

# **Design and Analysis of Electromagnetic Systems**

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L5 Electromagnetic Radiation - ACDC5009

Embedded Electronics Degree Apprenticeship

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## **Abstract**

This report investigates the simulation of two rectangular waveguides, a half-wave dipole and the recent technological developments related to detecting drones. The two waveguides vary based on their fillings, one with teflon and one with a vacuum. The results showed that depending on the filling of a waveguide, the cutoff frequency varies. This is due to the permittivity of the teflon dielectric causing the phase-velocity to be reduced. The half-wave dipole was investigated to discover the differences between the theoretical values and simulated values of the resonant frequency. This revealed that the resonant frequency in the simulation differs from that of the theoretical, with the explanation being due to field fringing. Research was undertaken into the field of detecting drones using radar systems to understand how they work, what's being developed and what impacts this may have socially and environmentally. It was discovered the primary method of detection is using higher frequency radars, typically X or K band and detecting the micro-doppler within the rotors of the drones.

## Introduction

This section of the report details the investigation into waveguides and half-wave dipoles. Research was undertaken in the subject area to understand the theory behind them and how to simulate them.

The simulation software used was Ansys for Students [1]. Ansys is a comprehensive design suite which includes the capabilities to simulate the waveguides and half-wave dipole [2]. The software was chosen based on these capabilities in addition to the fact it is free to download and use for education.

Waveguides are a type of transmission line that allows electromagnetic energy to travel through it [3]. Waveguides come in many shapes, but rectangular waveguides were investigated in this report. Waveguides act as low-pass filters, only allowing a minimum frequency of electromagnetic energy through [3]. This value is known as the dominant cutoff frequency and has a transverse electric (TE) mode of  $TE_{10}$ . The cutoff frequencies for a rectangular waveguide are determined by the width and height.

Half-wave dipoles are a type of antenna that rely on two conductive elements, separated by a gap which is used to feed a voltage to the elements [4]. The total length of the antenna is half the wavelength at the resonant frequency [5]. The gap splits the antenna into two poles, which create alternating, opposite electrical charges [4].

# Task 1: Waveguides

## Simulation Methodology

The two rectangular waveguides for this task were simulated using Ansys for Students. One waveguide used teflon as the dielectric material, while the other used a vacuum. For both of these waveguides all aspects of the simulation were identical apart from the dielectric used.

The values for the width (a) and the height (b) of the rectangle were based on a given student number, in this case that number was 2312456. The width value was the first two numbers of the student number and the height was the third and the fourth number divided by two. This meant:

$$\begin{aligned} \text{Width} &= 23\text{mm} \\ \text{Height} &= \frac{12}{2} = 6\text{mm} \end{aligned}$$

Using these values, a rectangle was created in Ansys. This rectangle served as the rectangular waveform's body in the simulation (**Figure 1**).

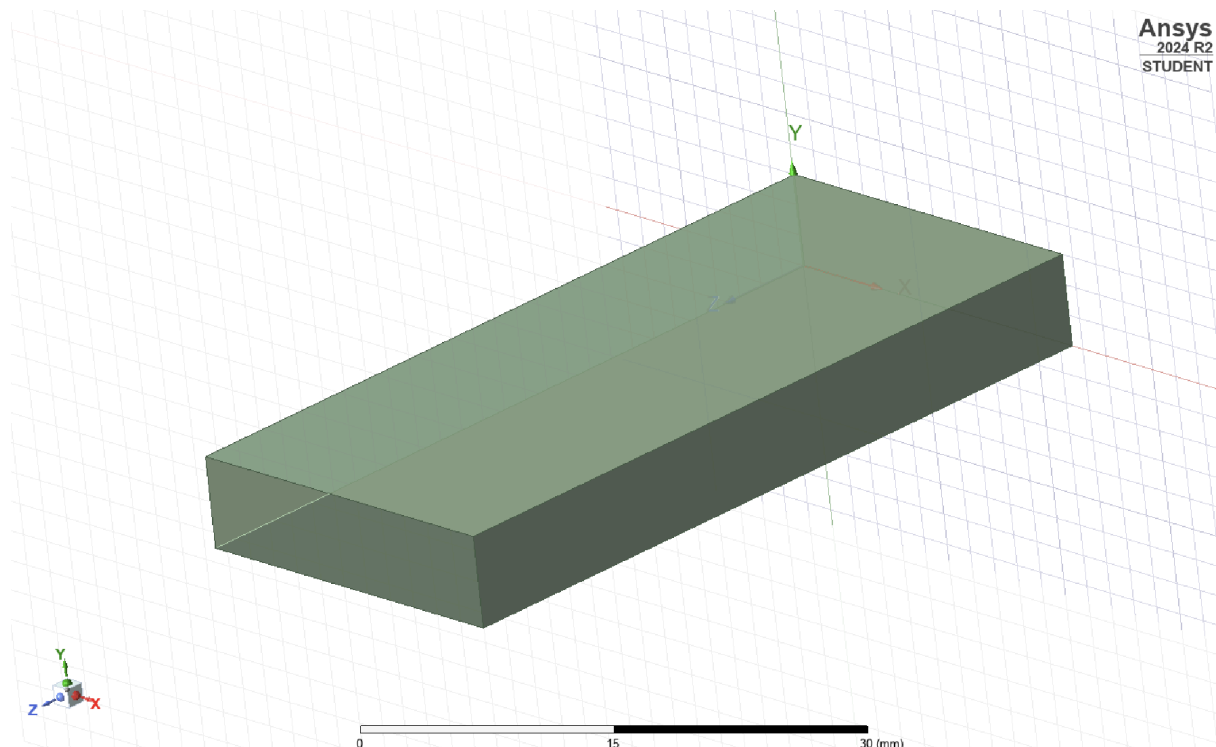


Figure 1: Waveguide Body in Ansys

Wave ports were added to this model to act as boundaries for emitting and absorbing the electromagnetic waves generated in the simulation. These can be seen in **Figure 2** and **Figure 3**:

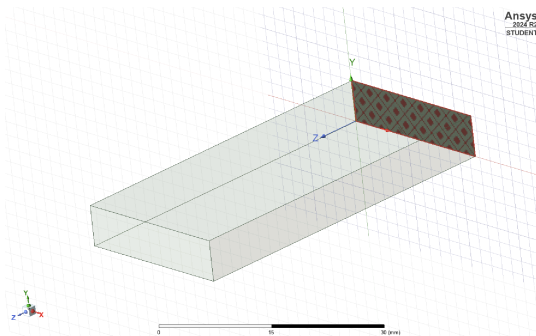


Figure 2: Wave Port 1

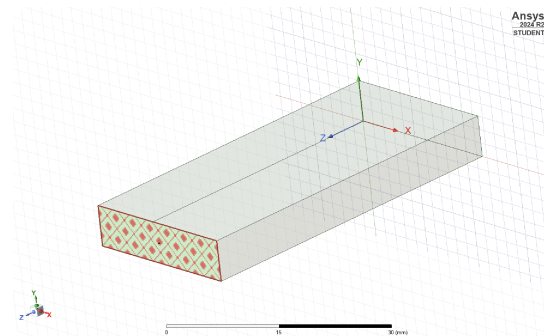


Figure 3: Wave Port 2

After creating these wave ports, the waveguide was simulated to generate the results required for analysis. The simulation was configured with the following parameters (**Figure 4**, **Figure 5**):

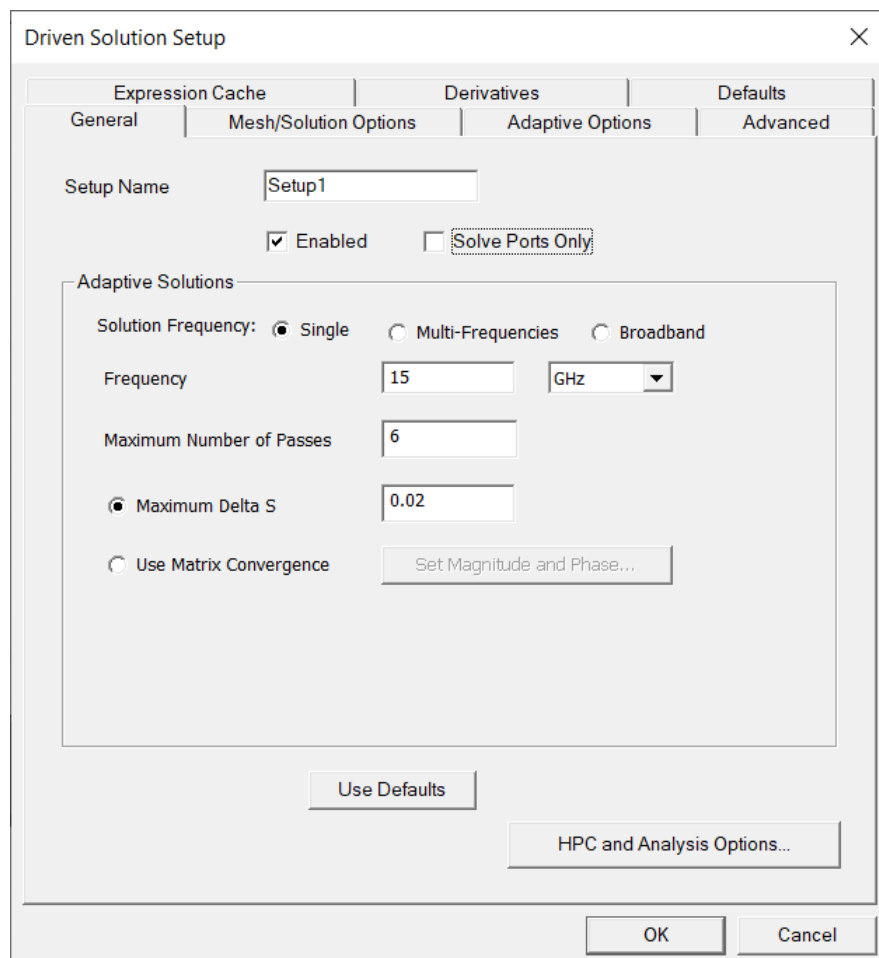


Figure 4: Simulation Configuration 1

Edit Frequency Sweep

General

Interpolation

Defaults

Sweep Name:

Sweep

☒ Enabled

Sweep Type:

Interpolating

Frequency Sweeps [401 points defined]

|   | Distribution | Start | End   |        |     |
|---|--------------|-------|-------|--------|-----|
| 1 | Linear Count | 2GHz  | 30GHz | Points | 401 |

Add Above

Add Below

Delete Selection

Preview ...

3D Fields Save Options

☒ Save Fields (At Basis Freqs)

☐ Save radiated fields only

Time Domain Calculation...

S Matrix Only Solve

☒ Auto

☐ Manual - Allow for frequencies above

1

MHz

OK

Cancel

Figure 5: Simulation Configuration 2

After running the simulation a rectangular plot ( $\gamma$ ), visualisations of the transverse electric (TE), transverse magnetic (TM) and the vectors associated with them were generated.

# Results

## Vacuum Simulation

With the generated results a rectangular plot (gamma) was created for the three modes of the waveguide (**Figure 6**).

This rectangular plot graphically shows the cutoff frequencies for the excitation modes. For this simulation, the cutoff frequencies values were shown as 6.48 GHz, 12.99 GHz and 19.50 GHz. These values were used to validate the simulation's results with the theoretical results that were calculated separately.

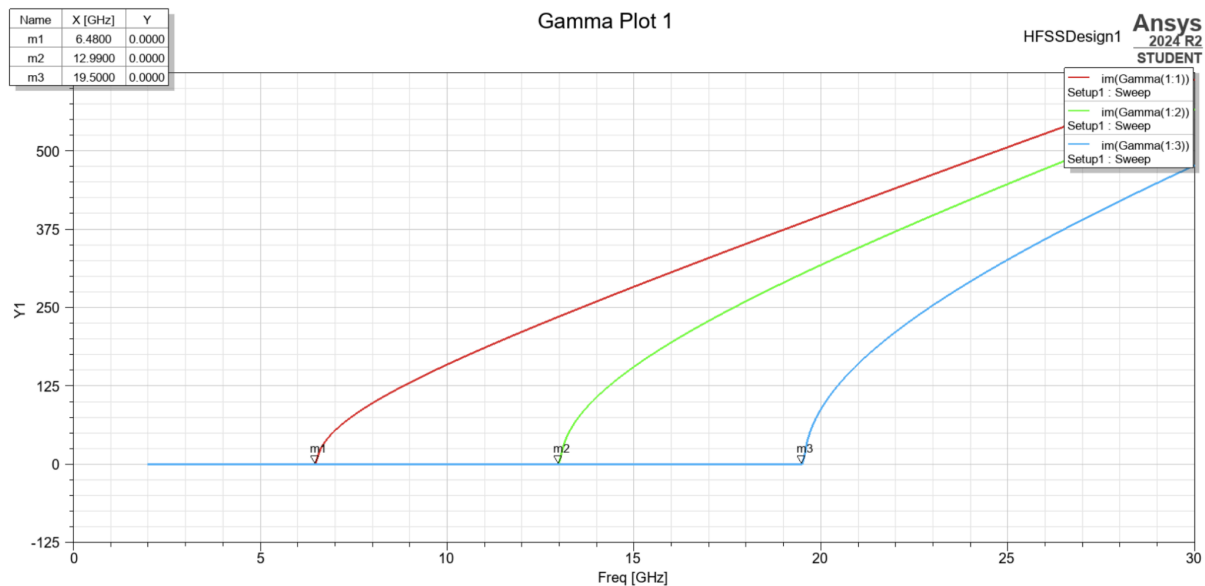


Figure 6: Gamma Plot (Vacuum)

On their own, these values do not indicate what the 3 modes actually are. To figure out this information, the electric and magnetic fields were plotted to identify this information. Using these plots, the modes were identified as  $TE_{10}$ ,  $TE_{20}$  and  $TE_{30}$  based on the amount of propagations in the X or Y axis. The port field vectors can also be observed to identify what modes are present.

The electric fields can be seen in **Figure 7**, **Figure 8** and **Figure 9**:

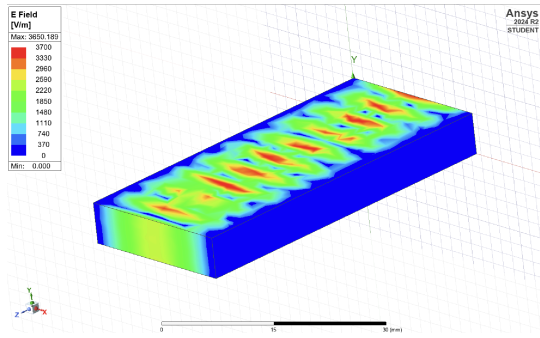


Figure 7: Vacuum Electric Field Mode 1

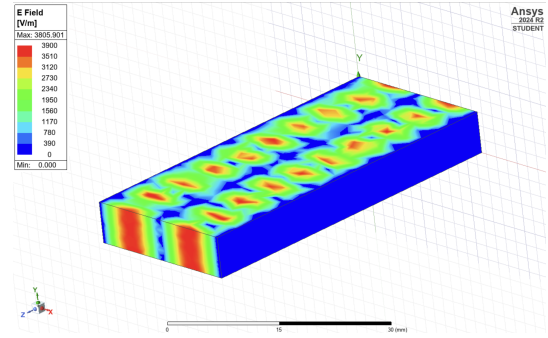


Figure 8: Vacuum Electric Field Mode 2

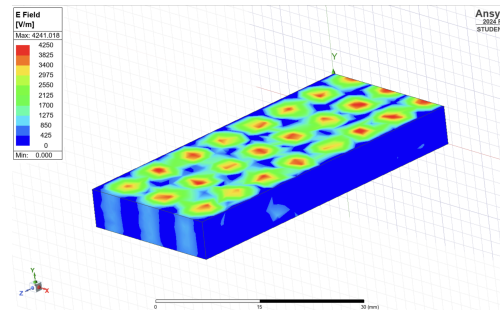


Figure 9: Vacuum Electric Field Mode 3

The plots the magnetic fields can also be seen in **Figure 10**, **Figure 11** and **Figure 12**:

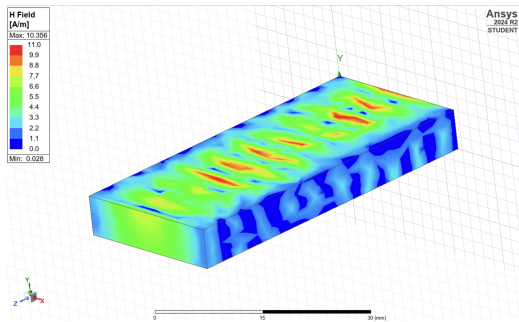


Figure 10: Vacuum Magnetic Field Mode 1

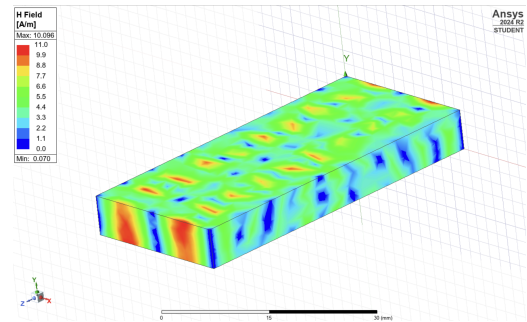


Figure 11: Vacuum Magnetic Field Mode 2

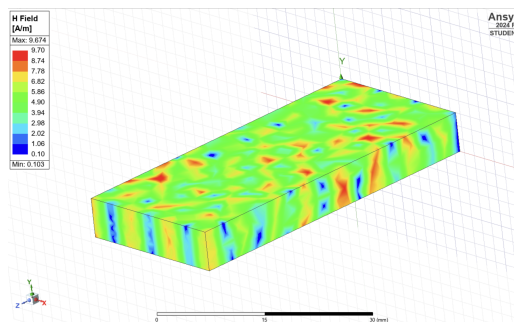


Figure 12: Vacuum Magnetic Field Mode 3

The port field vectors can also be seen below in **Figure 13**, **Figure 14**, **Figure 15**, **Figure 16**, **Figure 17** and **Figure 18**:

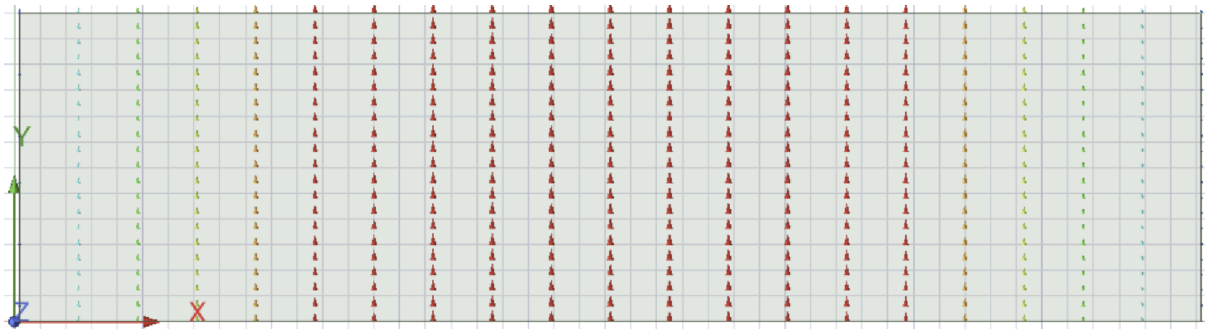


Figure 13: Port 1 mode 1

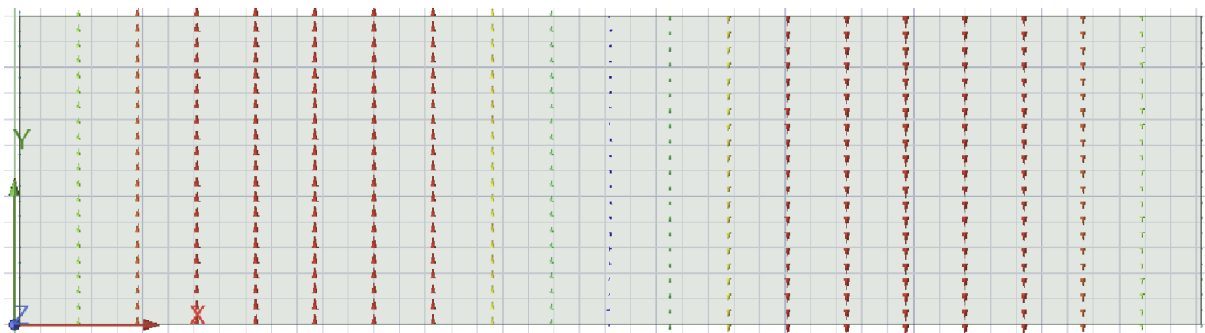


Figure 14: Port 1 Mode 2

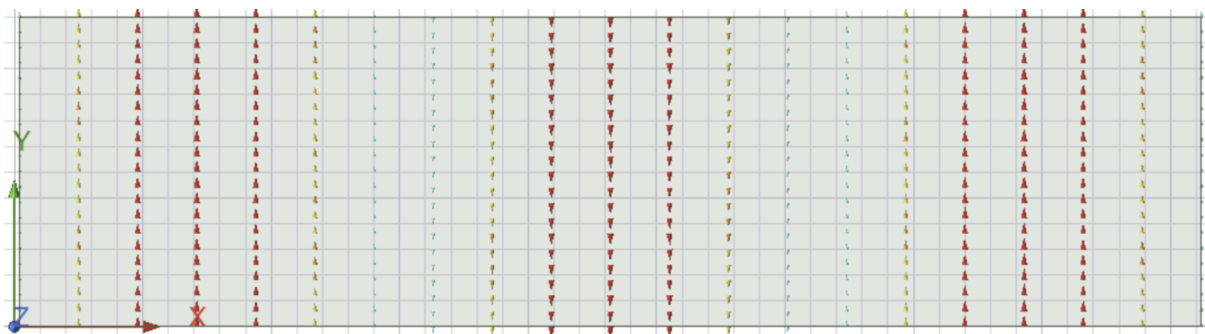


Figure 15: Port 1 Mode 3

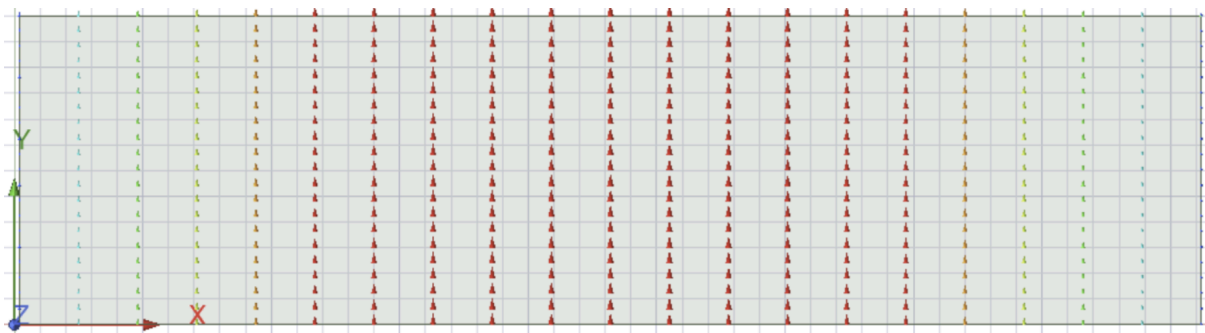


Figure 16: Port 2 Mode 1

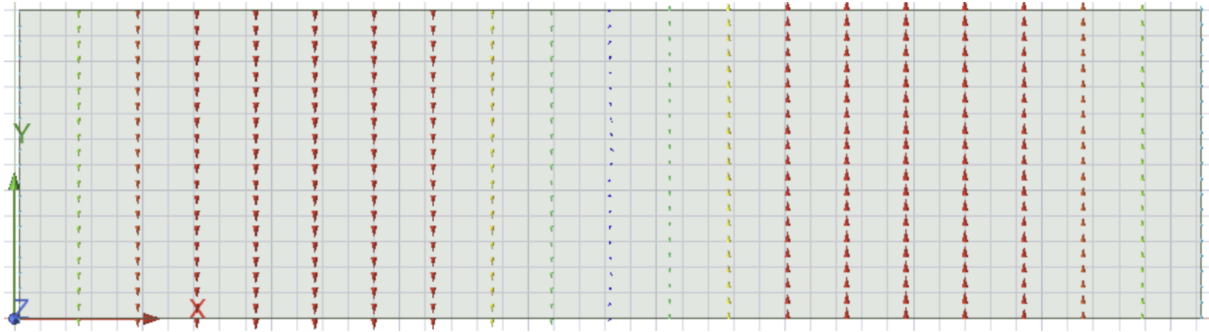


Figure 17: Port 2 Mode 2

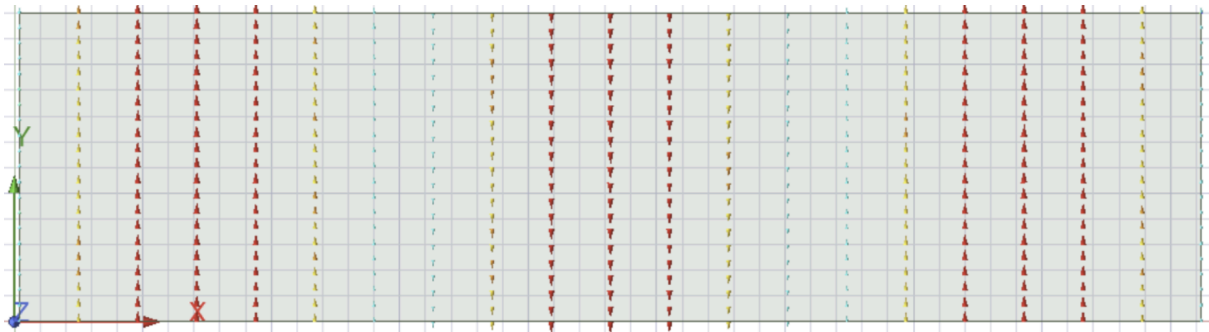


Figure 18: Port 2 Mode 3

## Teflon Simulation

As this simulation for the vacuum and teflon based waveguides had the same method, the analysis carried out was the same as well. However, the  $TE$  modes are based on the ratio between the length width and height, not the dielectric used. Because of this, no further information could be extracted from the analysis apart from the cutoff frequencies. The cutoff frequencies values were shown as 4.41 GHz, 8.93 GHz and 13.48 GHz. This can be seen in **Figure 19**:

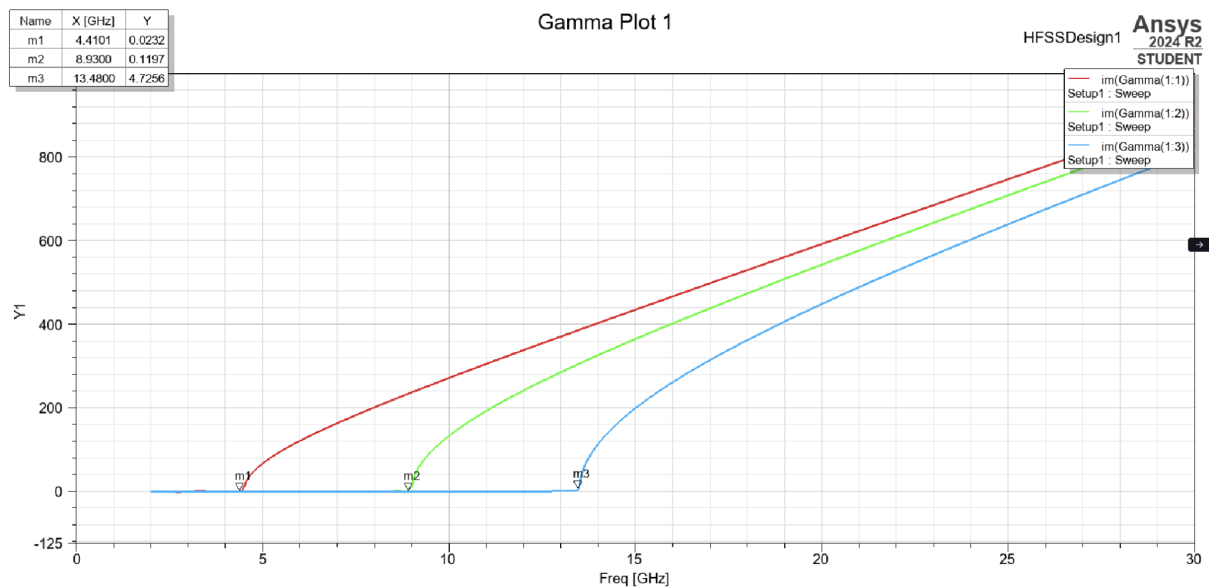


Figure 19: Gamma Plot (Teflon)

The electric fields can be seen in **Figure 20**, **Figure 21** and **Figure 22**:

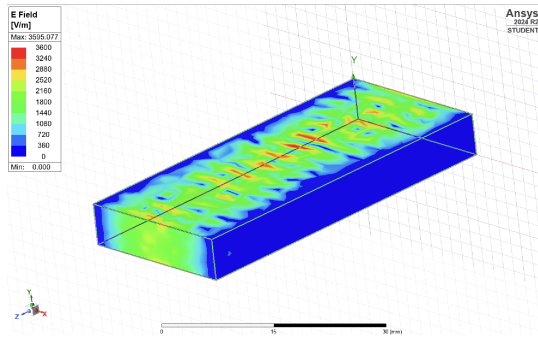


Figure 20: Teflon Electric Field Mode 1

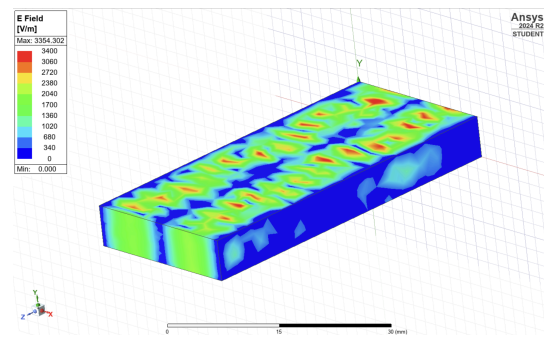


Figure 21: Teflon Electric Field Mode 2

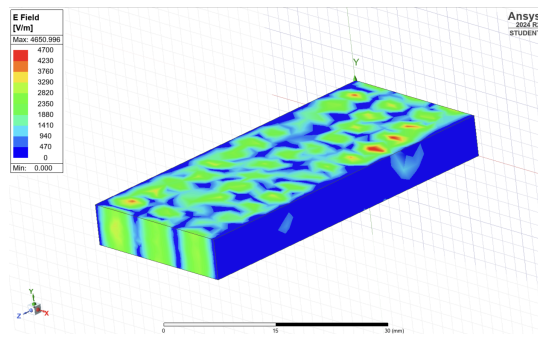


Figure 22: Teflon Electric Field Mode 3

The plots the magnetic fields can also be seen in **Figure 23**, **Figure 24** and **Figure 25**:

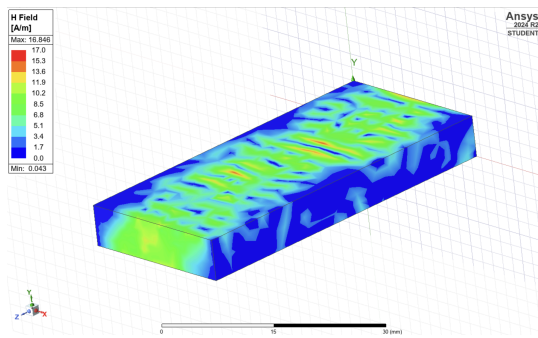


Figure 23: Teflon Magnetic Field Mode 1

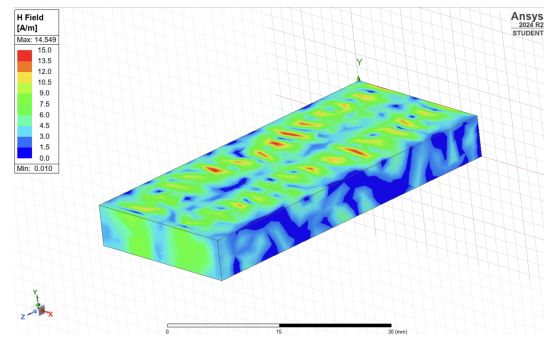


Figure 24: Teflon Magnetic Field Mode 2

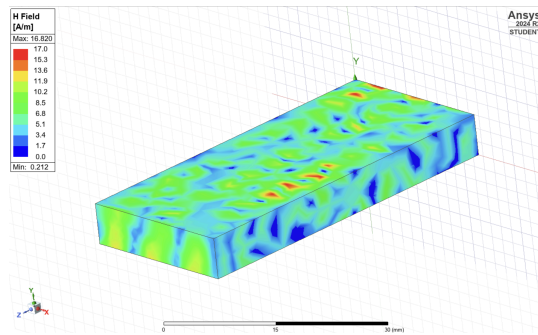


Figure 25: Teflon Magnetic Field Mode 3

The port field vectors can also be seen below in **Figure 26**, **Figure 27**, **Figure 28**, **Figure 29**, **Figure 30**, **Figure 31**:

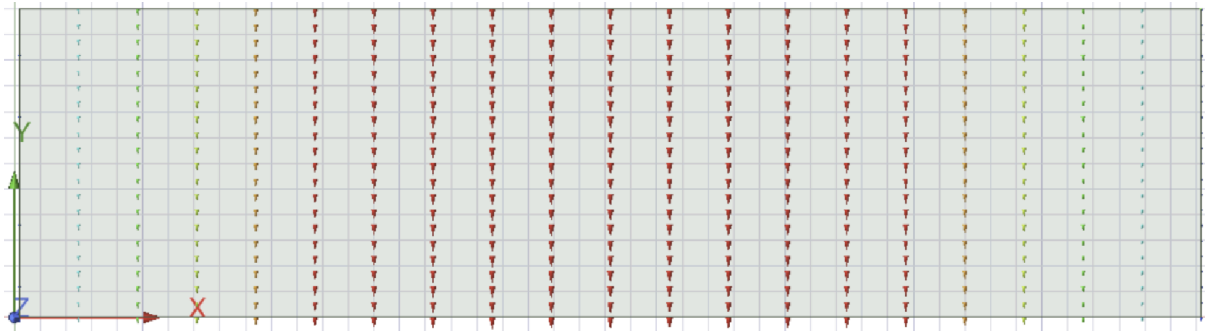


Figure 26: Port 1 mode 1

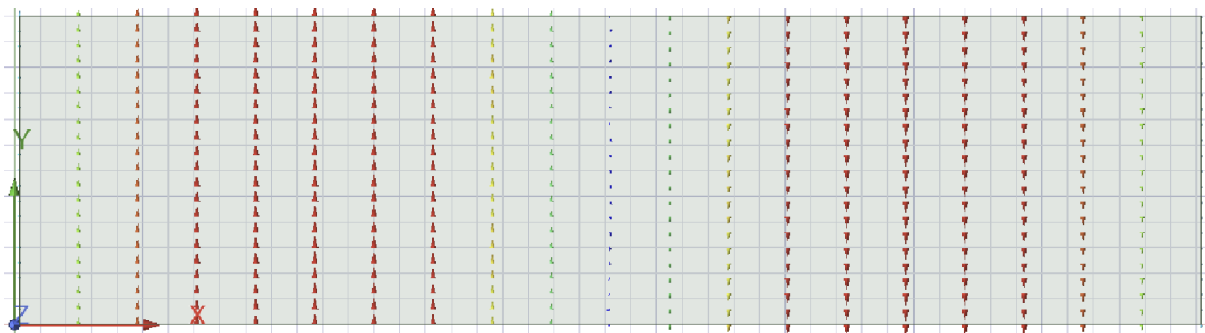


Figure 27: Port 1 Mode 2

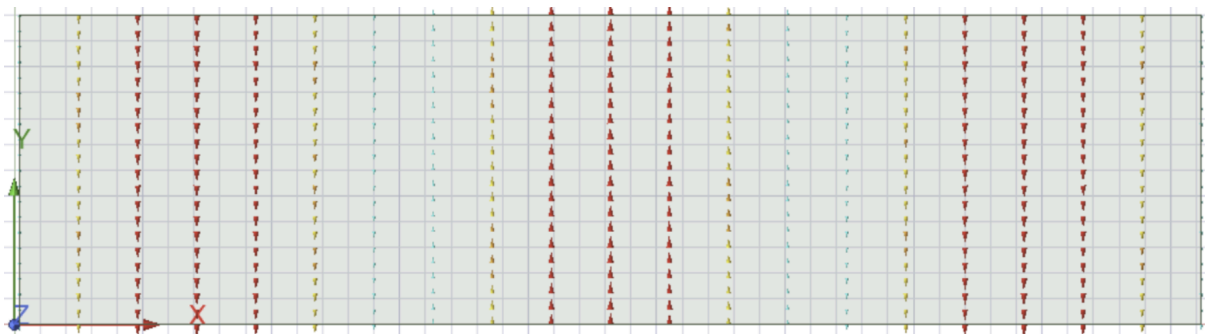


Figure 28: Port 1 Mode 3

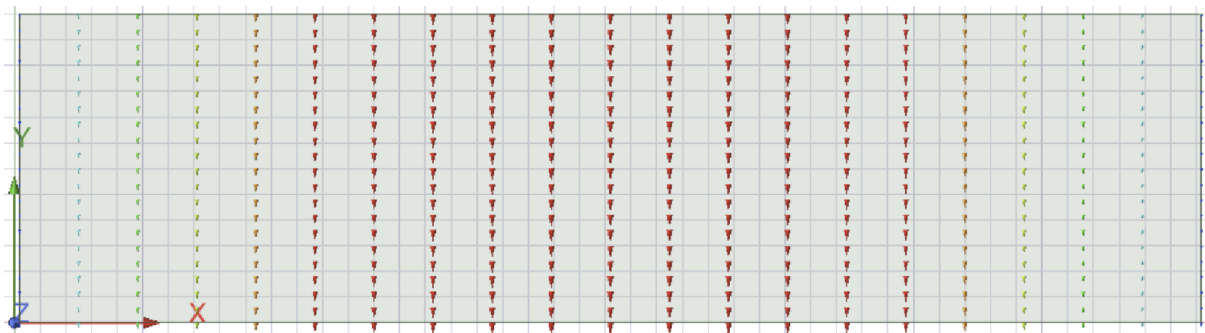


Figure 29: Port 2 Mode 1

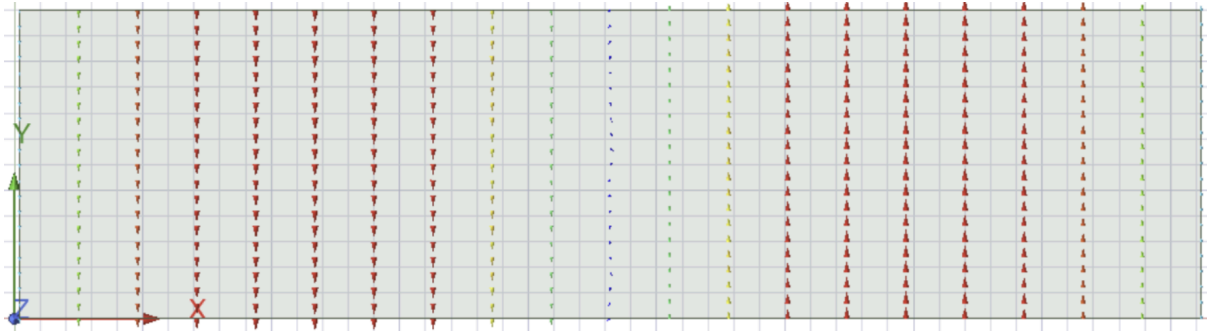


Figure 30: Port 2 Mode 2

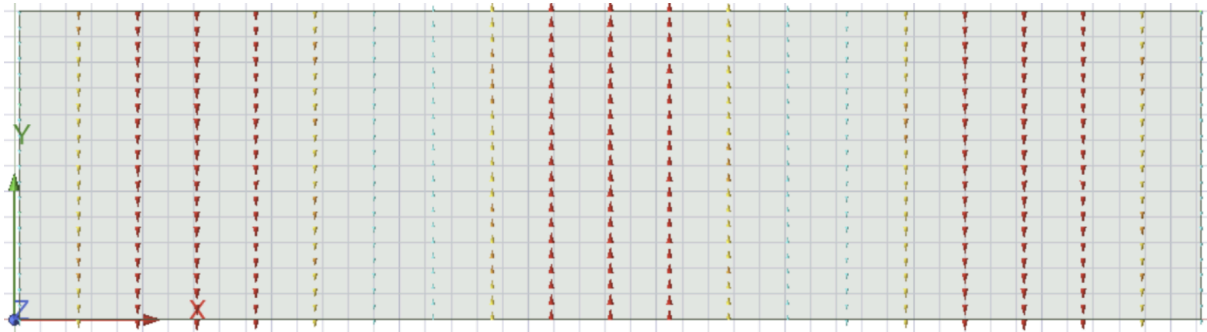


Figure 31: Port 2 Mode 3

## Theoretical Calculations

In Ansys, the first 3 modes are automatically chosen based on their cutoff frequencies. When visualised, the modes were visually inspected to identify modes. However this can also be confirmed mathematically.

The cutoff frequency values are dependent on the ratio of the width and height ( $\frac{a}{b}$ ). A formula can be used to calculate the cutoff frequency based on the values of  $a$ ,  $b$ ,  $m$  and  $n$ . These values dictate the resulting mode,  $TE_{mn}$ . The cutoff frequency for a vacuum based waveguide can be calculated using the formula: [6]

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

Before any further analysis is required, it can be deduced that  $m$  and  $n$  cannot both be zero, thus  $TE_{00}$  would not be one of the modes.

This formula can be used to confirm the mode's cutoff frequency mathematically, thus the mode configuration can be confirmed. It was visually identified the modes should be  $TE_{10}$ ,  $TE_{20}$  and  $TE_{30}$ . The cutoff frequencies with the relevant  $a$ ,  $b$ ,  $m$  and  $n$  values are calculated below:

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{1}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 6.52 \text{ GHz}$$

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{2}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 13.04 \text{ GHz}$$

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{3}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 19.57 \text{ GHz}$$

These calculated values coincide with those in **Figure 6**, confirming the modes were in fact  $TE_{10}$ ,  $TE_{20}$  and  $TE_{30}$ .

The values for the teflon based rectangular waveguide can also be calculated for further confirmation, however not with the exact same formula. The following formula that incorporates the permeability ( $\mu$ ) and permittivity ( $\epsilon$ ) must be used: [6]

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

The relative permeability for teflon is 1 and the relative permittivity is 2.1. These values can be substituted similarly to the previous formula:

$$f_c = \frac{3 \times 10^8}{2\sqrt{2.1}} \sqrt{\left(\frac{1}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 4.50 \text{ GHz}$$

$$f_c = \frac{3 \times 10^8}{2\sqrt{2.1}} \sqrt{\left(\frac{2}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 9.00 \text{ GHz}$$

$$f_c = \frac{3 \times 10^8}{2\sqrt{2.1}} \sqrt{\left(\frac{3}{23 \times 10^{-3}}\right)^2 + \left(\frac{0}{6 \times 10^{-3}}\right)^2} \approx 13.50 \text{ GHz}$$

Again, these values are extremely close to the values seen in **Figure 19**. It is reasonable to accept these values as being correct as well, further confirming the modes being  $TE_{10}$ ,  $TE_{20}$  and  $TE_{30}$ .

## Discussion

The results gathered demonstrate some fundamental principles about waveguides. First, the fact that a waveguide allows electromagnetic energy to travel within itself is proven by the simulation visualisations of the electric and magnetic field modes. Additionally, the comparison of a waveguide and a low-pass filter can be seen by the cutoff frequency, only allowing electromagnetic waves to travel above a certain frequency.

The initial value of the cutoff frequency describes the first  $TE$  mode. This first  $TE$  mode is commonly  $TE_{10}$  in which the waves are always perpendicular to the walls of the waveguide, as seen in **Figure 7**. This first mode is also known as the dominant mode.

The two variations of the rectangular waveguides resulted in different cutoff frequencies. The variation comes from the permittivity of teflon being 2.1, whereas for a vacuum this value is simply 1. This increase in the relative permittivity causes the phase velocity to be reduced.

## **Conclusion**

The investigation into waveguides revealed that the filling of the waveguide impacts the cutoff frequency, but has no effect on the TE modes. It was found that teflon, which has a permittivity of 2.1, has a lower cutoff frequency. This is due to the permittivity slowing down the velocity of the electromagnetic waves. Additionally, calculations to verify the TE modes in the waveguide were carried out to confirm the visual deductions.

## Task 2: Half-Wave Dipole Antenna

### Theoretical Calculations

To simulate the half-wave dipole, some initial values had to be calculated first. These values were the length of the antenna and the operating frequency. The length was used for creating the actual model of the antenna and the frequency was used for simulating the antenna. For a half-wave dipole, the length of the antenna is determined by the following formula: [5]

$$L = \frac{\lambda}{2}$$

The frequency can be calculated using the following formula:

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

The value for  $\lambda$  was also based on the student number, this time the value being the first 3 digits. This meant the wavelength was 231 mm. Using the previously described equations, the length and resonant frequency for the half-wave dipole can be calculated:

$$L = \frac{231}{2} = 115mm$$
$$f = \frac{3 \times 10^8}{231} \approx 1.3 \text{ GHz}$$

## Simulation

For this task a half-wave dipole was simulated using Ansys for Students. Using the length obtained in the theoretical calculations, the following antenna was designed (**Figure 32**):

Ansys  
2024 R2  
STUDENT

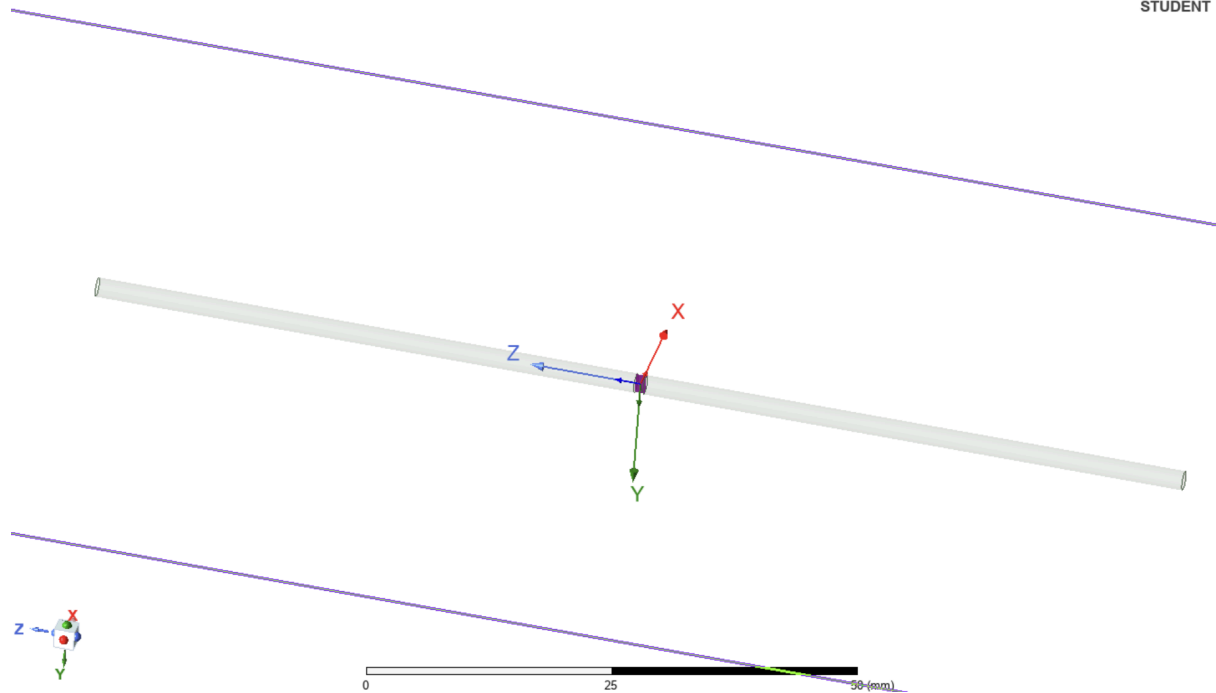


Figure 32: Half-wave dipole in Ansys

This antenna is a perfect electrical conductor (PEC) cylinder with a radius of 1 mm. The length is 231mm as previously described. The lumped port was configured with the standard impedance of  $73 \Omega$  for half-wave dipoles [4]. The simulation solution was then configured with the following values seen in **Figure 33**:

Driven Solution Setup

DC R (Beta)

Expression Cache

Derivatives

Defaults

General

Mesh/Solution Options

Adaptive Options

Advanced

Setup Name

Setup1

☒ Enabled
 ☐ Solve Ports Only

Adaptive Solutions

Solution Frequency:

☒ Single
 ☐ Multi-Frequencies
 ☐ Broadband

Frequency

1.3

GHz

Maximum Number of Passes

6

☒ Maximum Delta S
 

0.02

☐ Use Matrix Convergence
 

Set Magnitude and Phase...

Use Defaults

HPC and Analysis Options...

OK

Cancel

Figure 33: Half-Wave Dipole Solution Setup

After analysing the simulation, an S-Parameter plot was graphed as seen in **Figure 34**:

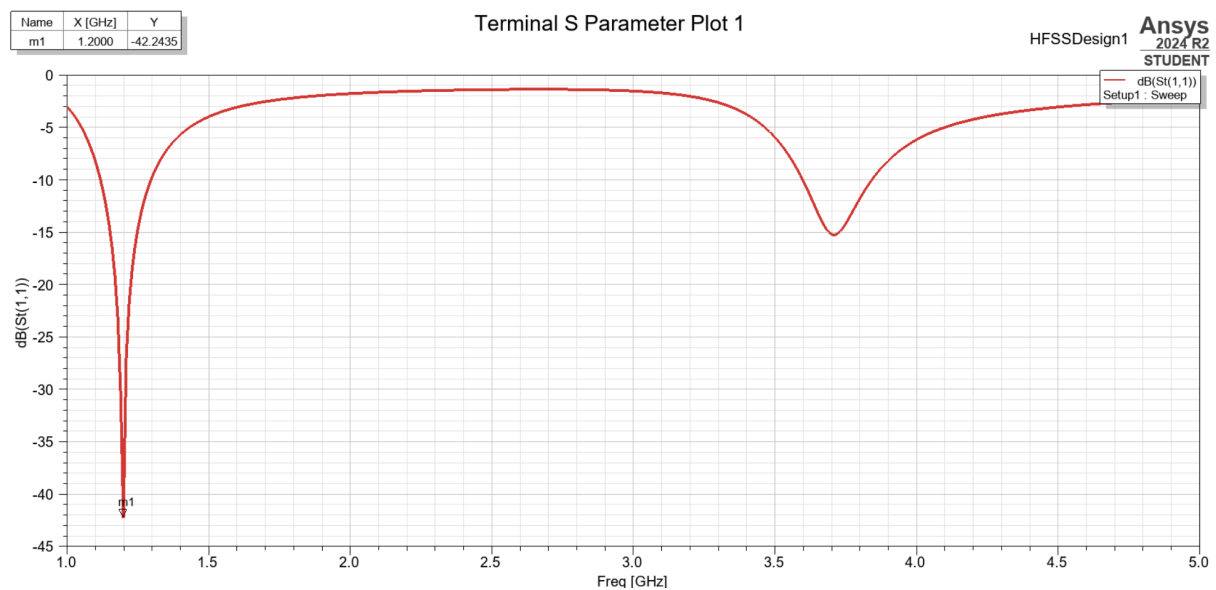


Figure 34: S Parameter Plot

This plot shows the resonant frequency as being 1.2 GHz.

A radiation pattern was also generated, this allowed the maximum magnitude of the directivity being 2.21 dB (**Figure 35**) [7]:

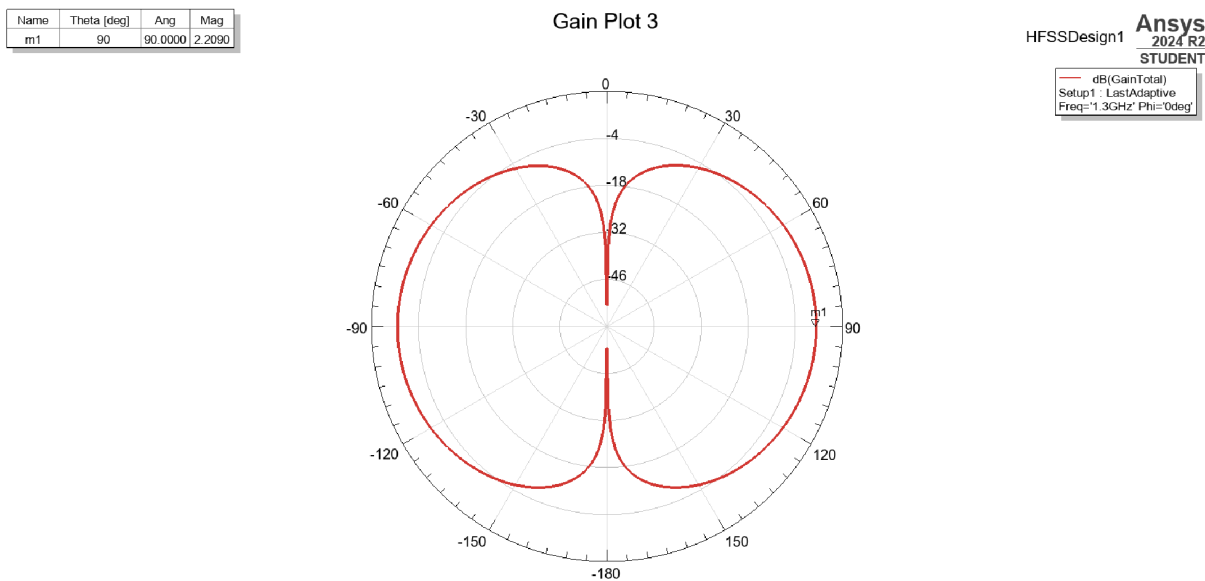


Figure 35: Dipole Radiation Pattern

When plotted in 3d space the maximum total gain is 2.29 dB (**Figure 36**):

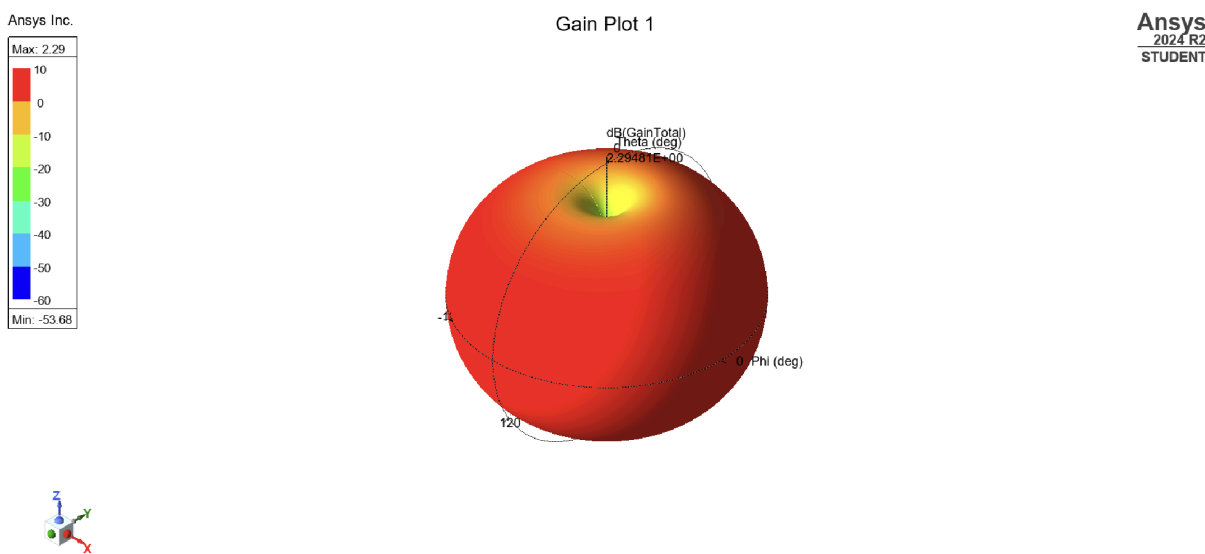


Figure 36: Half-Wave Dipole 3D Plot

## Discussion

The simulation and the theoretical calculations yielded different results for the resonant frequency, despite both using the same values for the wavelength / antenna length. This discrepancy is due to the fringing fields generated by the sudden truncation of the current path at either end of the dipole. There is a large charge concentration at those points and this concentration leads to high density fields. These density fields increase the potential effective length of the antenna (**Figure 37**). [5]

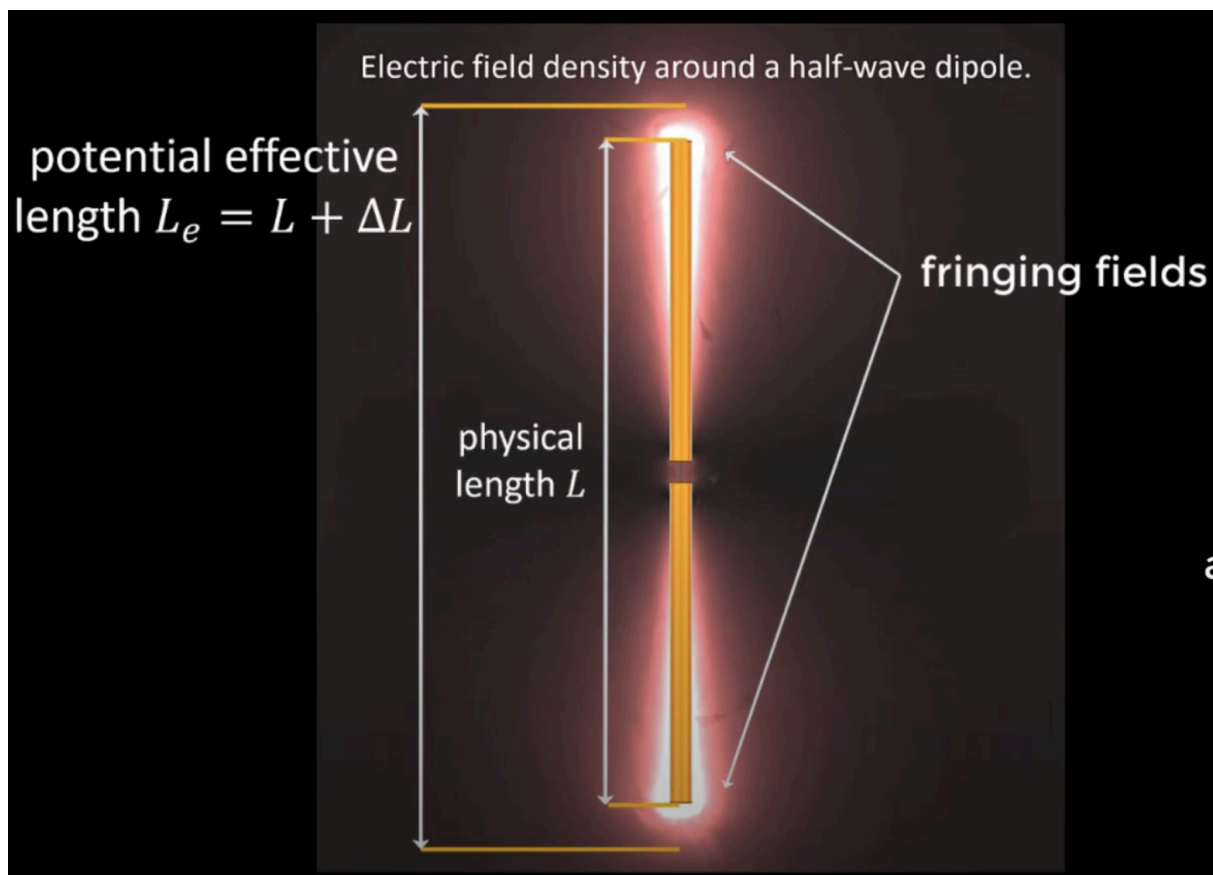


Figure 37: Field Fringes [5]

As  $f = \frac{c}{\lambda}$  and  $\lambda = 2L$ ,  $f = \frac{c}{2L}$  thus  $f$  is inversely proportional to  $L$ . This effect causes the resonant frequency to decrease instead of being at the theoretical value. The physical length of the antenna needs to be reduced by a few mm to achieve a total potential effective length of 115 mm.

## **Conclusion**

The investigation into the half-wave dipole revealed that the theoretical length of the antenna is not necessarily the practical length of the antenna. This is due to the effects of field fringes, which increase the potential effective length, thus decreasing the resonant frequency. It was determined that to achieve a resonant frequency equal to that of the theoretical value, the physical length of the antenna must be reduced.

## Task 3: Drone Detection

### Introduction

Unmanned aerial vehicles (UAV), otherwise known as drones, have seen increased technological development, interest and usage in recent years. Drones can be used for various reasons, however as they are becoming increasingly accessible and advanced, there is an emergence in nefarious uses ranging from: drug smuggling, carrying explosives for warfare and spying. Sometimes drones can be used innocently but still pose security concerns, for instance if flown near an airport a collision with an aircraft may accidentally occur. [8]

It is due to these reasons that countermeasures from drones have also seen an increased development. This section will detail the recent developments in radar technology to detect drones.

### Technological Developments

Traditional radars were designed for the detection of jet aircraft, however the characteristics of these aircraft highly differ from those of a drone. The jet aircraft typically detected usually fly at a high altitude with a high velocity, as well as a large wingspan and metallic body. The characteristics of drones vary, but the most accessible models usually fly at a low altitude and airspeed. This difference in altitude and airspeed is enough to be detected as clutter by radar systems. [9]

To combat this, higher resolution radars have been developed, typically operating in the X band or K bands which are more sensitive to finer details. Within these frequencies, micro-doppler signatures can be detected. Micro-doppler signatures are generated due micro motion within various targets such as wings flapping by a bird, or in this case, the rotors of a drone rotating at a high speed. [10]

As the rotors of a drone spin at a high velocity, they generate a complex and time-varying Doppler shift pattern (**Figure 38**). As these distinct pulses are not possibly generated by a bird, they are a reliable way to distinguish between the two.

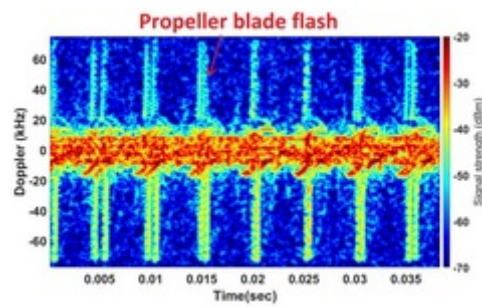


Figure 38: Micro-Doppler of a Drone [10]

## Possible improvements

The large, metallic body of jet aircraft results in a large radar cross section (RCS). The RCS of an aircraft represents the effective area that intercepts and scatters radar energy back towards the radar [11]. An example of an RCS plot can be seen in **Figure 39**:

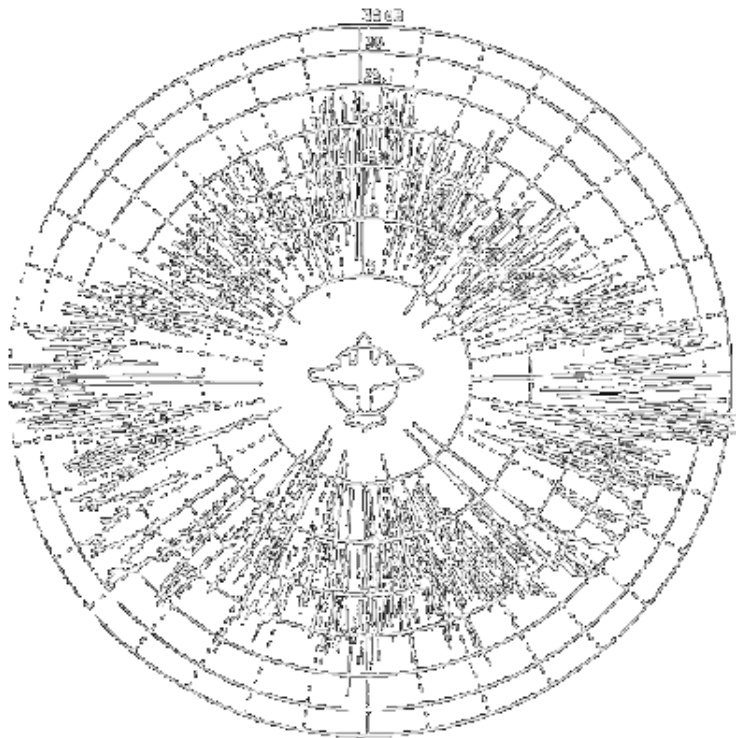


Figure 39: RCS of a B-26 Invader

However, drones are typically really small, for instance the size of a bird, which is an extreme contrast to existing technology. Additionally, the materials used for drones are typically plastic which radar signals usually pass through, thus only really small components such as the batteries or motors will reflect radar energy [12].

Due to the extremely small reflection of the signal, drones are often disregarded as clutter and not used by the radar system. [9] Most research for detecting drones is focused around micro-doppler as it is often more reliable than the RCS due to the similarity between that and birds [13]. There have been developments using convolutional neural networks (CNN), however as this is a new and emerging technology faults may still be prevalent [8].

Through further development of this detection method, improvements could potentially be deployed to already existing X and K band radar systems without a complete redesign of the system.

## **Societal and Environmental Impacts**

As drones continue to be developed and become more accessible, there is inevitably going to be an increase in bad actors acquiring these drones. Because of this, drone detection systems are becoming increasingly valuable as a way to counter these bad actors and keep the general public safe. Additionally, where drones may be used in warfare the detection of them is becoming increasingly important.

Environmentally, however, these radar systems come with a variety of negative impacts that must be considered. These radar systems consume a large amount of power to operate and cool, requiring more energy to be generated which may result in the use of non-renewable energy sources. The entire manufacturing process will require raw materials gathered from mining and the transport of the radar systems will generate carbon emissions, both negatively impacting the environment.

## **Conclusion**

Drone detection systems using radar are being developed to counter the recent increase in drone activity. These systems are using already established methods of detecting jet aircraft and adapting them to be able to detect drones. However, traditional radar systems that are not designed for detecting drones are still vulnerable to them, so in places of importance drone detection radar systems may become more prolific.

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