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Analysis of Electromagnetic Wave Propagation

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Ordnance, Munitions and Explosives (Safety)

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## **Abstract**

This report investigates the electromagnetic behaviour of a rectangular waveguide and a printed antenna using both theoretical analysis and simulation techniques. In Task 1, the dominant  $TE_{10}$  mode was identified, and cut-off frequencies were calculated and simulated for waveguides filled with vacuum and Teflon. The results showed close agreement between theoretical and simulated values, demonstrating the effect of dielectric materials on wave propagation. Task 2 focused on the design and analysis of a printed antenna operating at 1.35 GHz. The simulated resonant frequency was 1.22 GHz, and the radiation pattern displayed omnidirectional characteristics in the azimuthal plane, as expected.

## Abbreviations

|           |                                    |
|-----------|------------------------------------|
| dB        | Decibel                            |
| dBi       | Decibel Isotropic                  |
| GHz       | Gigahertz                          |
| Hz        | Hertz                              |
| MHz       | Megahertz                          |
| HFSS      | High-Frequency Structure Simulator |
| $Z_o$     | Impedance                          |
| $S_{11}$  | Reflection Coefficient             |
| RL        | Return Loss                        |
| $TE_{10}$ | Transverse Electric Mode 10        |
| PEC       | Perfect Electric Conductor         |

## Figures

|                                                                           |    |
|---------------------------------------------------------------------------|----|
| Figure 1 - Electromagnetic Wave .....                                     | 1  |
| Figure 2 - Flann Series 441/445 Waveguide .....                           | 2  |
| Figure 3 - Transverse Electric Mode .....                                 | 3  |
| Figure 4 - Transverse Magnetic Mode.....                                  | 3  |
| Figure 5 - Omnidirectional Radiation Pattern .....                        | 4  |
| Figure 6 - Omnidirectional Radiation Pattern vertical cross-section ..... | 4  |
| Figure 7 - Rectangular Waveguide Dimensions .....                         | 5  |
| Figure 8 - Task 1A - Port 1 Mode 1 ( $n=0, m=1$ ).....                    | 8  |
| Figure 9 - Rectangular Waveguide TE Modes .....                           | 8  |
| Figure 10 - Task 1A - Port 1 Mode 2 ( $n=0, m=2$ ).....                   | 9  |
| Figure 11 - Task 1A - Port 1 Mode 3 ( $n=0, m=3$ ).....                   | 9  |
| Figure 12 - Task 1A - Electric field magnitude.....                       | 10 |
| Figure 13 - Task 1A - Electric field vectors.....                         | 10 |
| Figure 14 - Task 1A - Magnetic field magnitude.....                       | 11 |
| Figure 15 - Task 1A - Magnetic field vectors .....                        | 11 |
| Figure 16 – Task 1a Gamma Plot .....                                      | 13 |
| Figure 17 - Task 1b - Port 1 Mode 1 ( $n=0, m=1$ ) .....                  | 14 |
| Figure 18 - Task 1b - Port 1 Mode 2 ( $n=0, m=2$ ) .....                  | 15 |
| Figure 19 - Task 1b - Port 1 Mode 3 ( $n=0, m=3$ ) .....                  | 15 |
| Figure 20 - Task 1b - Electric field magnitude .....                      | 16 |
| Figure 21 - Task 1b - Electric field vectors .....                        | 16 |
| Figure 22 - Task 1b - Magnetic field magnitude .....                      | 17 |
| Figure 23 - Task 1b - Magnetic field vectors .....                        | 17 |
| Figure 24 - Task 1b Gamma Plot .....                                      | 18 |
| Figure 25 - Task 2 - Antenna radiation pattern.....                       | 20 |
| Figure 26 - Task 2 - S-parameter plot .....                               | 20 |

## Tables

Table 1 - Task 1a - Ansys vs Calculation table ..... 22

Table 2 - Task 1b - Ansys vs Calculation table ..... 22

## Equations

Equation 1 - Cut-off frequency ..... 13

Equation 2 - Velocity of light for different materials ..... 19

Equation 3 - Dipole antenna length ..... 21

Equation 4 - Antenna operating frequency ..... 21

# Table of Contents

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| 1. Introduction .....                                                 | 1  |
| 1.1. What is Electromagnetic Radiation.....                           | 1  |
| 1.2. What is a waveguide .....                                        | 2  |
| 1.2.1. Types of Waveguides .....                                      | 2  |
| 1.2.2. Cut Off Frequencies.....                                       | 3  |
| 1.2.3. Transverse modes .....                                         | 3  |
| 1.3. What is an Antenna .....                                         | 4  |
| 2. Method .....                                                       | 5  |
| 2.1 Task 1a & 1b .....                                                | 5  |
| 2.2 Task 2.....                                                       | 6  |
| 3. Results .....                                                      | 7  |
| 3.1 Task 1a Data .....                                                | 7  |
| 3.1.1 Port Field Displays .....                                       | 8  |
| 3.1.2 Task 1a Electric and Magnetic Field Vectors and Magnitude ..... | 10 |
| 3.1.3 Task 1a Cut-off Frequency .....                                 | 13 |
| 3.1.4 Task 1a Cut-off Frequency Calculation .....                     | 13 |
| 3.2 Task 1b.....                                                      | 14 |
| 3.2.1 Task 1b Port Field Display .....                                | 14 |
| 3.2.2 Task 1b Electric and Magnetic Field Vectors and Magnitude ..... | 16 |
| 3.2.3 Cut-off Frequency .....                                         | 18 |
| 3.2.4 Task 1b Cut-off Frequency Calculation .....                     | 19 |
| 3.3 Task 2 Data .....                                                 | 20 |
| 3.3.1 Task 2 Calculations .....                                       | 21 |
| 4. Discussion.....                                                    | 22 |
| 4.1 Task 1A & 1B .....                                                | 22 |
| 4.2 Task 2 .....                                                      | 22 |
| 5. Conclusion .....                                                   | 23 |
| 6. References.....                                                    | 24 |
| 7. Appendix 1 .....                                                   | 25 |

# 1. Introduction

## 1.1. What is Electromagnetic Radiation

Electromagnetic radiation is a form of energy made up of oscillating electric and magnetic fields that propagate through space at the speed of light. These fields are perpendicular to each other and the direction of wave travel, forming a transverse wave. The electric field is a region around a charged particle where it exerts a force on other charges, attracting opposite charges and repelling like ones. It is defined as the force per unit positive test charge and is measured in volts per meter (V/m).

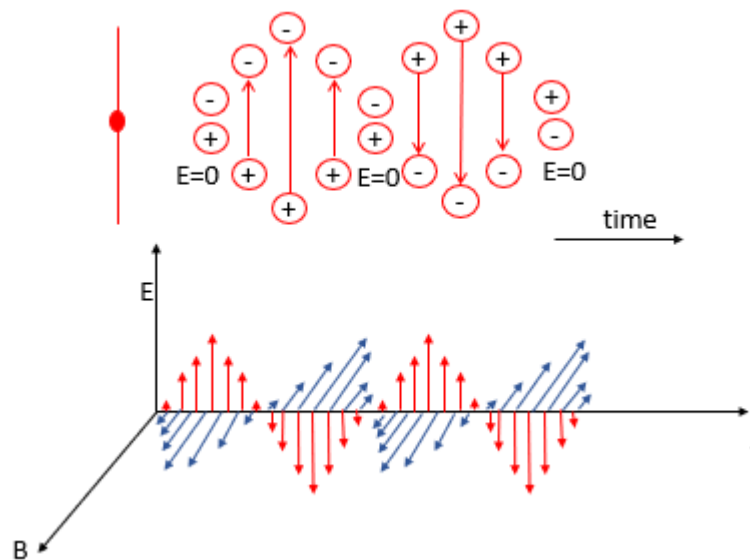


Figure 1 - Electromagnetic Wave

The magnetic field, on the other hand, arises around magnets or moving charges and exerts a force on moving charged particles. Its strength depends on the charge, velocity, and angle of motion. The interaction between electric and magnetic fields is fundamental to electromagnetic radiation as a changing magnetic field induces an electric field (Faraday's Law), and a changing electric field produces a magnetic field (Ampère-Maxwell Law). These interactions allow electromagnetic waves (e.g. radio waves, microwaves, visible light) to be generated and transmitted through both vacuum and matter.

## 1.2. What is a waveguide

A waveguide is a structure that directs electromagnetic waves with minimal energy loss by confining the transmission to a single direction. It enables efficient propagation of high-frequency waves such as microwaves, radio waves, and infrared radiation. In contrast, low-frequency waves ( $>1$  MHz) typically use parallel transmission lines or coaxial cables. Dielectric waveguides are employed for higher radio frequencies and optical guidance. A typical waveguide consists of a pipe made from a Perfect Electric Conductor (PEC) and filled with a perfect insulator. Waveguides are commonly used to transmit power between components in systems such as radios, radars, and optical devices. In simulations, the waveguide is assumed to be infinitely long, oriented along the z-axis, and uniform throughout its length.



Figure 2 - Flann Series 441/445 Waveguide

### 1.2.1. Types of Waveguides

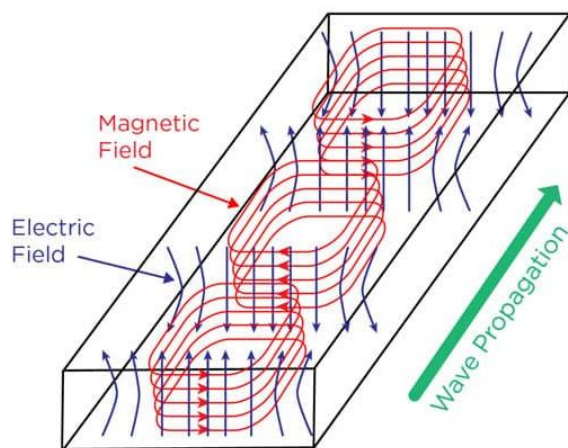
Waveguides come in various types, each suited to different frequency ranges and applications. Metal waveguides, typically made from a PEC, are commonly used for microwave transmission. These can be rectangular or cylindrical, with rectangular waveguides being the most widely used due to their simpler mode structure. Dielectric waveguides, made from non-conductive materials like Teflon, are used for higher-frequency applications such as optical communication. These include dielectric slabs and optical fibres, which are widely used in telecommunications for their low loss and high bandwidth.

### 1.2.2. Cut Off Frequencies

Waveguides have a specific cut-off frequency, which determines the minimum frequency at which signals can propagate through them. Signals with frequencies above this cut-off are allowed to propagate efficiently, while those below it experiences high reflection and are effectively blocked. This characteristic makes waveguides act as high-pass filters. They guide electromagnetic waves by reflecting them within a confined structure, such as a hollow metallic pipe or a dielectric medium, ensuring controlled and efficient transmission.

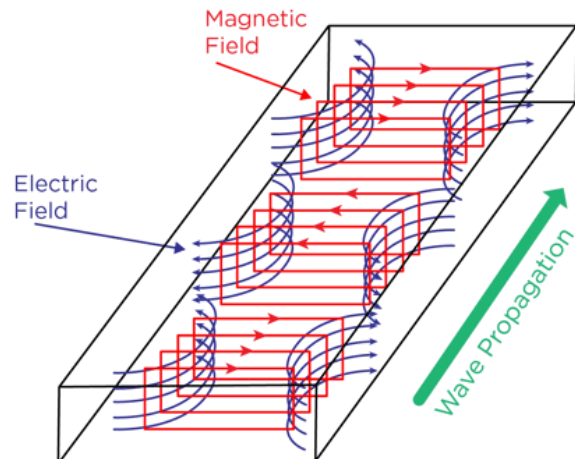
### 1.2.3. Transverse modes

Transverse modes describe the distribution of electromagnetic fields (electric and magnetic) in the cross-sectional plane perpendicular to the wave propagation direction. These modes are essential for the behaviour of radio, microwave, and optical signals confined within waveguides or optical fibres. The main types of transverse modes include Transverse Electromagnetic (TEM), Transverse Electric (TE), Transverse Magnetic (TM), and Hybrid modes [1].



**TE Mode**

Figure 3 - Transverse Electric Mode



**TM Mode**

Figure 4 - Transverse Magnetic Mode

TEM modes have both electric and magnetic fields entirely transverse to the propagation direction, typically seen in coaxial cables. TE modes, common in rectangular waveguides, have no electric field along the propagation axis, while TM

modes lack a magnetic field in that direction. Hybrid modes combine features of both, with electric and magnetic components along the wave path. These modes are essential for efficient wave guidance in waveguides and optical fibres.

### 1.3. What is an Antenna

An antenna converts electric current into electromagnetic waves for transmission and vice versa for reception. It can serve as a transmitter, receiver, or both, depending on the setup. Antenna design varies based on its use and operating frequency, with common applications in broadcasting, wireless communication, radar, and satellites. Signal loss can occur due to transmission line properties, reflection mismatches, and inefficient design, leading to interference and power loss. Proper impedance matching reduces these issues and enhances performance. Antennas are classified by structure, frequency, directionality, polarisation, and application, with performance illustrated through radiation patterns such as isotropic, omnidirectional, and directional [1].

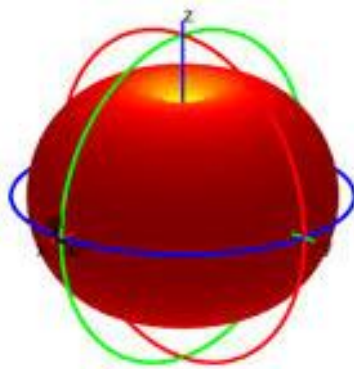


Figure 5 - Omnidirectional Radiation Pattern

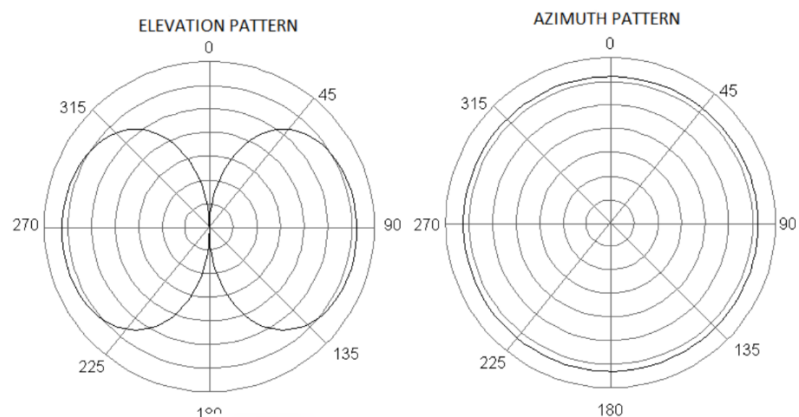


Figure 6 - Omnidirectional Radiation Pattern vertical cross-section

An isotropic radiation pattern radiates evenly in all directions but is theoretical, as real antennas have some directivity. Omnidirectional antennas approximate this by providing 360° coverage in one plane, with low gain and directivity. They're ideal for applications like FM radio and TV broadcasting, often used in monopole and dipole designs.

## 2. Method

### 2.1 Task 1a & 1b

The waveguide dimensions are defined as width (a), height (b), and a fixed length of 50 mm along the Z-axis. Dimensions “a” and “b” were obtained using the student identification number, as shown below:

2114212

$a$  = first two numbers of the student ID (2114212)      Length: 50mm

$\underline{a = 21}$       Width (a): 21mm

$b = \frac{\text{3rd and 4th number of the student ID}}{2}$       Height (b): 7mm

$$b = \frac{14}{2} \quad \underline{b = 7}$$

| Name              | Value      | Unit | Evaluated Value    |
|-------------------|------------|------|--------------------|
| Command           | CreateBox  |      |                    |
| Coordinate Sys... | Global     |      |                    |
| Position          | 0 ,-0.2 ,0 | mm   | 0mm , -0.2mm , ... |
| XSize             | 21         | mm   | 21mm               |
| YSize             | 7          | mm   | 7mm                |
| ZSize             | 50         | mm   | 50mm               |

Figure 7 - Rectangular Waveguide Dimensions

Once the dimensions are known, the waveguide can be modelled using Ansys Electronics with the High-Frequency Structure Simulator (HFSS) software plug-in [2] [3].

Before modelling, the solution type must be configured. Network analysis was chosen for its simplicity and flexibility in adjusting excitation values post-simulation. Secondly, select model, not terminal. “Model” refers to the entire 3D structure being simulated, while “Terminal” defines the electrical connection points or ports.

Next, plot a rectangle with the previously calculated dimensions. The material properties of this rectangle is a vacuum which must be applied. The material properties

are set to vacuum, and the transparency is set to 0.8 for improved internal visibility. A PEC boundary is applied to represent the conducting walls of the waveguide. Excitations are then assigned at the ports, providing fields and S-parameters that describe how radio frequency signals are transmitted and reflected [4] [5].

Wave ports are configured for three modes, with the characteristic impedance set to “Zpi” for efficiency and accuracy. The Full Port Impedance is set to 50 ohms. The wave ports are verified by expanding the excitations section, where patterns will be displayed. The adjacent excitation is configured similarly [6].

In the analysis section, a solution setup is added with the operating frequency set to 7 GHz, and the maximum number of passes set to 60 for accurate results. A frequency sweep is configured with a range from 2 GHz to 30 GHz and 401 points, using interpolating distribution for faster, accurate simulation. "Save Fields" is selected at Basis Frequencies to store the data.

After validating the model, a solution data report is generated to observe the cutoff frequencies. A gamma plot is created to mark the cutoff frequency. For further analysis, a Port Field Display is generated to visualise the electric fields at each port, and the Magnitude of Electric Field (Mag\_E) and Magnetic Field (Mag\_H) distributions are plotted to understand the waveguide's behaviour.

## **2.2 Task 2**

A new project was initiated in Ansys HFSS using the modal solution type, with units set to millimetres. A cylinder was created and its properties adjusted: radius set to 1 mm, height to 50 mm, and cantered at (0, 0, -25). The material was changed to PEC and its transparency adjusted to 0.8 for better visibility.

To form a gap in the cylinder, the original geometry was duplicated. The duplicate retained the 1 mm radius, but its height was reduced to 1 mm, with the centre positioned at (0, 0, -0.5). This smaller cylinder was assigned the material 'vacuum' and the same transparency. Using the Boolean subtraction tool, the smaller cylinder was

subtracted from the larger one, resulting in two PEC sections separated by a 1 mm gap.

A lumped port was then added across this gap. The YZ plane was selected at the gap location, and the port was defined as a modal lumped port with an impedance of 50 ohms. An integration line was drawn vertically across the port surface to complete the port setup.

An open region was added to simulate free space for radiation. The solution setup was configured with a frequency near the operating point and up to 99 adaptive passes. A frequency sweep from 1 GHz to 7.5 GHz was then defined.

After validating the setup, the project was run. The S-parameter results were plotted and recorded, followed by the 3D polar plot of the radiation pattern to visualize the antenna's performance [7].

## **3. Results**

### **3.1 Task 1a Data**

This section shows the model of a rectangular waveguide with PEC walls and a vacuum-filled interior. The two wave ports at either end of the waveguide were analysed across three different modes. The magnitudes and vectors of the electric and magnetic fields were obtained, and the cutoff frequency was plotted using a gamma plot.

### 3.1.1 Port Field Displays

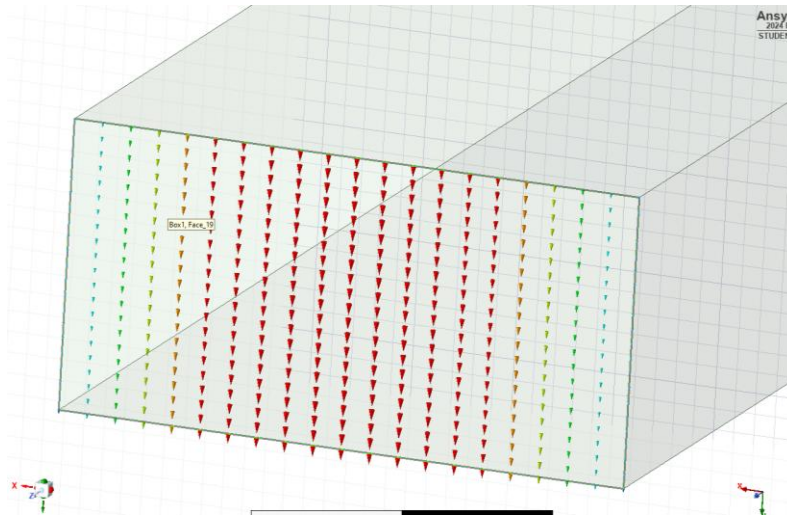


Figure 8 - Task 1A - Port 1 Mode 1 ( $n=0$ ,  $m=1$ )

As shown in Figure 8, the electric field lines displayed in the port field visualisation indicate that Mode 1 corresponds to the  $TE_{10}$  mode, meaning the electric field lines are perpendicular to the direction of propagation, while the magnetic field lies along the direction of propagation.

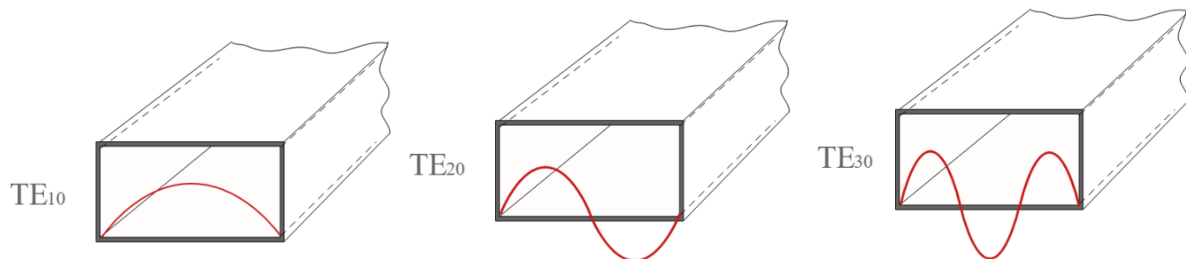


Figure 9 - Rectangular Waveguide TE Modes

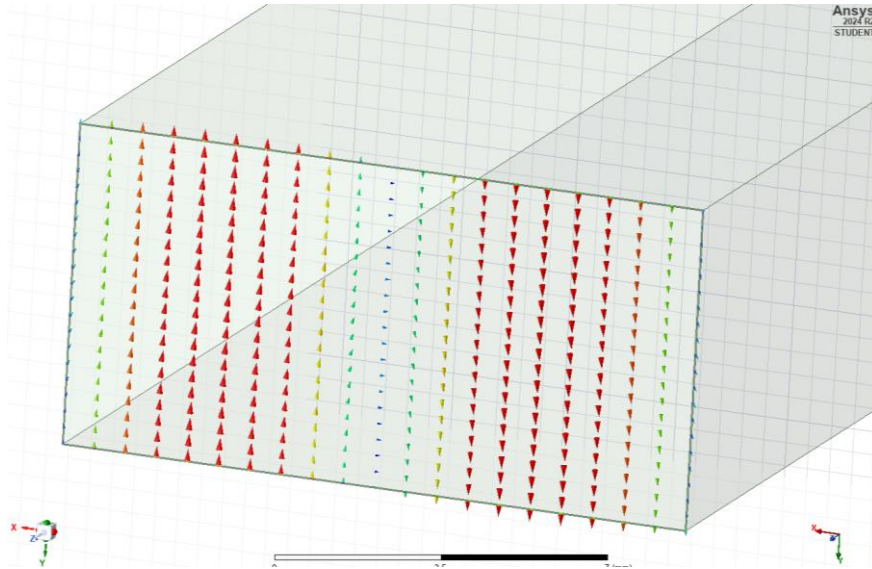


Figure 10 - Task 1A - Port 1 Mode 2 ( $n=0$ ,  $m=2$ )

As shown in Figure 2, Port 1 Mode 2 can be identified as the  $TE_{20}$  mode, as it exhibits two field maxima along the x-axis and none along the y-axis.

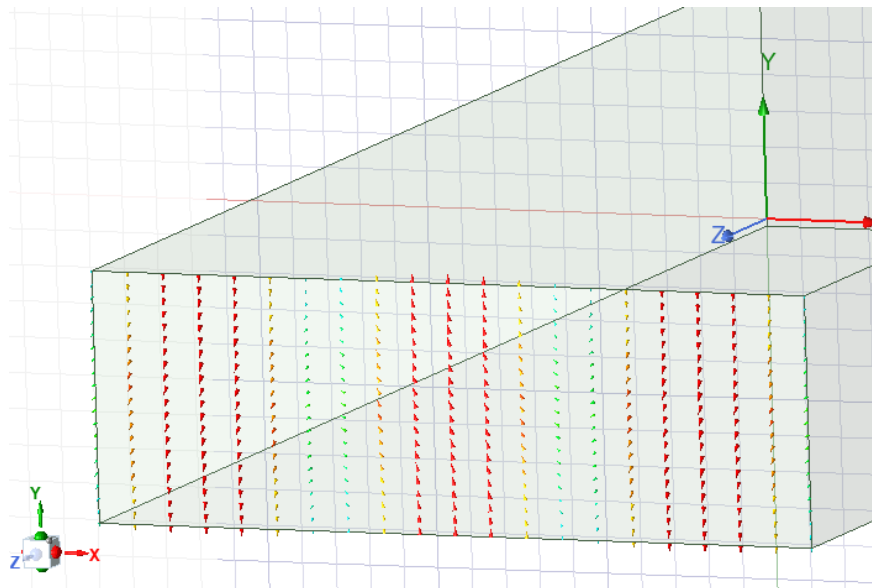


Figure 11 - Task 1A - Port 1 Mode 3 ( $n=0$ ,  $m=3$ )

By viewing the port field display in Figure 3, mode 3 is  $TE_{30}$  as it exhibits three field maxima along the y-axis but none in the x-axis.

### 3.1.2 Task 1a Electric and Magnetic Field Vectors and Magnitude

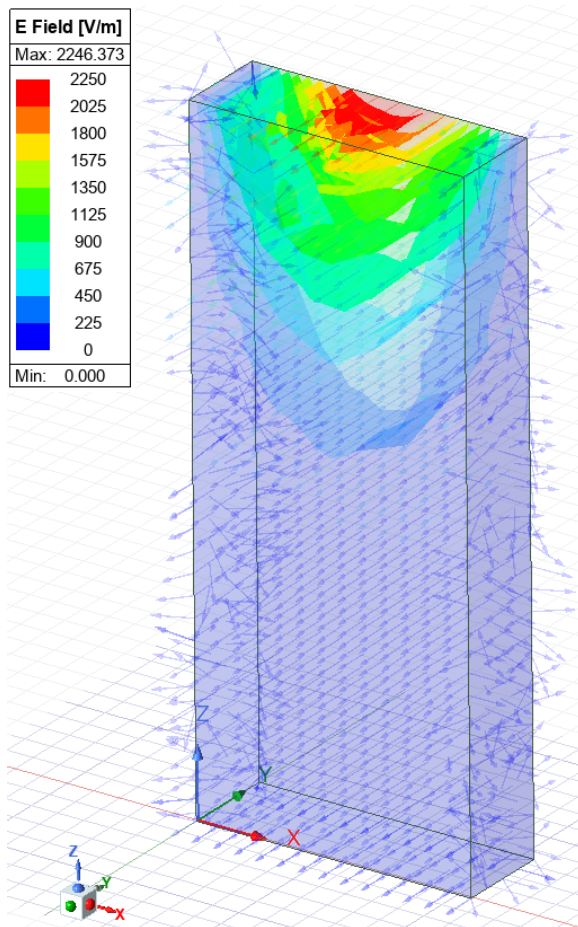


Figure 12 - Task 1A - Electric field magnitude

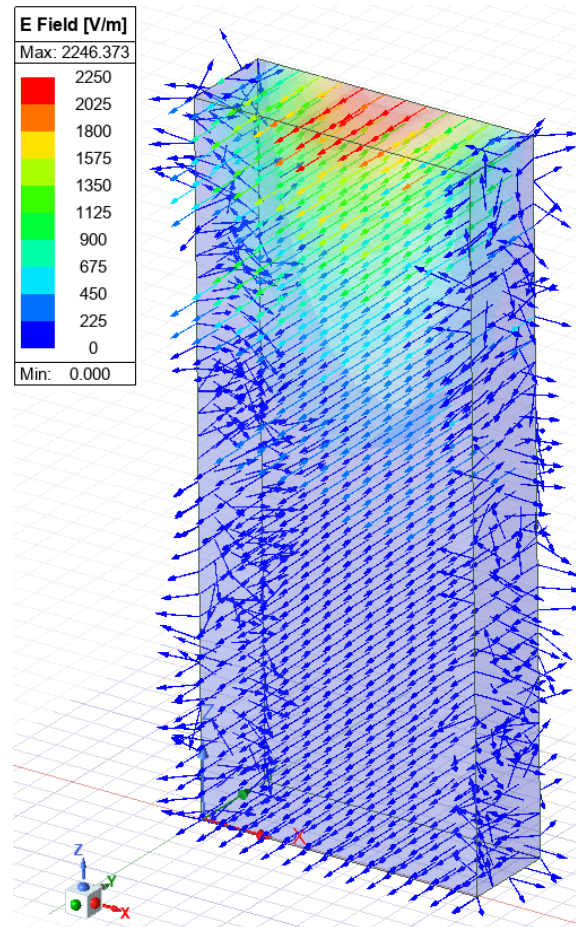


Figure 13 - Task 1A - Electric field vectors

Figure 12 shows the magnitude of electric field within the waveguide, and Figure 13 shows the direction of the electric field within the waveguide depicted by vectors. The blue indicates relatively low electric field intensity and red is the highest intensity, up to 2246.373 V/m.

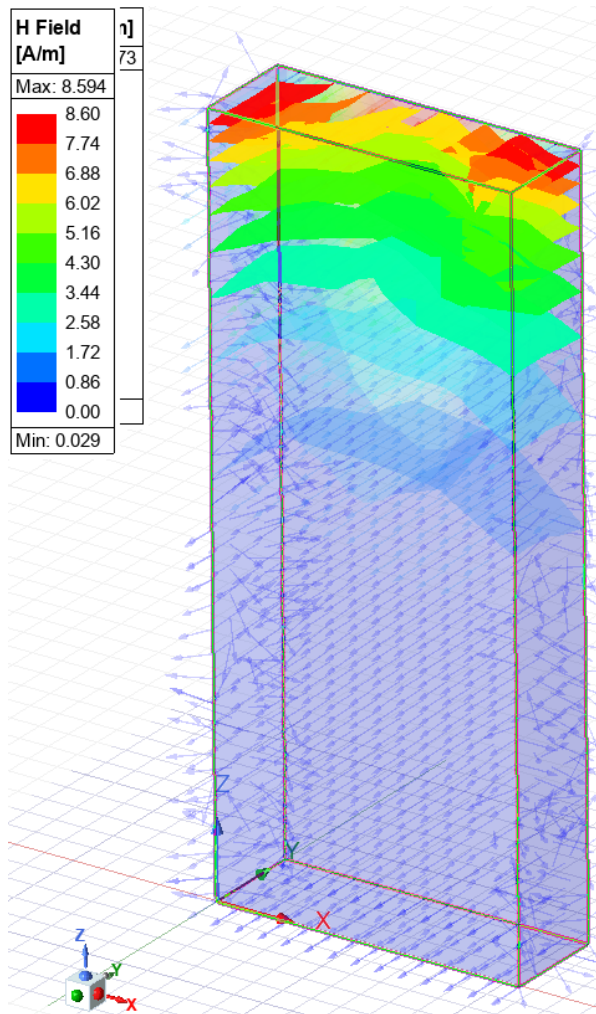


Figure 14 - Task 1A - Magnetic field magnitude

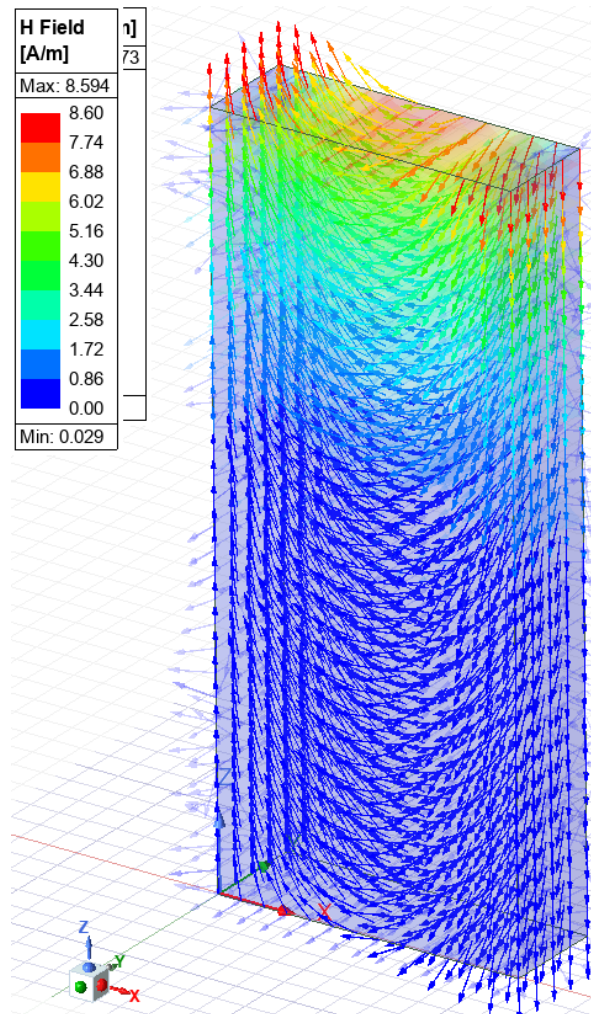


Figure 15 - Task 1A - Magnetic field vectors

### 3.1.3 Task 1a Cut-off Frequency

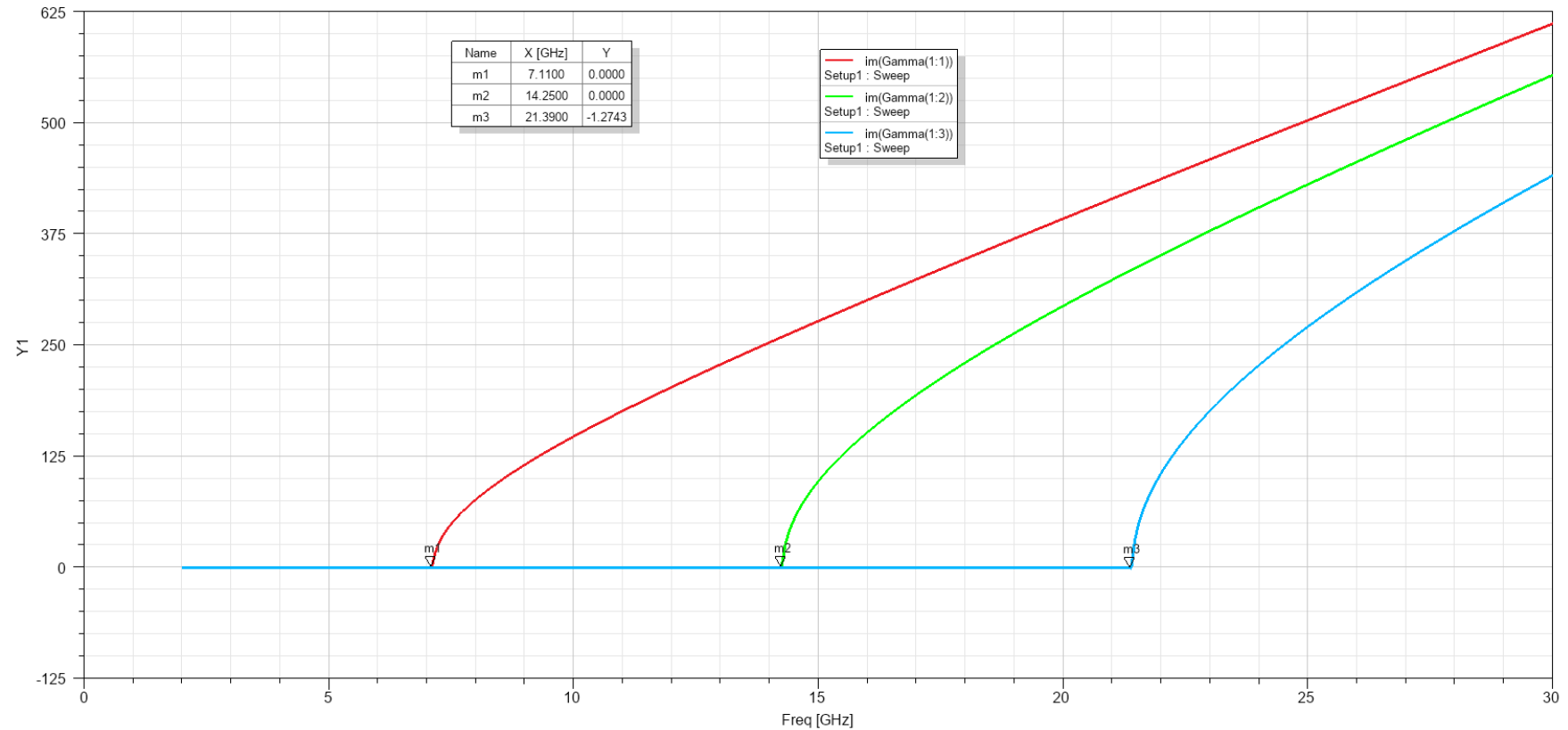


Figure 16 – Task 1a Gamma Plot

Figure 8 shows the gamma plot obtained for each propagation mode of the rectangular waveguide showing the cut-off frequency for mode 1 , 2 and 3.

### 3.1.4 Task 1a Cut-off Frequency Calculation

The cut-off frequency for a rectangular waveguide can be calculate using the following equation.

Where:

m – number of half-wavelength variations in the width of the waveguide

n – number of half-wavelength variations in the height of the waveguide

a – width of rectangular waveguide

b – height of rectangular waveguide

c – velocity of light in that material

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

Equation 1 - Cut-off frequency

As seen in Figure 1, in Mode 1 the waveguide was identified to be in TE<sub>10</sub> propagation mode. Therefore, the cutoff frequency for the waveguide in this mode is:

$$f_c = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$
$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{1}{0.021}\right)^2 + \left(\frac{0}{0.007}\right)^2}$$
$$f_c = 7.14 \text{ GHz}$$

The same calculation was done for mode 2 and mode 3 to give the following values:

Mode 2 –  $f_c = 14.29 \text{ GHz}$

Mode 3 –  $f_c = 21.43 \text{ GHz}$

## 3.2 Task 1b

This section shows the model of a rectangular waveguide with PEC walls and a Teflon-filled interior.

### 3.2.1 Task 1b Port Field Display

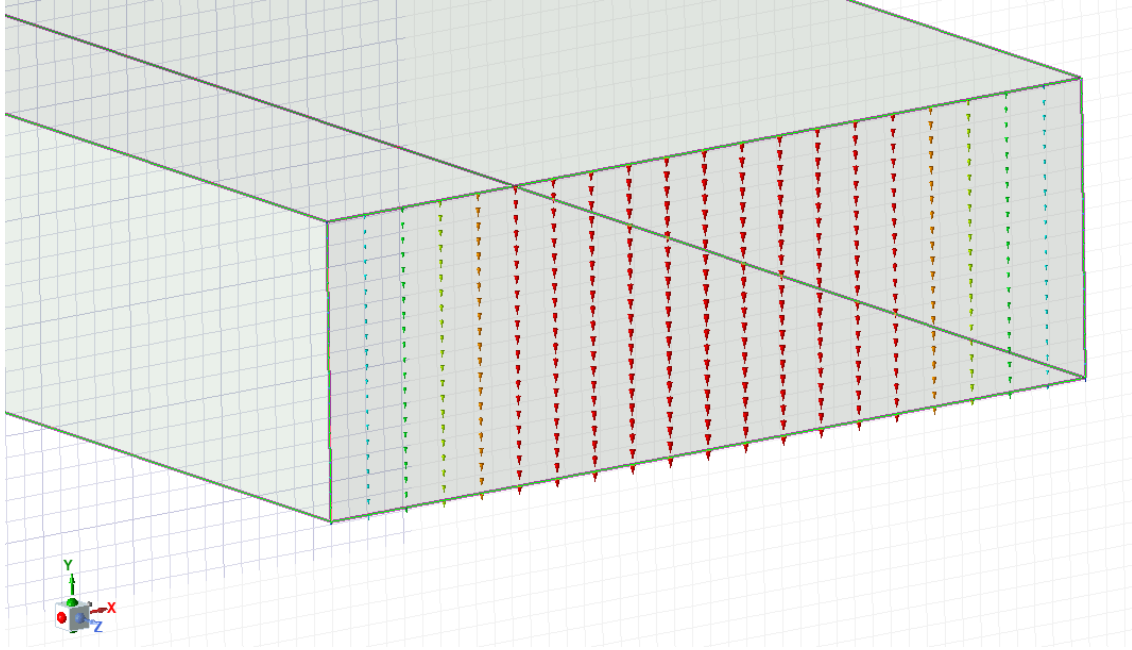


Figure 17 - Task 1b - Port 1 Mode 1 ( $n=0$ ,  $m=1$ )

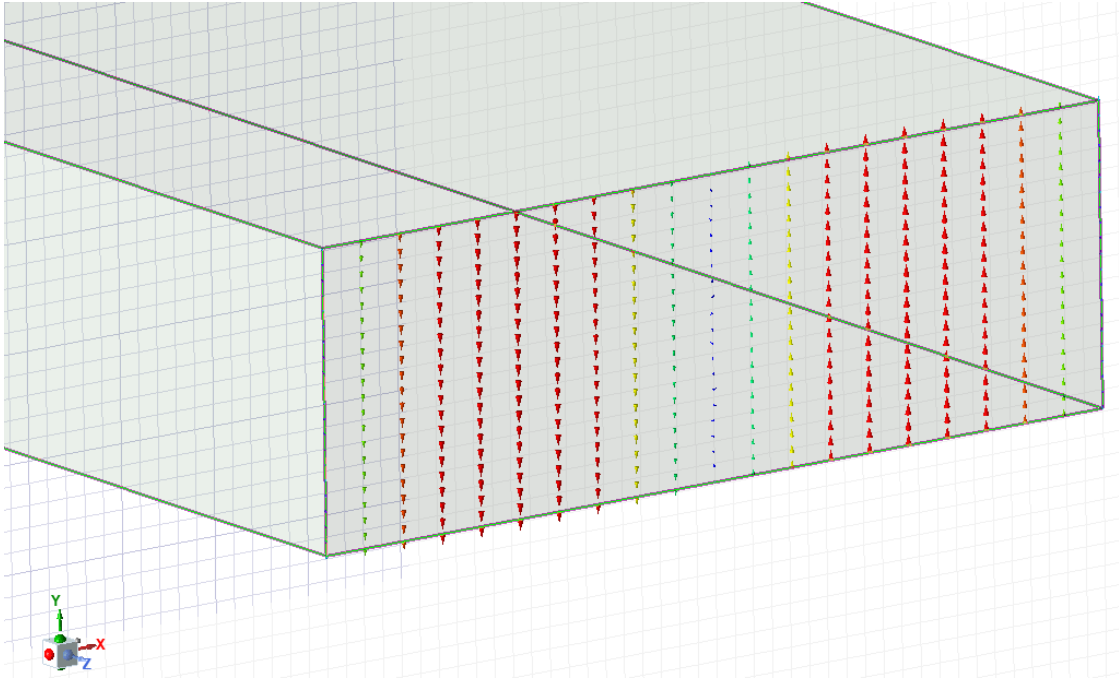


Figure 18 - Task 1b - Port 1 Mode 2 ( $n=0, m=2$ )

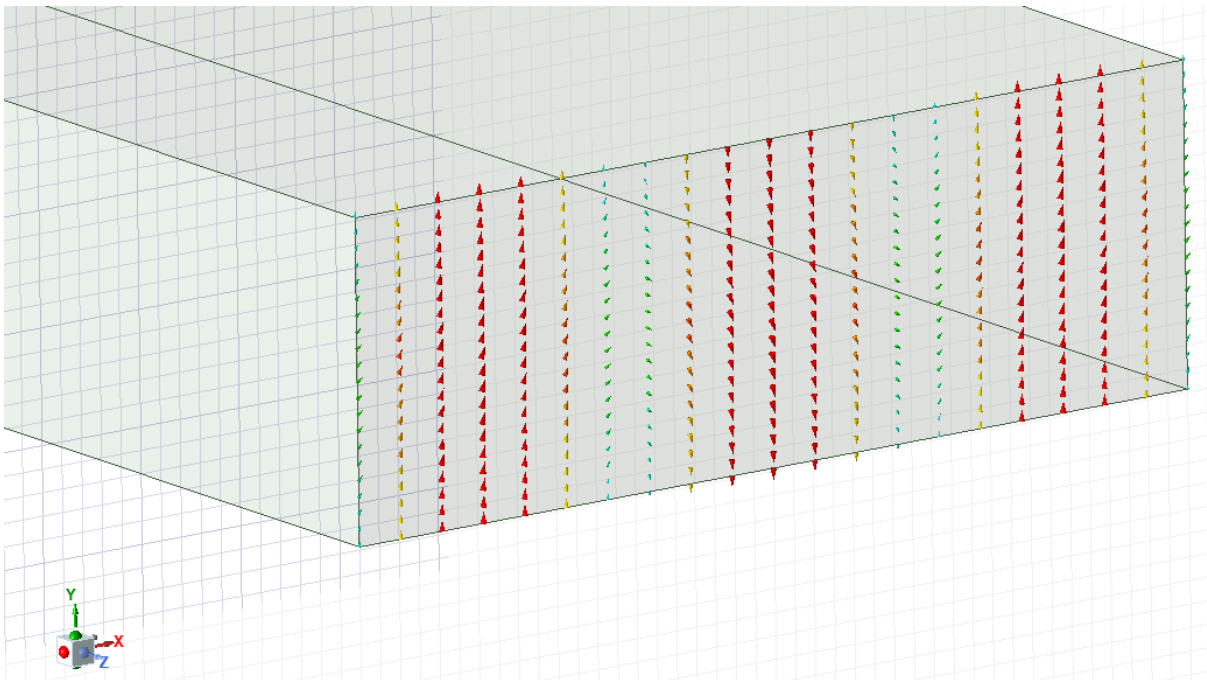


Figure 19 - Task 1b - Port 1 Mode 3 ( $n=0, m=3$ )

### 3.2.2 Task 1b Electric and Magnetic Field Vectors and Magnitude

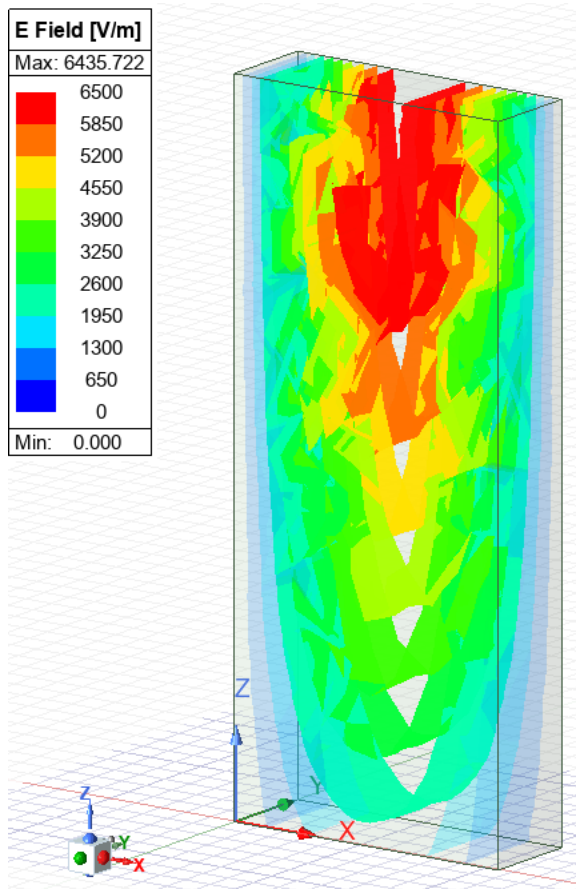


Figure 20 - Task 1b - Electric field magnitude

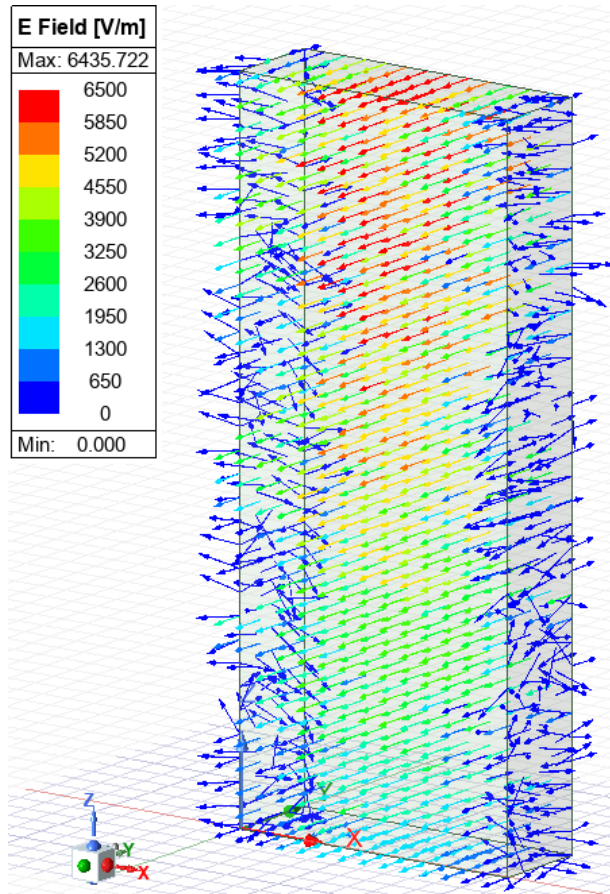


Figure 21 - Task 1b - Electric field vectors

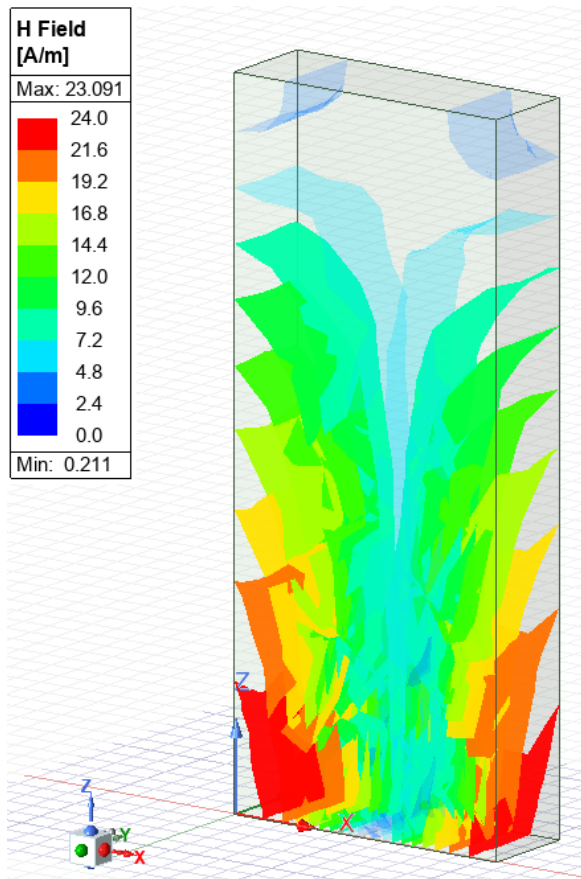


Figure 22 - Task 1b - Magnetic field magnitude

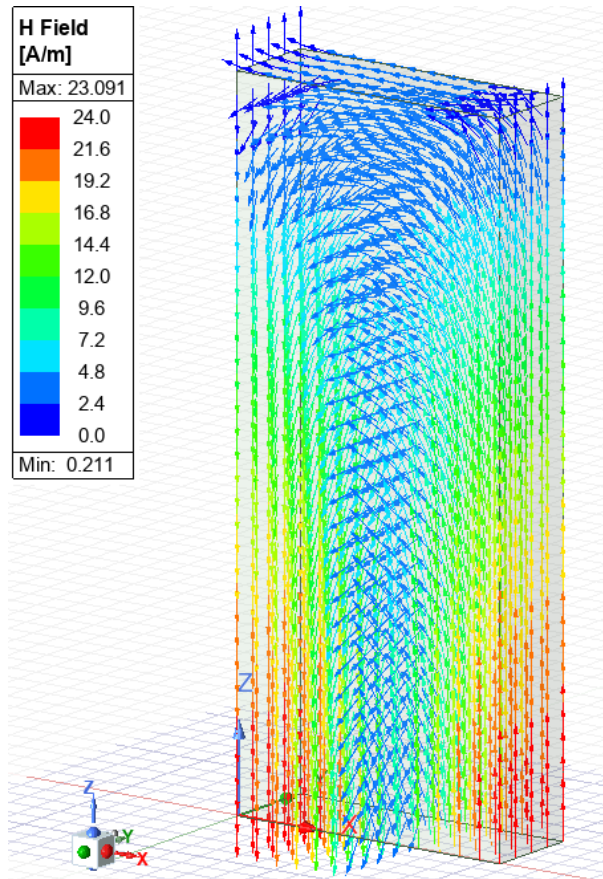


Figure 23 - Task 1b - Magnetic field vectors

3.2.3 Cut-off Frequency

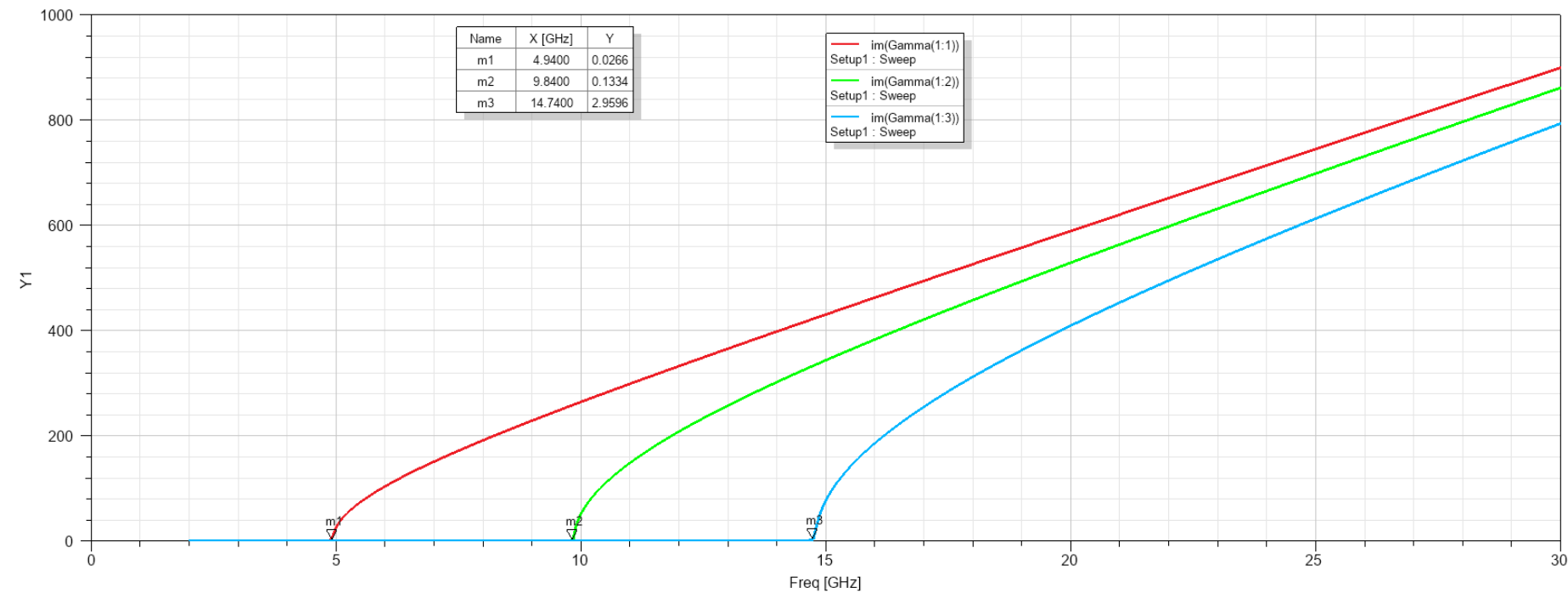


Figure 24 - Task 1b Gamma Plot

### 3.2.4 Task 1b Cut-off Frequency Calculation

The cut-off frequency for the rectangular waveguide with a Teflon centre was then calculated. To do this the speed of light in Teflon must be calculated using the following formula:

$$c = \frac{1}{\sqrt{\epsilon\mu}}$$

Where:

$c$  – velocity of light (multiplied by velocity of light in air)

$\epsilon$  – permittivity of the medium

$\mu$  – permeability of the medium

Equation 2 - Velocity of light for different materials

The permittivity of Teflon is 2.1, and the permeability is 1, so the velocity of light in Teflon can be calculated as:

$$c = \frac{1}{\sqrt{\epsilon\mu}}$$

$$c = \frac{1}{\sqrt{2.1(1)}}$$

$$c = 0.69 \times 3 \times 10^8$$

$$c = 2.07 \times 10^8 \text{ m/s}$$

Using the speed of light  $c$ , the cutoff frequency for the waveguide in Mode 1 can be calculated as follows:

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

$$f_c = \frac{2.07 \times 10^8}{2} \sqrt{\left(\frac{1}{0.022}\right)^2 + \left(\frac{0}{0.011}\right)^2}$$

$$f_c = 4.93 \text{ GHz}$$

The same method can be applied to Mode 2 and Mode 3, giving the following results:

Mode 2:  $f_c = 9.86 \text{ GHz}$

Mode 3:  $f_c = 14.79 \text{ GHz}$

### 3.3 Task 2 Data

The designed model is a half-wave dipole antenna made with PEC material and excited through a lumped port with a port impedance of 50 ohms. The radiation pattern and S-parameter plot will be analysed to determine the antenna's operating frequency.

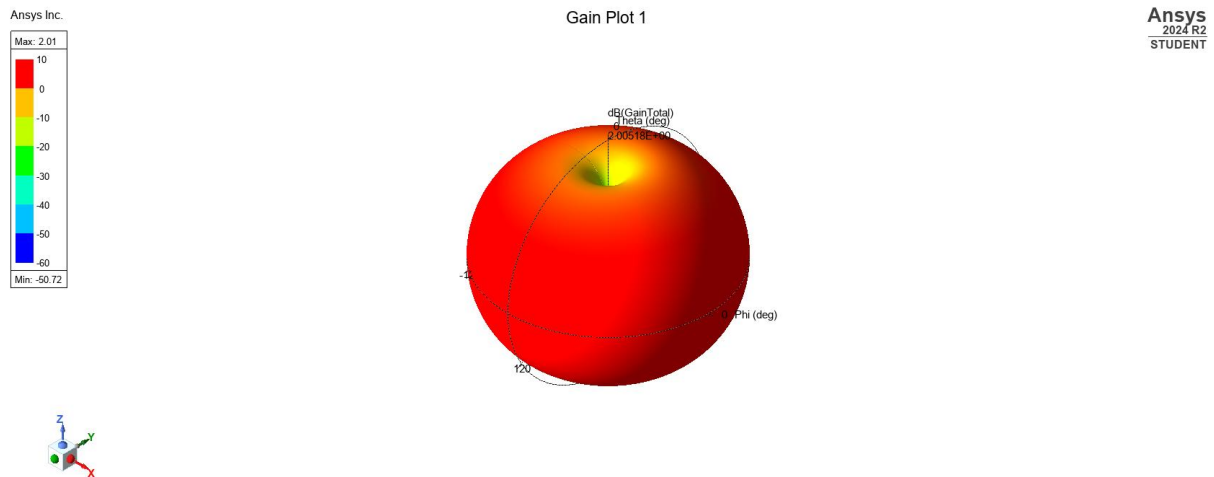


Figure 25 - Task 2 - Antenna radiation pattern

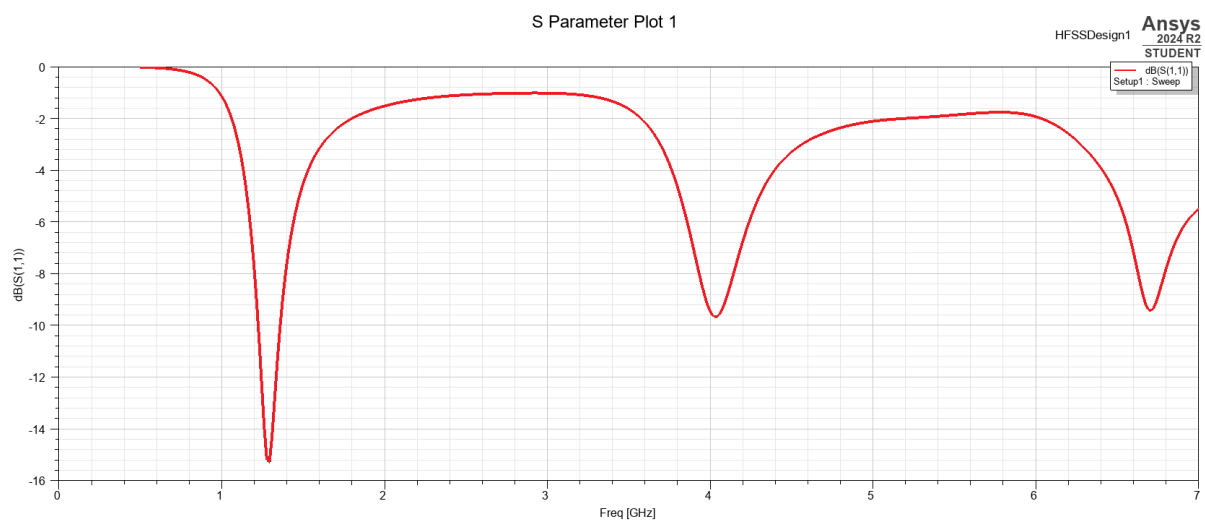


Figure 26 - Task 2 - S-parameter plot

As shown in Figure 13, the operating frequency of the antenna can be determined from the lowest point on the graph, which corresponds to the first resonant frequency on the left. This indicates an operating frequency of approximately 1.3 GHz.

### 3.3.1 Task 2 Calculations

The length where the dipole antenna is most efficient can be calculated using the following formula.

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

Equation 3 - Dipole antenna length

The wavelength at which the antenna radiates electromagnetic waves is 211mm so which can be used to calculate the optimum length of the antenna.

$$L = \frac{0.211}{2}$$

$$L = 0.1055\text{m}$$

The operating frequency can then be calculated using the formula:

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

Where:

c – velocity of light in medium

$$f = \frac{3 \times 10^8}{0.211}$$

$\lambda$  – wavelength

$$f = 1.42\text{GHz}$$

f – frequency

Equation 4 - Antenna operating frequency

## 4. Discussion

### 4.1 Task 1A & 1B

|               | <b>Ansys</b> | <b>Calculation</b> |
|---------------|--------------|--------------------|
| <b>Mode 1</b> | 7.11GHz      | 7.14Ghz            |
| <b>Mode 2</b> | 14.25GHz     | 14.29GHz           |
| <b>Mode 3</b> | 21.39GHz     | 21.43GHz           |

Table 1 - Task 1a - Ansys vs Calculation table

Table 1 compares the modes in Task 1a which has minimal discrepancy, indicating the reliability and precision of both simulation and calculation approaches in analysing waveguide or electromagnetic systems.

|               | <b>Ansys</b> | <b>Calculation</b> |
|---------------|--------------|--------------------|
| <b>Mode 1</b> | 4.94GHz      | 4.93GHz            |
| <b>Mode 2</b> | 9.84GHz      | 9.86GHz            |
| <b>Mode 3</b> | 14.74GHz     | 14.79GHz           |

Table 2 - Task 1b - Ansys vs Calculation table

Table 2, referring to the Teflon waveguide also demonstrates excellent agreement between the two methods.

Based on the computed cut-off frequencies shown in Table 1 and Table 2 for a rectangular waveguide filled with either vacuum or Teflon, mode 1 exhibited a cut-off frequency of 7.11 GHz in vacuum and 4.94 GHz in Teflon. This decrease in cut-off frequency is attributed to the fact that electromagnetic waves propagate more slowly in Teflon than in a vacuum. The  $TE_{10}$  mode is the dominant propagation mode in the rectangular waveguide, as it possesses the lowest cut-off frequency.

### 4.2 Task 2

Figure 25 illustrates the dipole antenna's toroidal radiation pattern, which is consistent in the z-plane, and demonstrates how electromagnetic energy is emitted. It features a main lobe that surrounds the antenna and nulls at both ends along its axis.

The operating frequency of the antenna was calculated to be 1.42 GHz using Equation 4, while the S-parameter plot indicates an operating frequency of approximately 1.3 GHz. This discrepancy arises due to ideal assumptions made during the analytical calculation, such as perfect material properties, ideal geometries, and no losses, which may not fully align with the more realistic conditions simulated in HFSS, including material imperfections, meshing accuracy, and boundary effects.

## 5. Conclusion

In Task 1, the dominant propagation mode in the rectangular waveguide was correctly identified as  $TE_{10}$ . For the vacuum-filled waveguide, the cut-off frequency obtained through simulation was 6.76 GHz, which closely aligned with the theoretical value of 6.82 GHz. When the waveguide was filled with Teflon ( $\epsilon = 2.1$ ), the simulated cut-off frequency dropped to 4.66 GHz, again showing strong correlation with the calculated theoretical value of 4.705 GHz. These results confirm the expected influence of dielectric materials on waveguide performance and validate the accuracy of both simulation and analytical methods.

In Task 2, the antenna was designed to operate at a frequency of 1.35 GHz, with simulation results showing a resonant frequency of 1.22 GHz. This demonstrates reasonable agreement and highlights potential design refinements. The simulated radiation pattern exhibited omnidirectional behaviour in the z plane, consistent with theoretical predictions for this type of antenna. The simulation further provided valuable insights into the gain and S-parameters, reinforcing understanding of antenna performance in practical applications.

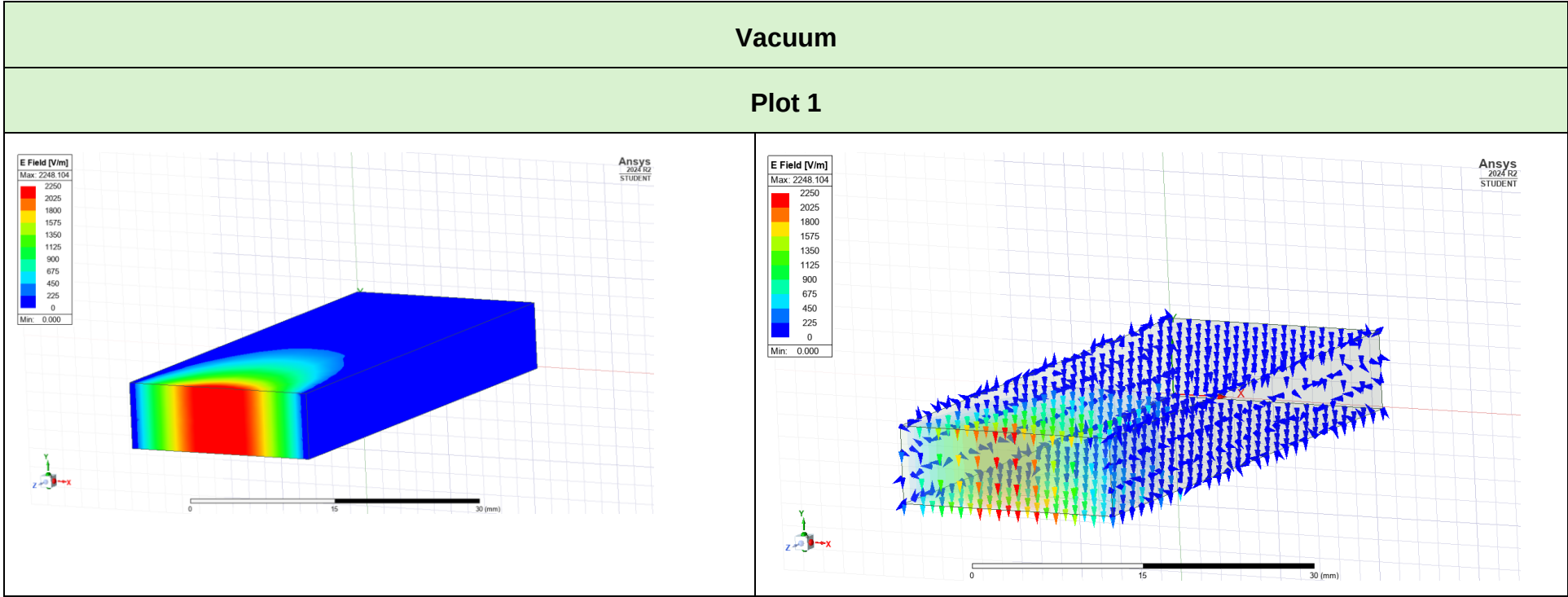
## 6. References

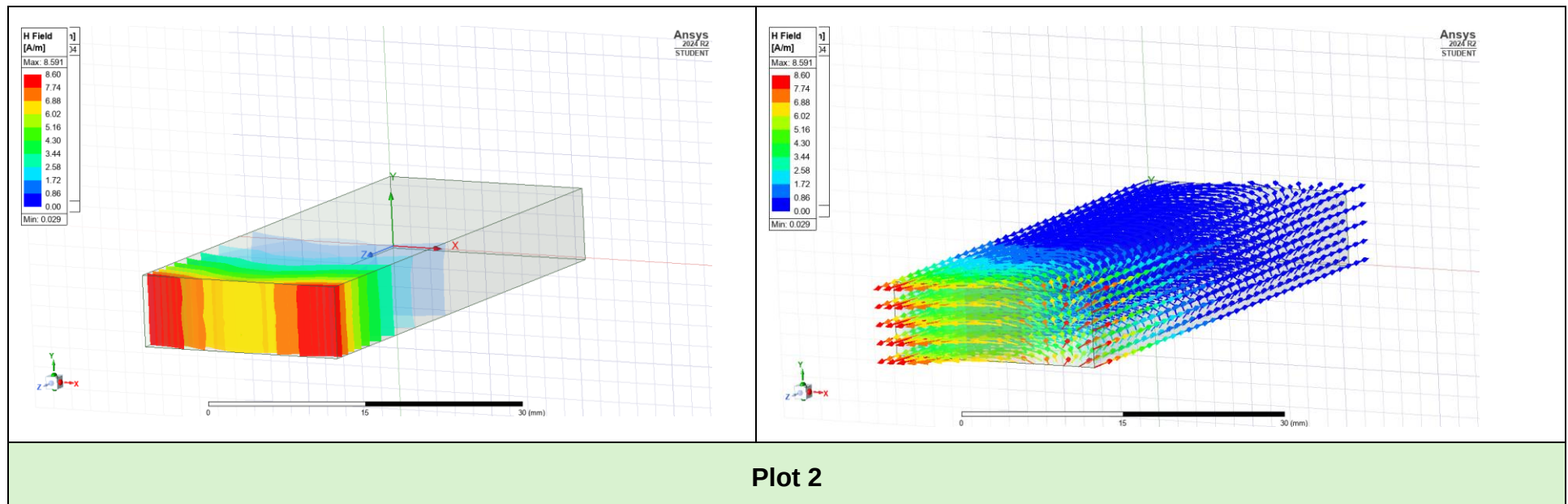
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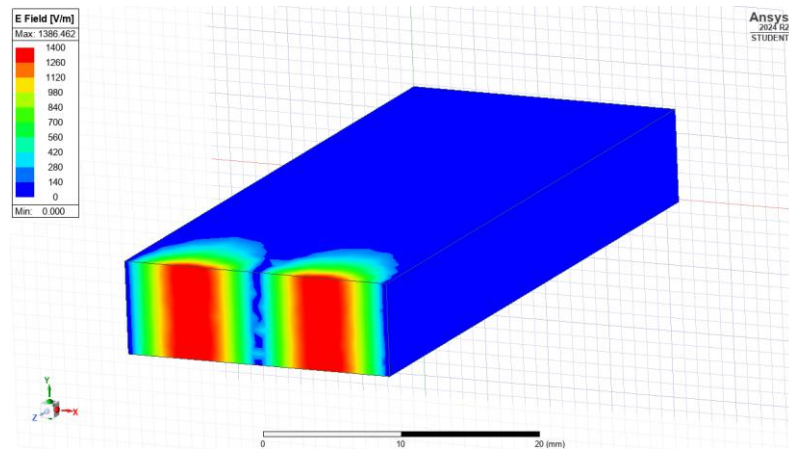
content/uploads/sites/5/2021/07/HFSS\_GS\_2020R2\_EN\_LE6\_Port\_Basics.pdf.  
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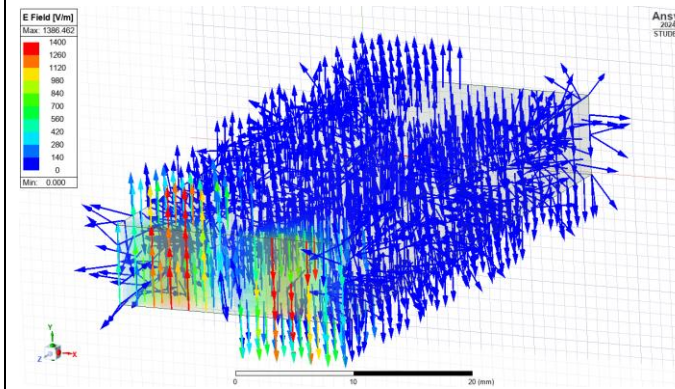
7. Appendix 1



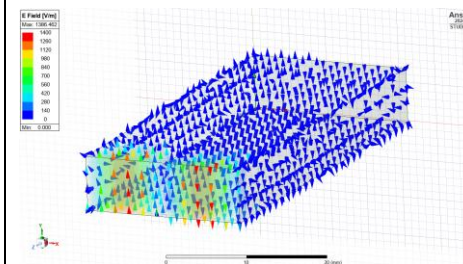




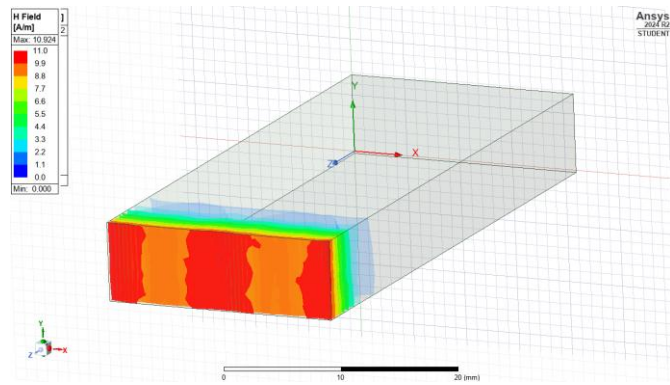
Electric field Magnitude



VECTOR Electric field

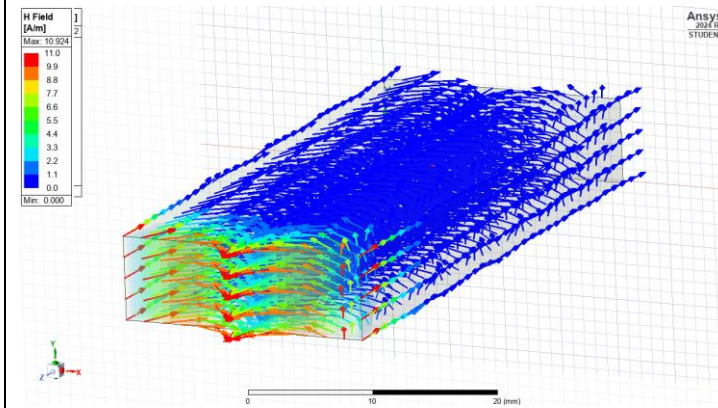


Short arrows. Density less



Magnetic Field

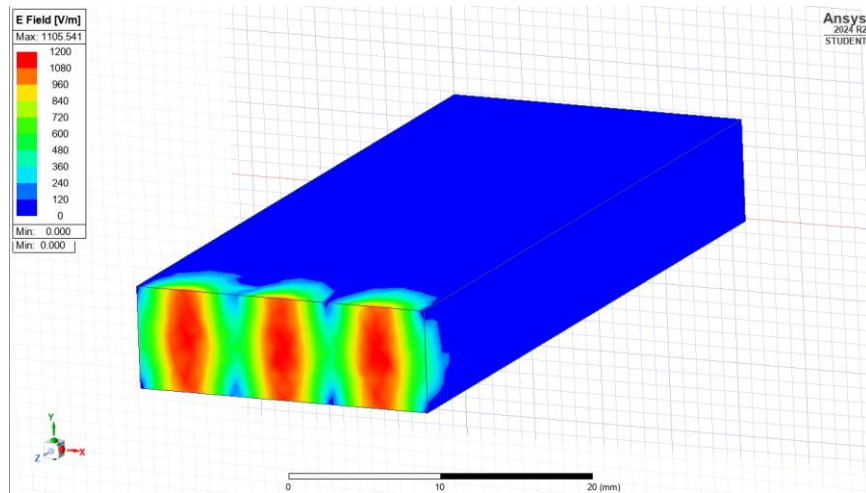
Magnitude



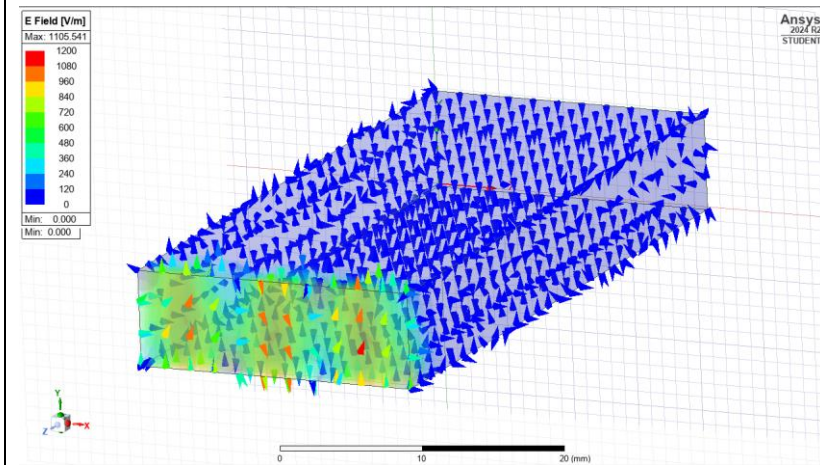
Magnetic Field

Vector

Plot 3

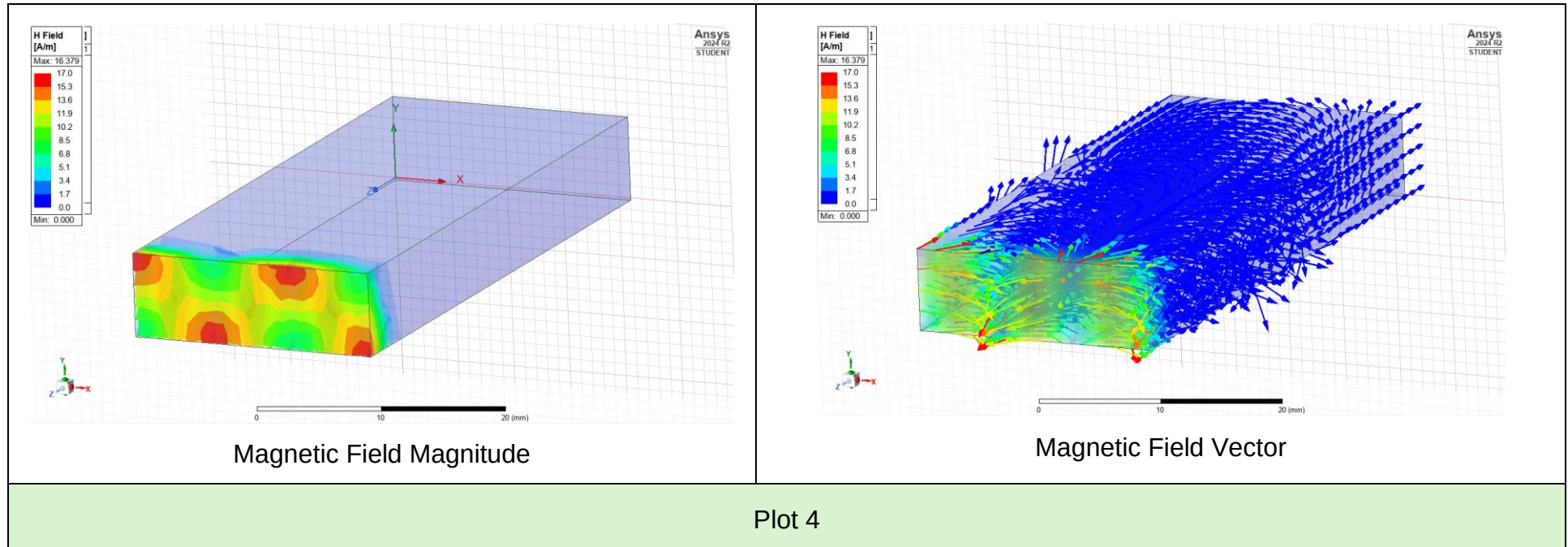


Electric Field Magnitude



Electric field

VECTOR



Plot 4

