is required. This can be added using the properties panel of the cuboid.

2.2.2 Dominant mode & port field displays

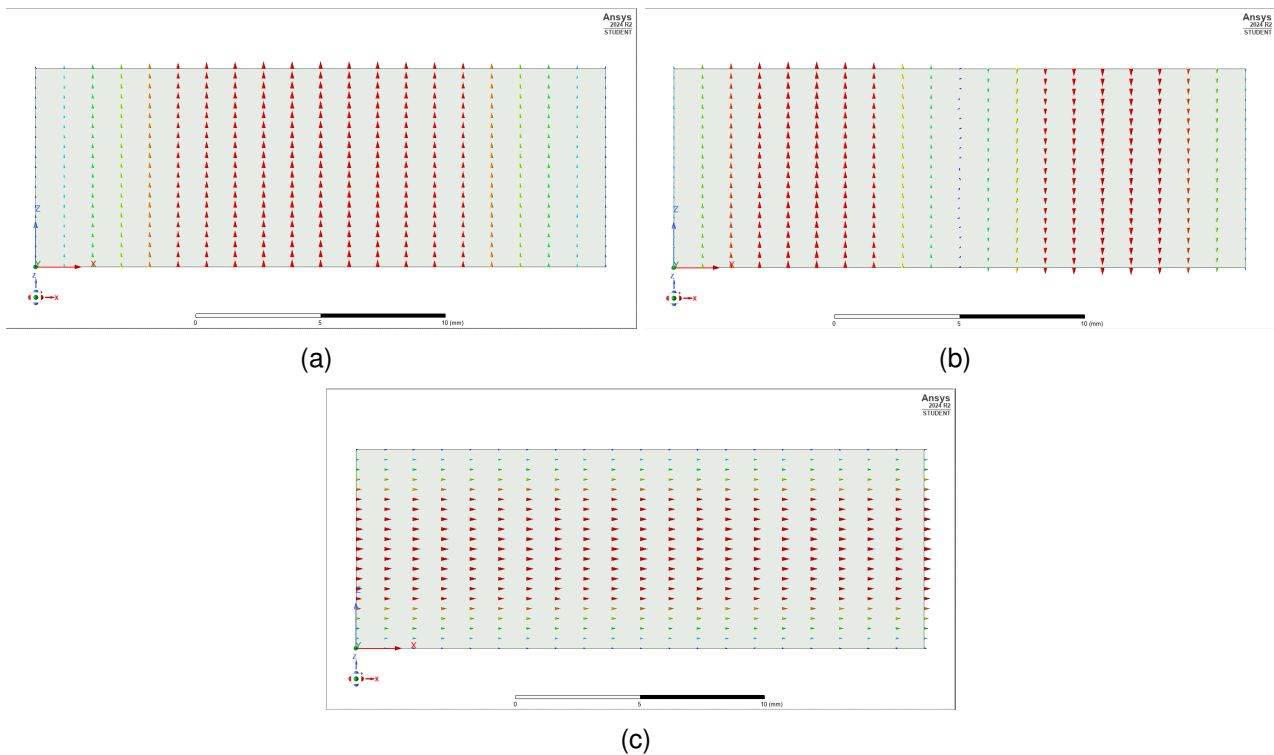


Figure 6: Task 1B port 1 field displays

Figure 6 shows the three dominant ports simulated for task 1B, which are relatively similar to task 1A. They both represent similar dominant modes, mode 1 (a) being TE_{10} , mode 2 (b) being TE_{20} and mode 3 (c) being TE_{01} .

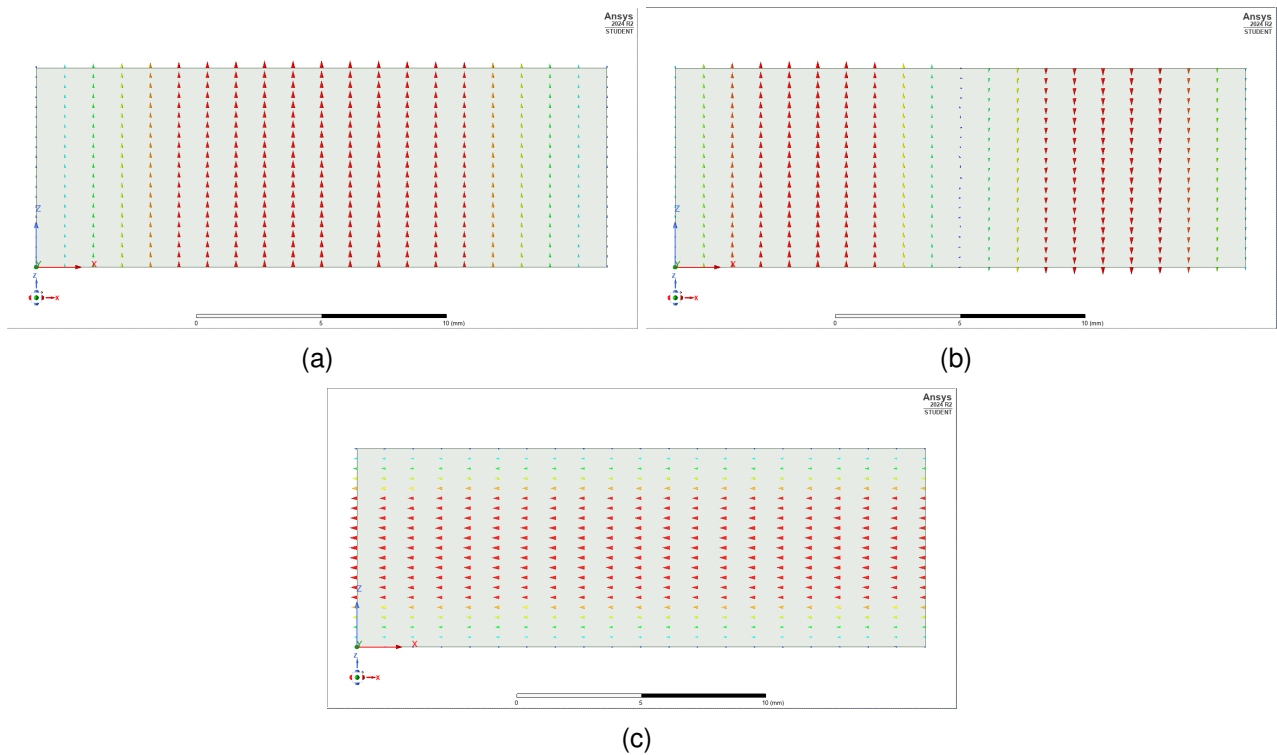


Figure 7: Task 1B port 2 field displays

2.2.3 Magnitude and vectors

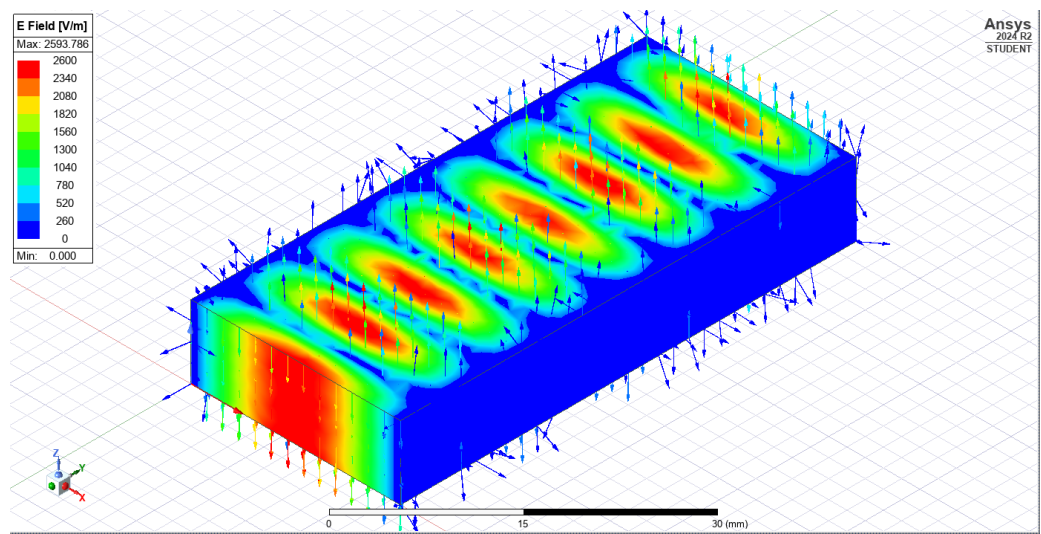


Figure 8: Task 1B Electric field magnitude and vectors

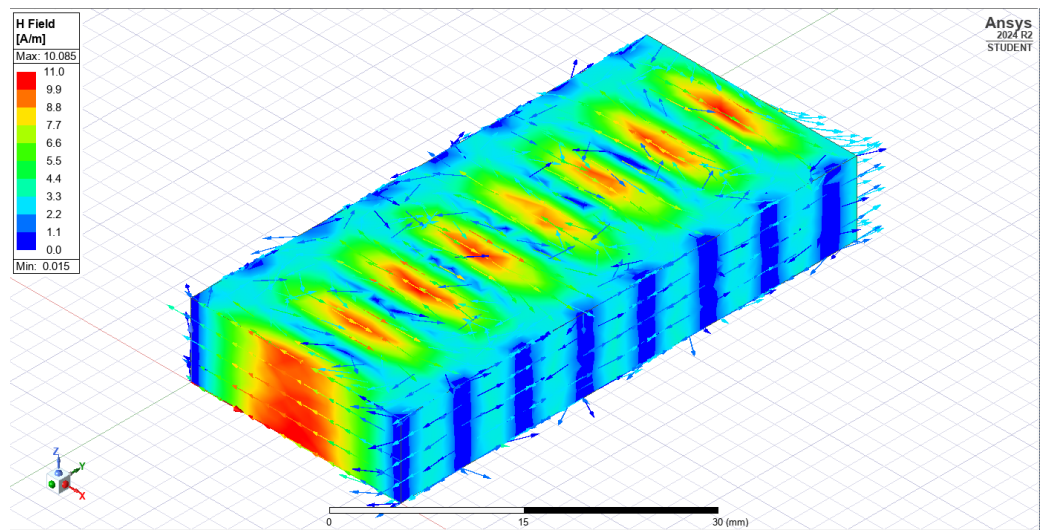


Figure 9: Task 1B Magnetic field magnitude and vectors

2.2.4 Cut off frequencies

As shown in Figure 10, the modes have a similar shape but different cut off points. Mode one at approximately 4.5GHz , measured to 4.45GHz . Mode 2 at 9GHz , measured to 8.93GHz . Mode 3 at 13GHz , measured to 12.92GHz .

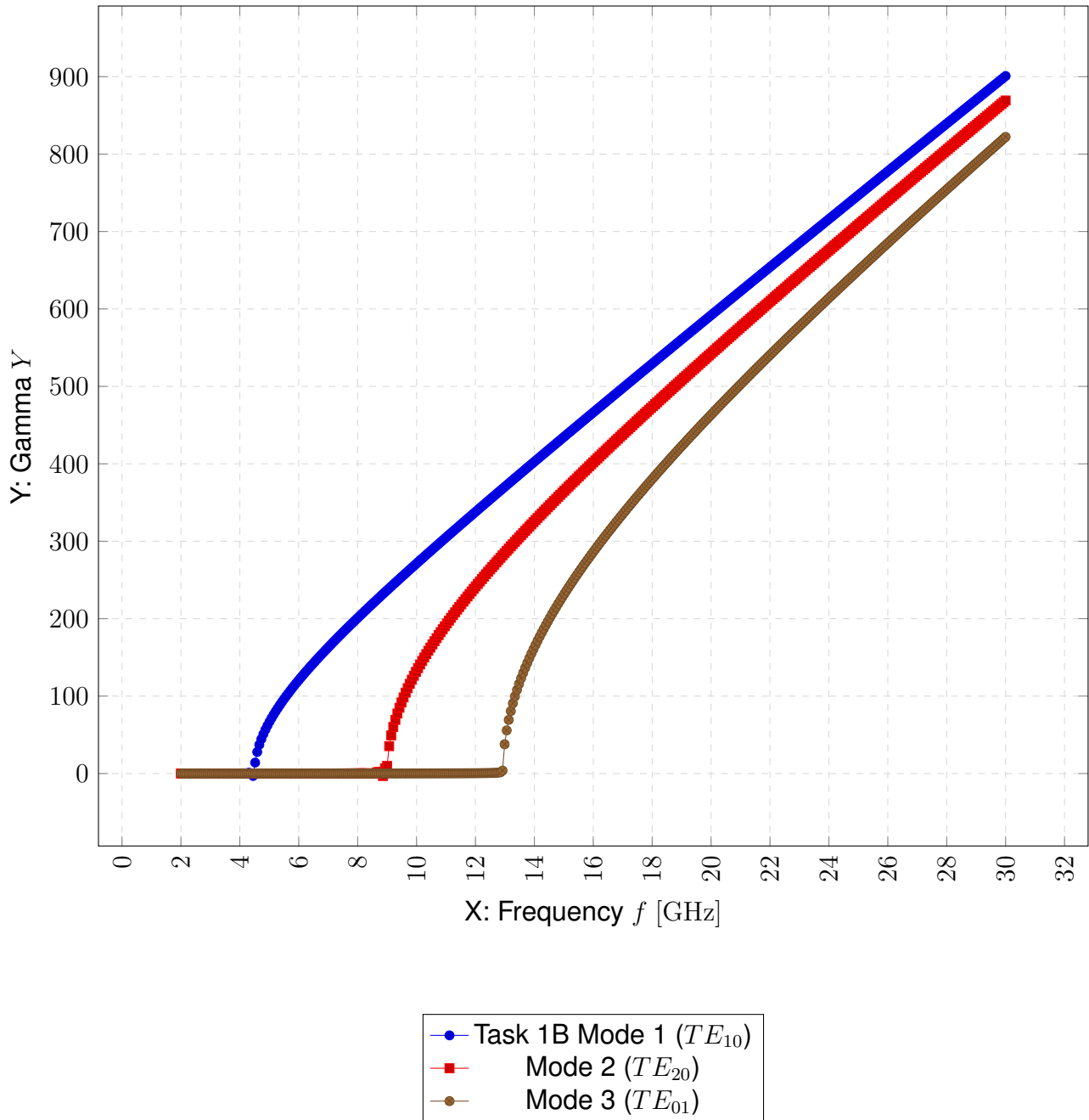


Figure 10: Gamma with respect to frequency.

2.2.5 Cut off calculations

In this case, waveguide dimensions (a & b) will stay constant, in this case being $23mm$ and $8mm$ respectively.

The speed of light (c) can be calculated using:

$$\begin{aligned}c &= \frac{1}{\sqrt{\epsilon\mu}} \\ \epsilon &= \epsilon_0\epsilon_r \\ \mu &= \mu_0\mu_r\end{aligned}$$

$$\begin{aligned}\epsilon_0 &= 8.854 \times 10^{-12} F/m, \epsilon_r = 2.1 \text{ in Teflon} \\ \mu_0 &= 4\pi \times 10^{-7} H/m, \mu_r = 1 \text{ in Teflon}\end{aligned}$$

$$\begin{aligned}c &= \frac{1}{\sqrt{(8.854 \times 10^{-12} \times 2.1)(4\pi \times 10^{-7} \times 1)}} \\ &= 206,878,644.4 m/s \\ &\approx 2.07 \times 10^8 m/s\end{aligned}$$

The cut off frequency can be given by the size and mode of the waveguide. As such:

$$f_c = \frac{c}{2} \left(\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \right)$$

For mode 1, $m = 1$, $n = 0$, giving:

$$\begin{aligned}f_c &= \frac{2.07 \times 10^8}{2} \left(\sqrt{\left(\frac{1}{23}\right)^2 + \left(\frac{0}{8}\right)^2} \right) \\ &= 4,500,000,000 Hz \\ &= 4.5 GHz\end{aligned}$$

For mode 2, $m = 2$, $n = 0$, giving:

$$\begin{aligned}f_c &= \frac{3 \times 10^8}{2} \left(\sqrt{\left(\frac{2}{23}\right)^2 + \left(\frac{0}{8}\right)^2} \right) \\ &= 9,000,000,000 Hz \\ &= 9.00 GHz\end{aligned}$$

For mode 3, $m = 0$, $n = 1$, giving:

$$\begin{aligned}f_c &= \frac{3 \times 10^8}{2} \left(\sqrt{\left(\frac{0}{23}\right)^2 + \left(\frac{1}{8}\right)^2} \right) \\ &= 12,937,500,000 Hz \\ &\approx 12.94 GHz\end{aligned}$$

2.3 Comparison

Table 1 shows the output of the simulations and calculations from the Teflon and vacuum examples. As is expected, the frequency of the Teflon waveguide is lower. Most likely due to the lower velocity of waves in a higher density material, as was shown in the calculations above.

The frequency in Vacuum is approximately $1\frac{1}{2}$ times larger than that of Teflon. This correlates to the difference between the speed of light within the mediums. As per section 2.1.5, the frequency in vacuum is $3.00 \times 10^8 m/s$ and $2.07 \times 10^8 m/s$ in section 2.2.5. As such, it can be taken that the fundamental difference between the two mediums is the density, which affects the velocity and created the difference in cut off frequency. This can also be mathematically gathered, as the size of the waveguide and modes being constants in both examples. As such, the only variable is the speed of light. Overall, the results are relatively consistent between the theory and simulation. Most of which, fall within $\pm 2.5\%$ of each other.

Table 1: Cut off frequencies of modes in differing mediums

Mode / material	Mode 1	Mode 2	Mode 3
Vacuum theory	6.53GHz	13.04GHz	18.75GHz
Vacuum simulation	6.48GHz	12.99GHz	18.73GHz
Teflon theory	4.5GHz	9GHz	12.94GHz
Teflon simulation	4.45GHz	8.93GHz	12.92GHz

As is anticipated based on the physical dimensions of the waveguide, the dominant modes remain consistent across different materials. This is due to the dominant mode in a waveguide being primarily determined by its geometry and is lesser so the material. Furthermore, this aligns with theoretical calculations, which compound this fact. As such, the change in material would not change the dominant mode.

3 Dipole antenna (Task 2)

3.1 Length & operation frequency calculation

Calculating the length (l) of the dipole antenna.

$$\text{Antenna length: } l = \frac{\lambda}{2}$$

$$\lambda = 231mm \quad l = \frac{231}{2}$$

$$l = 115.5mm$$

Antenna operating frequency:

$$c = \lambda f$$

$$c = 3 \times 10^8 \text{ in a vacuum, } \lambda = 0.231m$$

$$f = \frac{c}{\lambda}$$

$$f = \frac{3 \times 10^8}{0.231}$$

$$f = 1,298,701,299Hz$$

$$f \approx 1.30GHz$$

3.2 Simulation creation

In HFSS set to driven modal mode, a cylinder should be created and its dimensions set to l + the size of the gap. This should be centred at 0,0,0. As vacuum is required as the material, it doesn't need to be changed. Next, another cylinder should be created with the same radius and the height set to the size of the gap required centred at 0,0,0. Then use a subtract function with the clone box checked. This will create the gap and leave the cylinder so that a lumped port can be created. This can be done through using the section function to create a plain from the gap. Hence, an excitation can be applied to the plain through selecting the plain and adding a lumped port then drawing a line vertically along the centre of the plain. An open region is required to simulate the antenna, as such, the create open region function is used and the operating frequency is set. This will automatically create a bounding box around the antenna. An analysis can then be created similar to that in section 2.1.1.

3.3 S-Parameter plot

The S-parameter plot can be gained through plotting the gain against the frequency. The data can be exported through creating a graph of the S-parameter plot under the results tab. As shown in Figure 11, there's two distinct points where the gain is lowest, showing its operating frequencies. One at approximately 1.25GHz , which was measured to 1.18GHz in Ansys. Another at 3.60GHz , measured to 3.70GHz . These results show that the gain is lowest at 1.25GHz which means that this is the main operating frequency. As is expected, there are other bands that a higher gain at approximately three times the operating frequency.

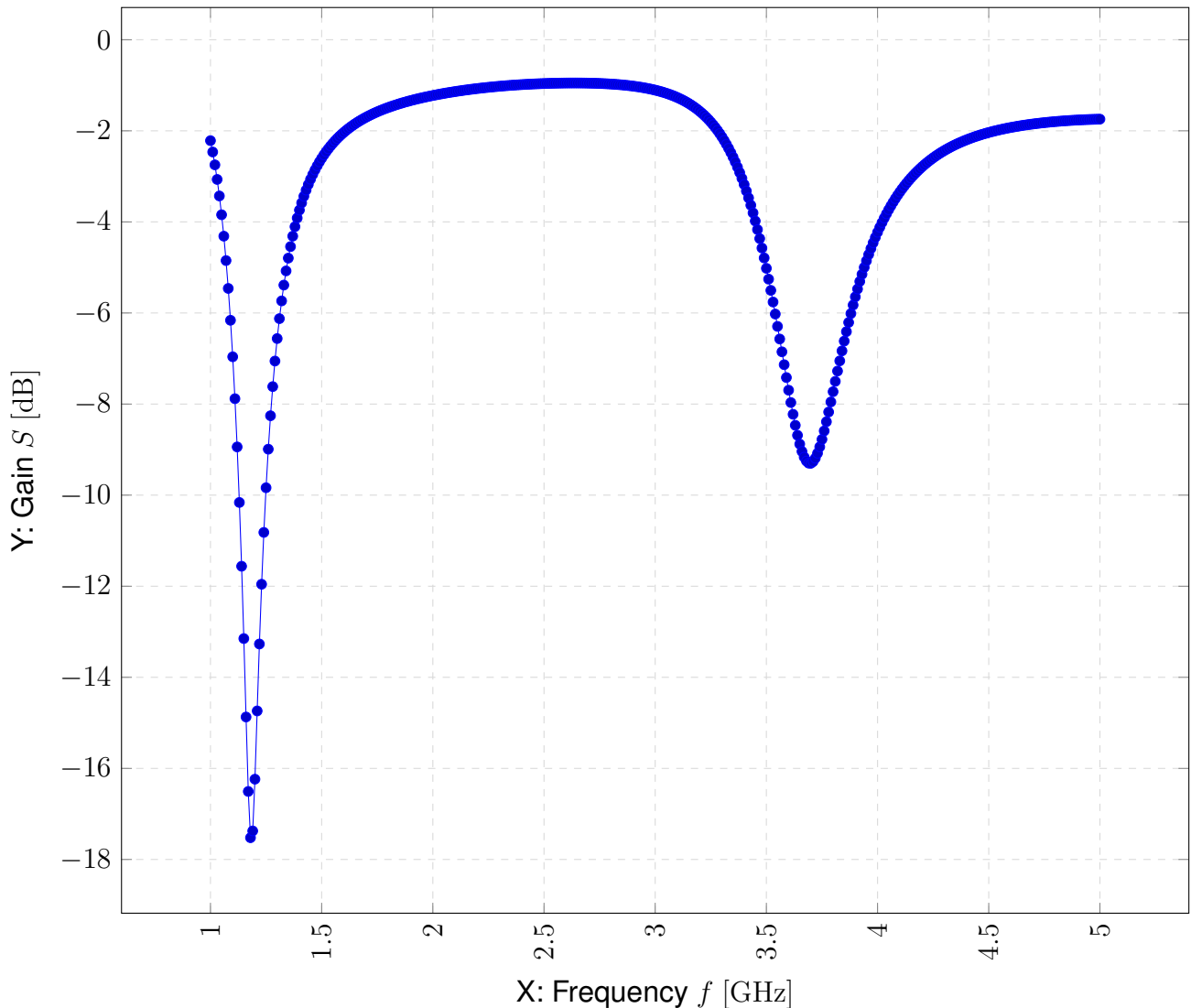


Figure 11: S over frequency

3.4 Design and plotting

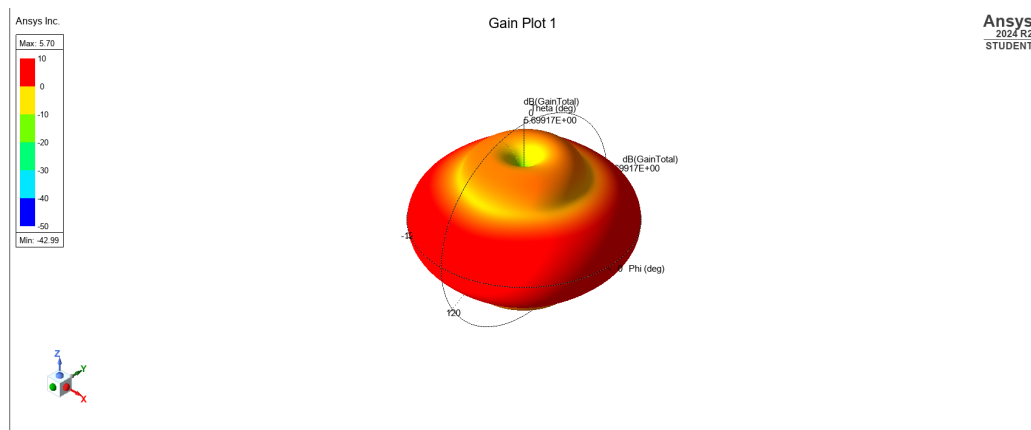


Figure 12: Task 2 radiation plot

3.5 Comparison

Both the theoretical and simulated operating frequency match within 10%, meaning that they're likely to be accurate. The source of the error may be rounding in the original values, which were used in the equation, such as the speed of light.

Although not calculated, it's likely that the radiation plot matches too, as it follows the isotropic nature of the antenna. Relative to the radiation patterns found in literature, they seem to follow the correct pattern and follow the approximately correct characteristics set out within them [2].

4 Conclusion

This part has successfully carried out a comprehensive evaluation of the composition and structure of a waveguide, examining in detail how various materials influence its overall performance and electromagnetic properties. In addition to this analysis, a dipole antenna was tested to assess its key characteristics, including parameters such as gain, impedance, and radiation pattern. These investigations were further reinforced by theoretical calculations, which served to validate the experimental results. The close agreement between theoretical predictions and observed data confirms that the models and methodologies employed are functioning as expected and are reliable for continued use in similar applications.

References

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A Length, width and height calculations

Given that student number (n herein):

$$\begin{aligned}n &= 2,315,404 \\z &= 50mm \text{ (Constant set in specification)} \\x &= 23mm \text{ First two letters of number} \\y &= \frac{15}{2}mm \text{ Rounded to } 8mm, \text{ given by third and forth digit of } n\end{aligned}$$

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Design and Analysis of Electromagnetic Systems Part 2.

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1 Radar research (Task 3)

1.1 Introduction

In this section, the advances in radio detection and ranging (RADAR) will be discussed, in conjunction with the tertiary effects it could have on a population. This will be done through compounding the literature surrounding advances in RADAR infrastructure.

1.2 Literature review

Recent advances in the use of synthetic aperture radar (SAR) and digitising radar arrays, which allows for greater control over their characteristics. Namely, recent advancements in fully digital array radars which can be used for better managing the power output in specific directions [1]. This can be beneficial as targets can have power allocated to them based on their characteristics, such as their radar cross section (RCS) this can help to increase their range and allow for multiple targets to be tracked efficiently.

Furthermore, the post processing done can better characterise the target and what state they're in [2]. In addition to this, it would be ideal to be able to communicate this with other aircraft and potentially split the work required across multiple airframes. This has been shown in both the F35 and future air combat system (FCAS) projects [3]. Hence, this could greatly increase the capability of platforms by allowing for work to be divided and shared between aircraft, hence, allowing for better paths of engagement to be used. This is beneficial for better understanding threats and prioritising targets, such as prioritising targets based on their flight characteristics or weaponry they have. In addition to this, it would be ideal to completely interconnect all systems to allow for the widest possible array of materiel to be used against an adversary.

For smaller RCS objects like drones, there needs to be significantly more sensitive and accurate sensors to ensure that the drone can be tracked properly. One such uses the doppler effect to detect the rotation of propeller blades on drones [4]. Although, having a high signal to noise ratio, this would greatly improve the detection of drones in shorter ranges such as for point defence applications.

Another paper suggests a you only look once (YOLO) methods, where deep learning is used for both classification and detection [5]. This would involve training a model to identify the characteristics mentioned above, like doppler effect to detect blades.

This would be massively beneficial for accelerating the detection process, making detection quicker and a fire control order to be formulated more precisely and earlier. Furthermore, not requiring an array to stare at a small area is ideal, as a large area can be scanned and require only one return to be useable.

Continuous wave RADARs can be beneficial for outputting over a large area; in conjunction with modulating the signal [6]. This will give the capability of detecting range and velocity which can be fed into the algorithms mentioned above.

Commercial, off the shelf systems are becoming available for use for detecting small objects like birds and drones at Royal Air Force (RAF) bases, where they can be tracked and logged for use by RAF air traffic control (ATC) [7]. Although this doesn't differentiate them, it would be massively beneficial for logging events and early detection of threats whilst a plane is landing or taking off.

1.3 Discussion

To be able to detect smaller, fast moving objects such as drones RADARs will have to be incredibly precise; they need to be able to identify objects that could be easily mistaken for noise or birds. However, with the advancements in detect smaller objects, more data will be available to exploit and use for training new systems. With the widespread adoption of artificial intelligence (AI) which will help to discriminate drones from other objects. This can be leveraged by the propulsion often used by drones; propellers.

Alltogether, this can be combined into a system that could quickly and accurately identify drones through the adoption of more complex RADAR types that can scan an area faster and more precisely than legacy systems could due to the lack of mechanical parts, which may have to overcome the momentum of the RADAR being moved or the limited number of scan patterns that could be carried out within a given timeframe. Furthermore, the ability to control individual elements individually can be greatly leveraged to favour the ability of simultaneous scanning multiple locations.

1.4 Conclusion

Due to the recent widespread adoption of drones for direct offensive operations, the need for effective counter drone capabilities has become more urgent. However, the development of systems to detect, track, and neutralize these threats is still ongoing and faces a number of complex problems to solve. Drones are becoming smaller and faster which makes legacy systems less effective against them. Nevertheless, with the rapid advancements in machine learning, along with significant progress in the development of next-generation RADAR systems specifically designed to detect drones have been introduced pre-emptively, this is likely to be countered soon as the defence industry realises the potential threat they pose. These enhanced RADARs, combined with AI algorithms, are likely to dramatically improve response times and accuracy in identifying potential drone threats, thereby bolstering national security and critical infrastructure. defense capabilities.

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