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Analysis of Electromagnetic Wave Propogations

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Academic Year: 2024 - 2025

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Academic integrity declaration

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- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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Abstract

An investigation into waveguide and antenna properties was undertaken, utilising theoretical formula and High Frequency modelling software.

Two waveguides of identical dimensions and differing materials were modelled, with both theoretical investigation and computer simulation demonstrating the effects of this material change. It was seen that a waveguide containing an area of vacuum attenuated electromagnetic waves less than an identical waveguide filled with Teflon. It was also shown that the vacuum waveguide demonstrated higher cut-off frequencies for all modes.

A half-wave dipole antenna was also modelled, and theoretical calculations of operating frequency compared to the operating frequency demonstrated during computer simulation. While the computer simulation showed the correct omnidirectional radiation pattern for a dipole antenna, the operating frequency of the antenna differed slightly.

Keywords:

Waveguide, Teflon, Antenna, Dipole, Modelling, Calculation

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List of Abbreviations

dB	Decibels
EM	Electromagnetic
GHz	Gigahertz
PEC	Perfect Electrical Conductor

1 Introduction

1.1 Electromagnetism

An electromagnetic (EM) field consists of positively and negatively charged particles [1] which propagate in a wavelike manner.

Faraday's Law states that

'The electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path' [2]

This means that a changing magnetic field will induce an electric field.

Ampere's Law states that:

'The magnetic field in space around an electric current is proportional to the electric current which serves as its source' [3]

This means that a changing electric field will induce a magnetic field.

Therefore, an EM field is made up of two components: the electric component (known as the E field) and the magnetic component (known as the H field). The intensity of the two fields is directly proportional: a wave with a stronger H field will have a correspondingly strong E field.

An EM wave moving through an isotropic medium (a medium which retains the same properties throughout its volume) will conform to Fleming's 'Right Hand Rule':

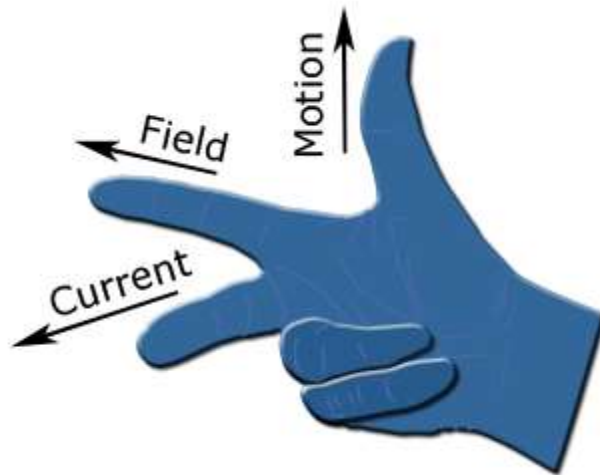


Figure 1 - Fleming's Right Hand Rule

Fleming's right hand rule shows the arrangement of an EM wave, where the current and field are at right angles to each other. A wave arranged in this manner is known as a transverse wave [1].

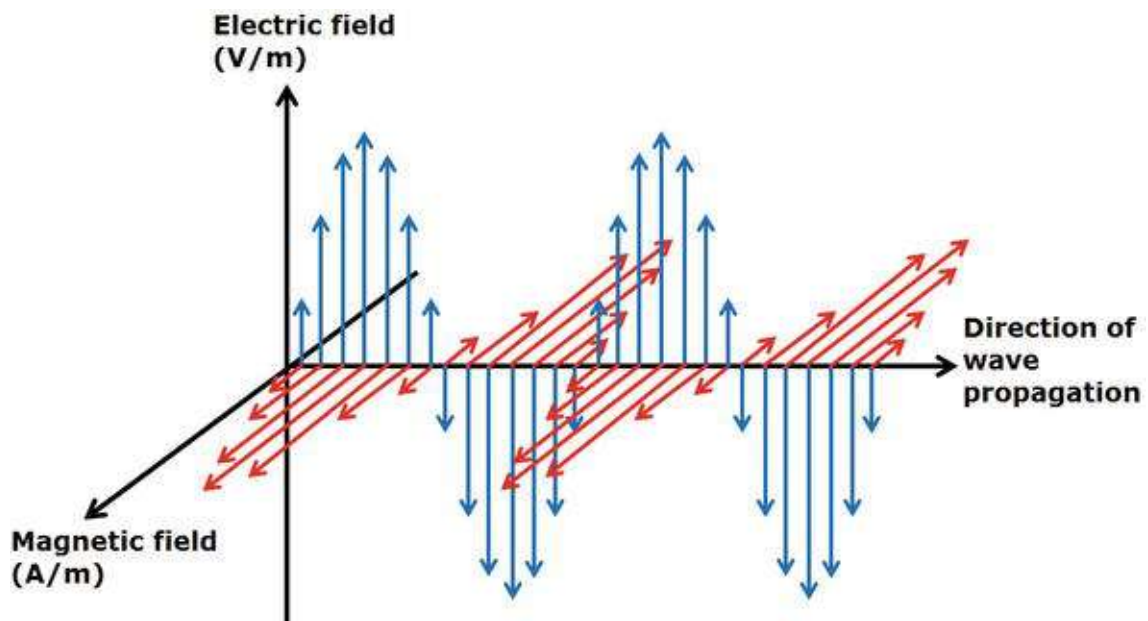


Figure 2 - A Transverse Electromagnetic Wave [1]

Figure 2 shows the arrangement of a transverse EM wave, with the E field shown in blue and the H field in red. In accordance with Faraday's law, the E field and H field are proportionate to each other.

A wave is a repeating pattern of cycles. The distance between two cycles (for example, between two peaks in the H field) is known as the wavelength (λ), while the number of times the cycle repeats in a given timeframe is known as the frequency (f). This is illustrated in Figure 3:

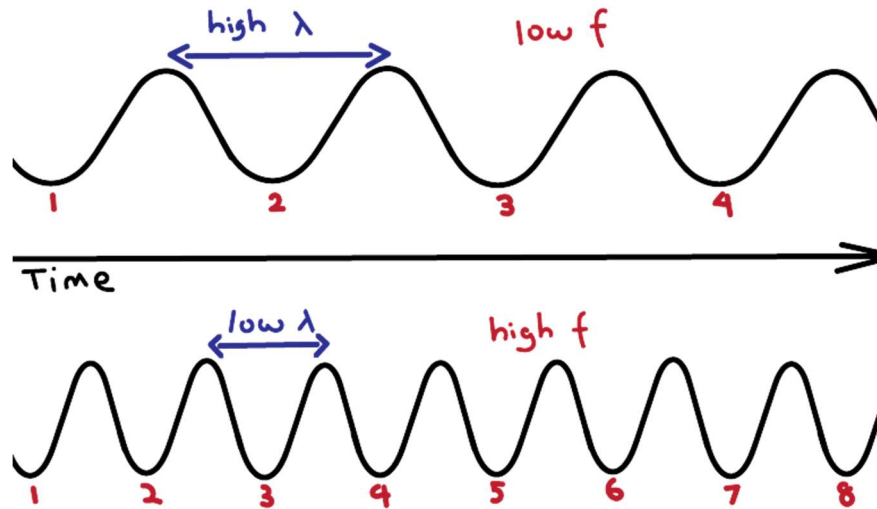


Figure 3 - Frequency and Wavelength

Figure 3 also illustrates the relationship between frequency and wavelength, which are inversely proportional to each other. A wave with a high frequency will have a shorter wavelength, and vice versa. This is shown in Equation 1:

$$\lambda = \frac{1}{f\sqrt{\mu\epsilon}}$$

Equation 1 - Relationship Between Wavelength and Frequency

Where

λ = Wavelength

f = Frequency

μ = the permeability of the medium

ε = the permittivity of the medium

Permittivity and permeability are properties of a medium through which a wave is travelling. Permittivity concerns the degree to which a wave is polarised by an electric field [1], essentially influencing the degree to which a wave is attenuated (or reduced) by a material. Materials with lower permittivity values (such as gases and metals [4]) will attenuate a wave less.

Permeability concerns how much the material can support the magnetic field [1], influencing the degree to which a material can support a wave passing through it. A material with a high permeability, such as metals [5], will enable a wave to pass through more easily.

Electromagnetic waves are extensively used for communication [6], weather monitoring [7], and widely within the defence industry for detection [8] and tracking [9] of targets, among many other applications.

1.2 Waveguides

In free space, an EM wave will propagate in a spherical manner [10]. In this case, the energy of the wave reduces as it travels further from the source.

If a wave is required to propagate in a certain direction, waveguides can be used to confine the propagation of a wave in only one dimension. Waveguides, especially optical fibres [11], are widely used within electronics.

A critical feature of any waveguide is the cut-off frequency. This is the frequency below which EM waves will no longer propagate along the waveguide [11], and therefore a vital consideration when selecting a waveguide for a system.

This report will examine the effect of waveguide material on EM wave propagation. Two rectangular waveguides will be simulated using High Frequency simulation software, and both their own properties and the properties of the EM waves travelling through them analysed.

The first waveguide (Waveguide 1) will be simulated with Perfect Electrical Conductor (PEC) walls surrounding an area of vacuum. The second waveguide

(Waveguide 2) will be simulated with PEC walls surrounding a Teflon core. The dimensions of both waveguides will be identical.

Teflon and vacuum have identical permeability [5] but differ in permittivity [4]. This is expected to effect the properties of the waveguide and the behaviour of the EM waves travelling through.

1.3 Antenna

Antenna are used to transmit and receive EM waves. The characteristics of an antenna influence the characteristics of waves propagated by it and the pattern in which they are propagated, as well as the antennas efficiency in receiving waves of various properties.

This report will examine the properties of a half-wave dipole antenna using theoretical formula and compare this to an identical antenna modelled using High Frequency simulation software. In particular, the following features of the antenna will be explored:

- **Operating frequency:** The operating frequency of a dipole antenna is directly linked to its length [12]. This report will use theoretical formula to determine the operating frequency of the antenna.
- **Radiation pattern:** Dipole antennae produce an omnidirectional radiation pattern [12]. It is expected that the antenna modelled in this report will conform to this.

2 Method

2.1 Equations

The following equations were used in this analysis:

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

Equation 2 – Cut-off Frequency of a Solid Rectangular Waveguide

Where:

c = The speed of light (3×10^8 m/s)

m = The number of half-wavelength variations in the azimuthal direction

n = The number of half-wavelength variations in the transverse direction

a = Width of the waveguide

b = Height of the waveguide

ϵ = the absolute permittivity of the medium.

μ = the absolute permeability of the medium

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

Equation 3 - Antenna Length

Where:

L = The length of the antenna

λ = Wavelength

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

Equation 4 - Operating Frequency

Where:

f = Frequency

C = The speed of light

λ = Wavelength

2.2 Task 1a:

Waveguide 1 was designed with the following dimensions:

a: 23mm

b: $13/2 = 6.5\text{mm}$

The waveguide was modelled with PEC walls around an area of vacuum.

A frequency sweep of 2 – 30 GHz was performed. For each mode, the following were generated and analysed:

- Port field displays.
- E field vector and magnitude.
- H field vector and magnitude.

The cut-off frequency for each mode was calculated using Equation 2.

2.3 Task 1b:

Waveguide 2 was designed with the following dimensions:

a: 23mm

b: $13/2 = 6.5\text{mm}$

The waveguide was modelled with Perfect Electric Conductor (PEC) walls filled with Teflon.

A frequency sweep of 2 – 30 GHz was performed. For each mode, the following were generated and analysed:

- Port field displays.
- E field vector and magnitude.
- H field vector and magnitude.

The cut-off frequency for each mode was calculated using Equation 2.

2.4 Task 2

A halfwave dipole antenna was designed with a wavelength of 231mm and a radius of 1mm. The antenna was made from PEC, with excitation applied through a lumped port with a port impedance of $50\ \Omega$. The model was placed on a rectangular radiating surface.

A frequency sweep of 1 – 7.5 GHz was performed, and the following reports generated:

- The antenna gain plot.
- The antenna S parameter plot.

The antenna length was calculated using Equation 3, and the operating frequency was calculated using Equation 4.

3 Results

3.1 Task 1a:

Illustrations for this section may be found in Appendix A.

i) Figure six shows that Mode 1 has a single half-wavelength variation in the transverse direction, and no variation in the azimuthal direction.

Figure Five shows that Mode 2 has two half-wavelength variations in the transverse direction, and none in the azimuthal direction.

Figure four shows that Mode 3 has three half-wavelength variations in the transverse direction, and none in the azimuthal direction.

The modes of Waveguide 1 can therefore be expressed as:

Mode 1: TE₁₀

Mode 2: TE₂₀

Mode 3: TE₃₀

ii) The port field displays for Waveguide 1 are shown in Appendix 1.

iii) The magnitude and vectors of the E and H fields for each mode are shown in Appendix 1.

iv) The cut-off frequency for a rectangular waveguide can be calculated using Equation 2 and the characteristics in i) above. Calculations are shown below:

TE₁₀

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{1}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 6.25 \times 10^9 \text{ Hz}$$

$$f_c = 6.25 \text{ GHz}$$

TE₂₀

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{2}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 1.30 \times 10^{10} \text{ Hz}$$

$$f_c = 13 \text{ GHz}$$

TE₃₀

$$f_c = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{3}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 1.96 \times 10^{10} \text{ Hz}$$

$$f_c = 19.6 \text{ GHz}$$

v) Graph 1 within Appendix 1 shows a rectangular plot illustrating the cut-off frequencies for the three modes. These cut-off frequencies are shown as:

TE₁₀ (m1): 6.48 GHz

TE₂₀ (m2): 12.9 GHz

TE₃₀ (m3): 19.5 GHz

Mode	Theoretical Cut-off Frequency (GHz)	Simulated Cut-off Frequency (GHz)
TE ₁₀	6.25	6.48
TE ₂₀	13	12.9
TE ₃₀	19.6	19.5

Table 1 - Results of Task 1a

3.2 Task 1b:

Illustrations for this section may be found within Appendix B.

i) Figure 20 shows that Mode 1 has a single half-wavelength variation in the transverse direction, and no variation in the azimuthal direction.

Figure 21 shows that Mode 2 has two half-wavelength variations in the transverse direction, and none in the azimuthal direction.

Figure 22 shows that Mode 3 has three half-wavelength variations in the transverse direction, and none in the azimuthal direction.

The modes of Waveguide 2 can therefore be expressed as:

Mode 1: TE₁₀

Mode 2: TE₂₀

Mode 3: TE₃₀

ii) The port field displays for Waveguide 2 are shown in Appendix B.

iii) The magnitude and vectors of the E and H fields for each mode are shown in Appendix B.

iv) Teflon has a relative permittivity of 2.1 and a relative permeability of 1. The calculations for the cut-off frequency for each mode, using the characteristics in b)i) above, can now be calculated using Equation 3:

TE₁₀

$$f_c = \frac{\left(\frac{3 \times 10^8}{2}\right)}{\sqrt{(2.1 \times 1)}} \sqrt{\left(\frac{1}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 4.5 \times 10^9 \text{ Hz}$$

$$f_c = 4.5 \text{ GHz}$$

TE₂₀

$$f_c = \frac{\left(\frac{3 \times 10^8}{2}\right)}{\sqrt{(2.1 \times 1)}} \sqrt{\left(\frac{2}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 9 \times 10^9 \text{ Hz}$$

$$f_c = 9 \text{ GHz}$$

TE₃₀

$$f_c = \frac{\left(\frac{3 \times 10^8}{2}\right)}{\sqrt{(2.1 \times 1)}} \sqrt{\left(\frac{3}{0.023}\right)^2 + \left(\frac{0}{0.0065}\right)^2}$$

$$f_c = 1.35 \times 10^{10} \text{ Hz}$$

$$f_c = 13.5 \text{ GHz}$$

v) Graph 2 within Appendix B shows a rectangular plot illustrating the cut-off frequencies for the three modes. These cut-off frequencies are shown as:

TE₁₀ (m1): 4.52 GHz

TE₂₀ (m2): 9 GHz

TE₃₀ (m3): 13.48 GHz

Mode	Theoretical Cut-off Frequency (GHz)	Simulated Cut-off Frequency
TE ₁₀	4.5	4.52
TE ₂₀	9	9
TE ₃₀	13.5	13.48

Table 2 - Results of Task 1b

3.3 Task 2

Illustrations for this section may be found within Appendix C.

i) The length of the dipole antenna was calculated using Equation 3:

$$L = \frac{231}{2}$$

$$L = 115.5 \text{ mm}$$

ii) The operating frequency of the antenna was calculated using Equation 4:

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

$$f = 1.3 \times 10^9$$

$$f = 1.3 \text{ GHz}$$

iii) Graph 3 within Appendix C shows the S-parameter plot for the antenna.

iv) Figure 35 within Appendix C shows the radiation pattern of the antenna.

4 Discussion

4.1 Task 1a

The port field displays for Waveguide 1 (see Appendix A) show three modes propagating through the waveguide: TE_{10} , TE_{20} and TE_{30} .

The calculations in Section 3.1 above show that TE_{10} is the dominant mode for Waveguide 1, as it has the lowest cut-off frequency (see Table 1).

Figures 7, 11, and 15 within Appendix A show a constant E field throughout Waveguide 1 for all modes. This indicates no attenuation of the E field by the medium through which it is travelling (vacuum).

Figures 9, 13, and 17 within Appendix A show a constant H field throughout Waveguide 1 for all modes. This shows no attenuation of the H field by the medium through which it is travelling.

This is to be expected as free space (vacuum) has a permittivity of 0 [4] and a permeability of 1 [5].

4.2 Task 1b

The port field displays for Waveguide 2 (see Appendix B) show three modes propagating through the waveguide: TE_{10} , TE_{20} and TE_{30} .

The calculations in Section 3.2 above show that TE_{10} is the dominant mode for Waveguide 2, as it has the lowest cut-off frequency (see Table 2).

Figures 23, 27, and 31 within Appendix B show a steady decline in the E field for all modes as the wave travels through Waveguide 2, while figures 25, 29, and 33 show a similar decline in the H field.

This decline is due to the material properties of Teflon, which has the same relative permeability as free space [5] with a higher relative permittivity [4] (see Table 3). The Teflon fill of Waveguide 2 can therefore support the H field of EM waves in a manner identical to free space, but does not support the E field as effectively.

Material	Relative Permeability	Relative Permittivity
Free Space (Vacuum)	1	0
Teflon	1	2.1

Table 3 - Material Properties of Waveguides

As the dimensions and casing of the waveguides was unchanged, it is considered that the Teflon fill of the second waveguide attenuated the E field of the EM waves passing through. As the E field was reduced, it could no longer support the H field, which was therefore reduced proportionally in accordance with Ampere's law.

This is reflected in the reduced cut-off frequencies seen during the simulations, and illustrated in Table 4 below:

Mode	Simulated Cut-off Frequency (GHz)		Difference (dB)
	Waveguide 1 (Free Space)	Waveguide 2 (Teflon)	
TE ₁₀	6.48	4.52	1.56
TE ₂₀	12.9	9	1.56
TE ₃₀	19.5	13.48	1.57

Table 4 - Comparison of Cut-off Frequencies for Two Waveguides

Table 4 shows that for each mode, the cut-off frequency for Waveguide 2 was approximately 1.5 dB lower than the same mode in Waveguide 1.

4.3 Task 2

Graph 3 within Appendix C shows the operating frequency of the antenna to be roughly 1.2 GHz. This is slightly lower than the theoretical operating frequency, which was calculated as 1.3 GHz. This discrepancy may be a result of errors in modelling during the simulation.

The gain plot of the antenna (Figure 34, Appendix C) shows an omnidirectional radiation pattern, with uniform intensity along the lateral plane. This is to be expected from a dipole antenna.

5 Conclusion

The simulations in question 1 demonstrated the attenuating effect of Teflon on EM waves. This was due to the difference in permittivity between Teflon and free space, resulting in the attenuation of the EM wave E field. The reduced E field caused a proportional reduction in the H field, resulting in a decrease in field strength along the length of the waveguide.

The simulation in question 2 did not confirm the theoretical calculations made of the operating frequency of a halfwave dipole antenna, λ 231 mm. This is likely due to errors made during the modelling and simulation process. The simulated antenna displayed the correct omnidirectional radiation pattern.

6 Bibliography

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Appendix A Results of Task 1a

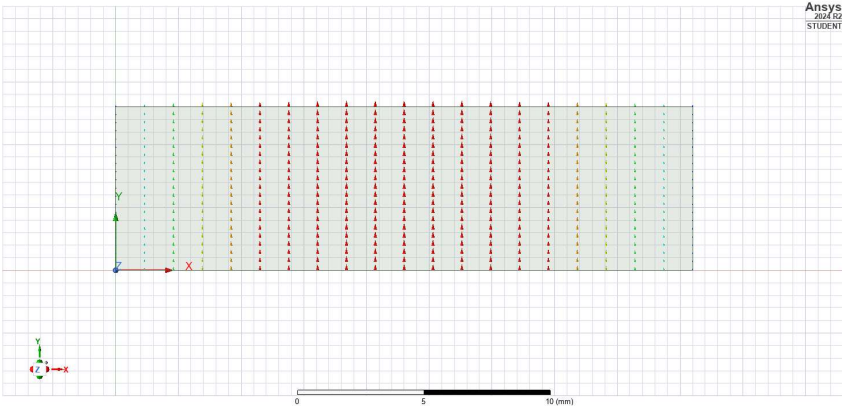


Figure 6 - Port Field Display for Mode 1

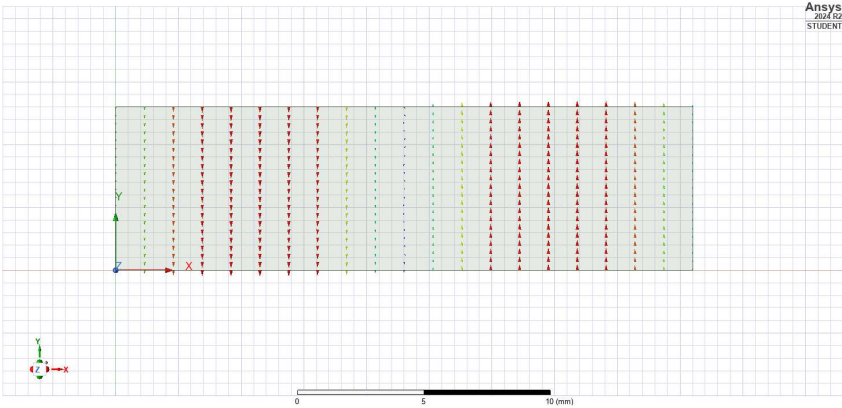


Figure 5 - Port Field Display for Mode 2

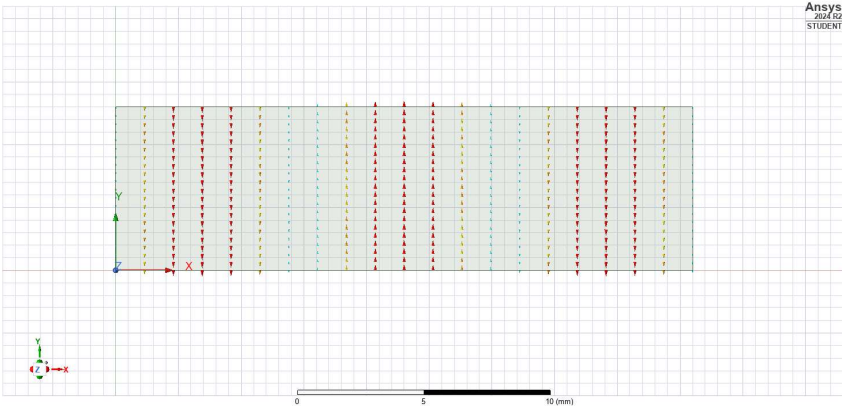


Figure 4 - Port Field Display for Mode 3

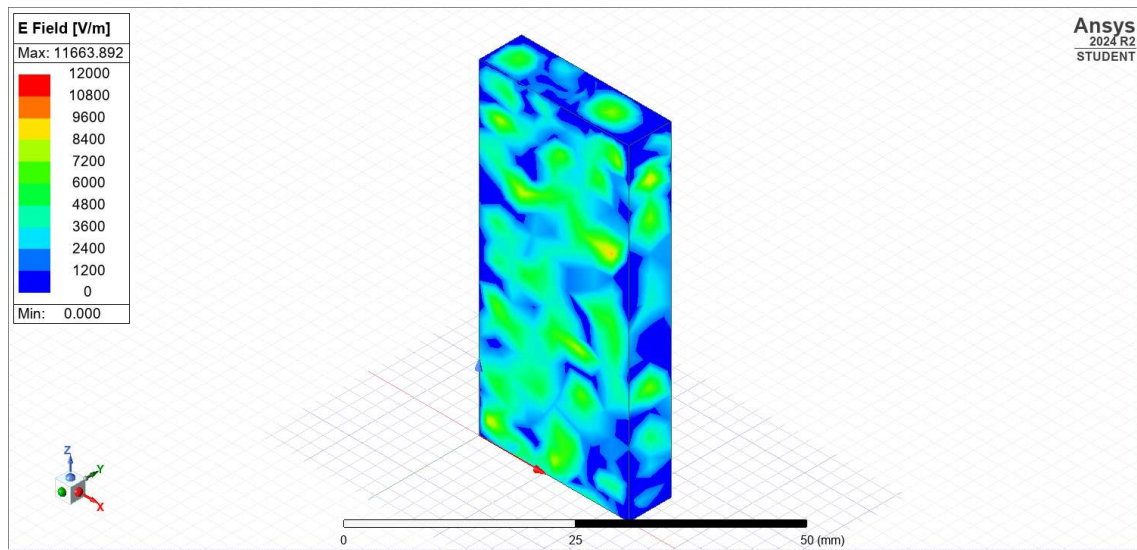


Figure 7 - Mode 1 E Field Magnitude

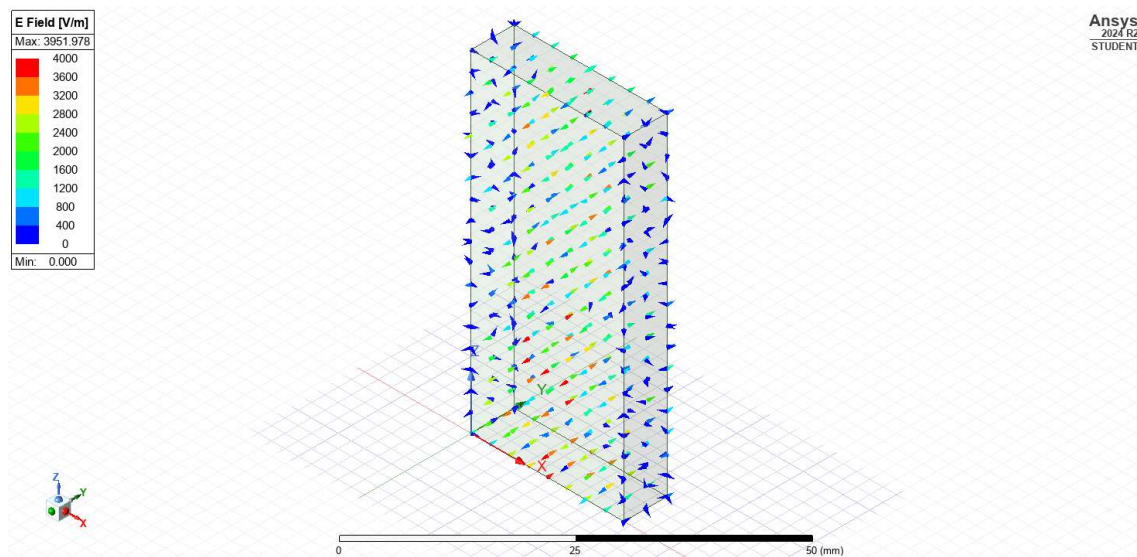


Figure 8 - Mode 1 E Field Vector

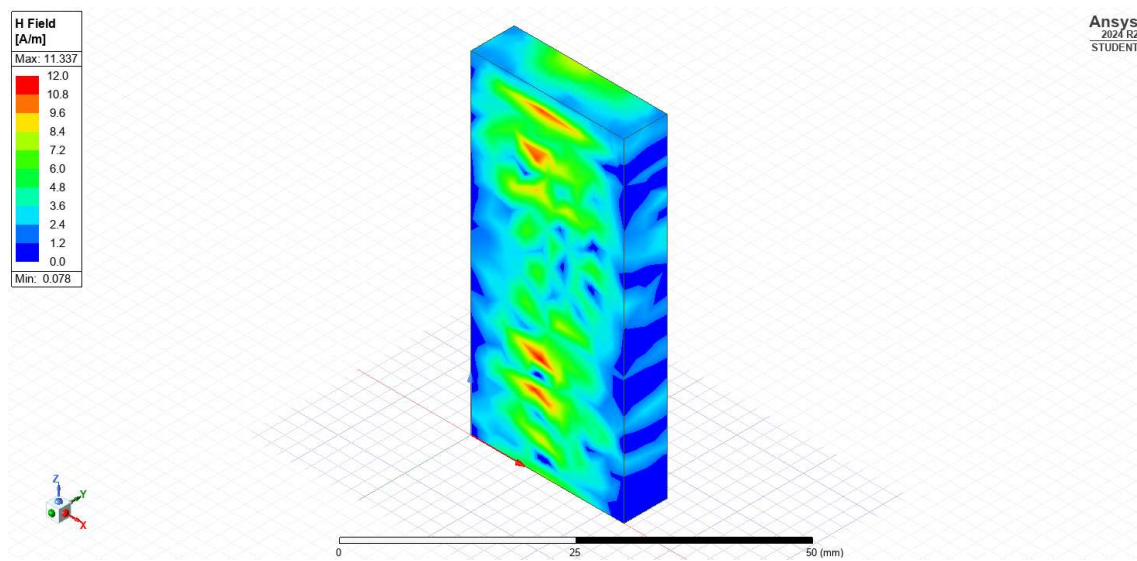


Figure 9 - Mode 1 H Field Magnitude

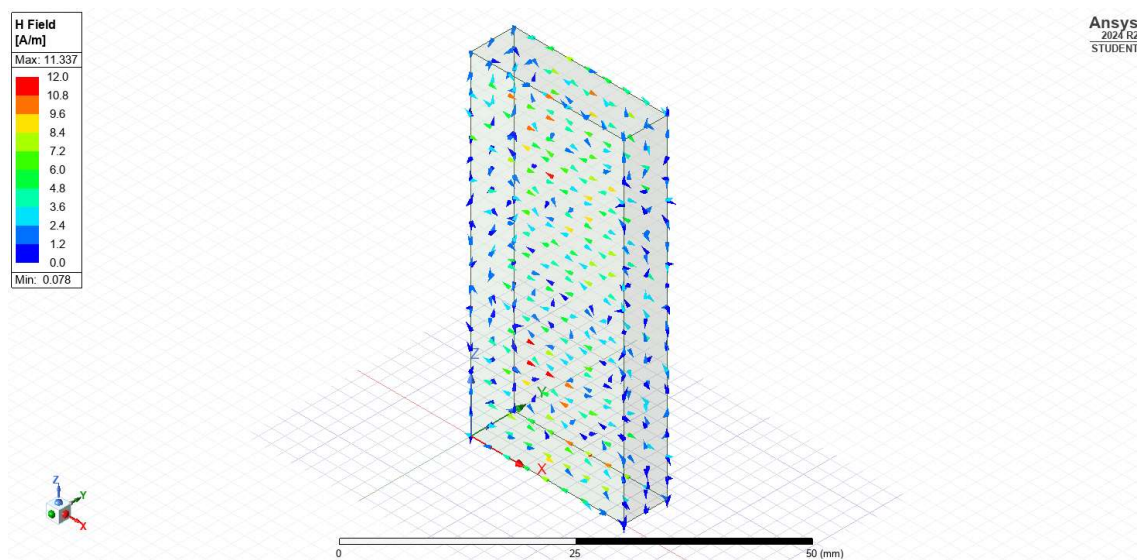


Figure 10 - Mode 1 H Field Vector

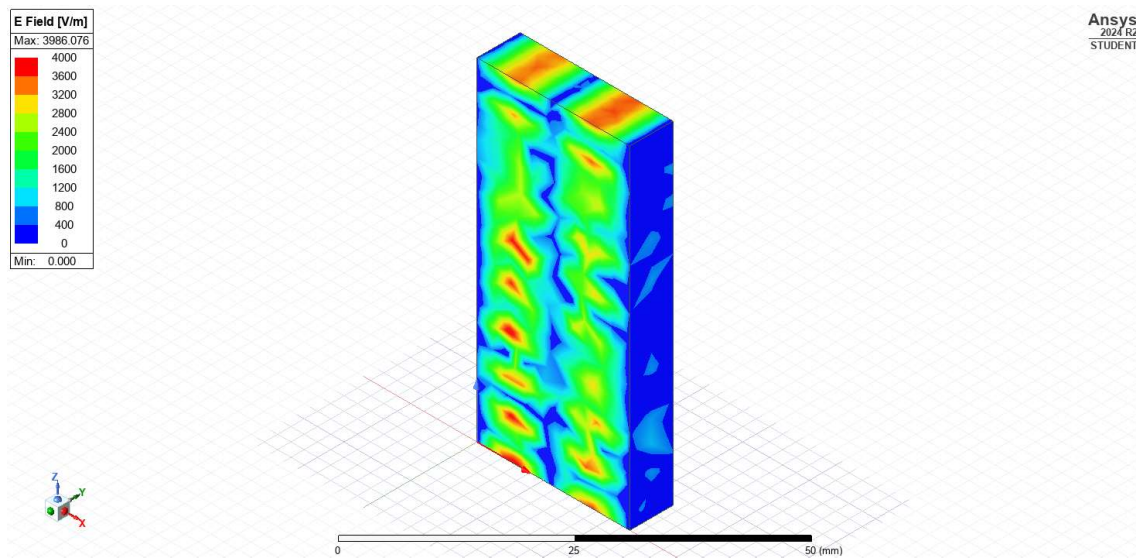


Figure 11 - Mode 2 E Field Magnitude

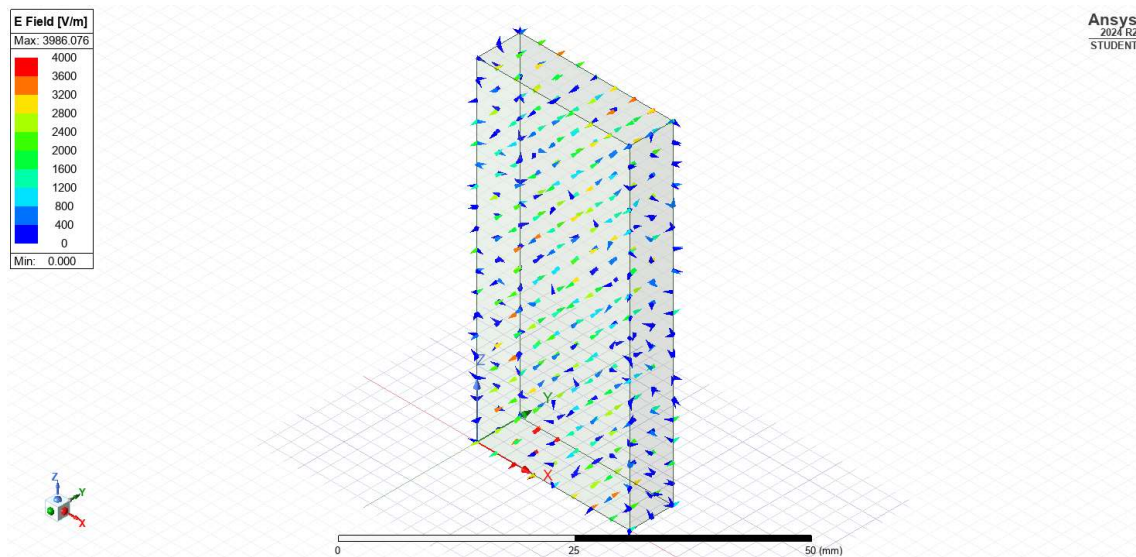


Figure 12 - Mode 2 E Field Vector

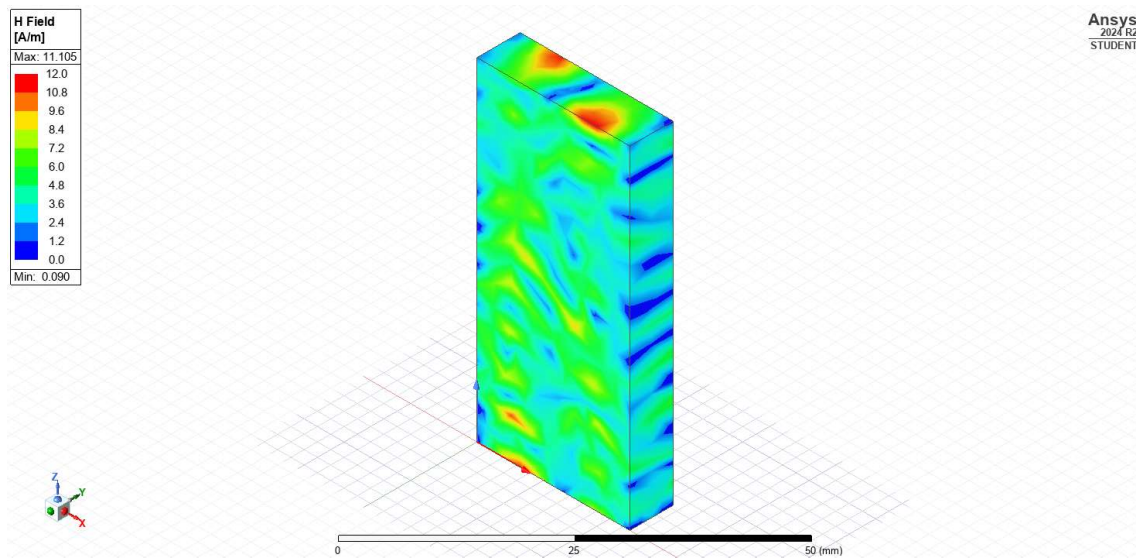


Figure 13 - Mode 2 H Field Magnitude

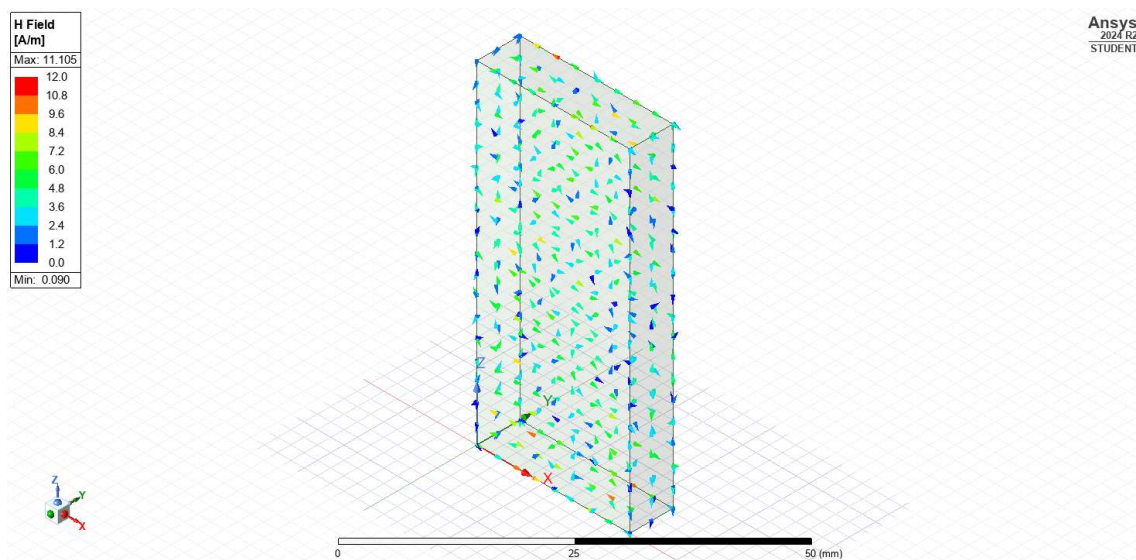


Figure 14 - Mode 2 H Field Vector

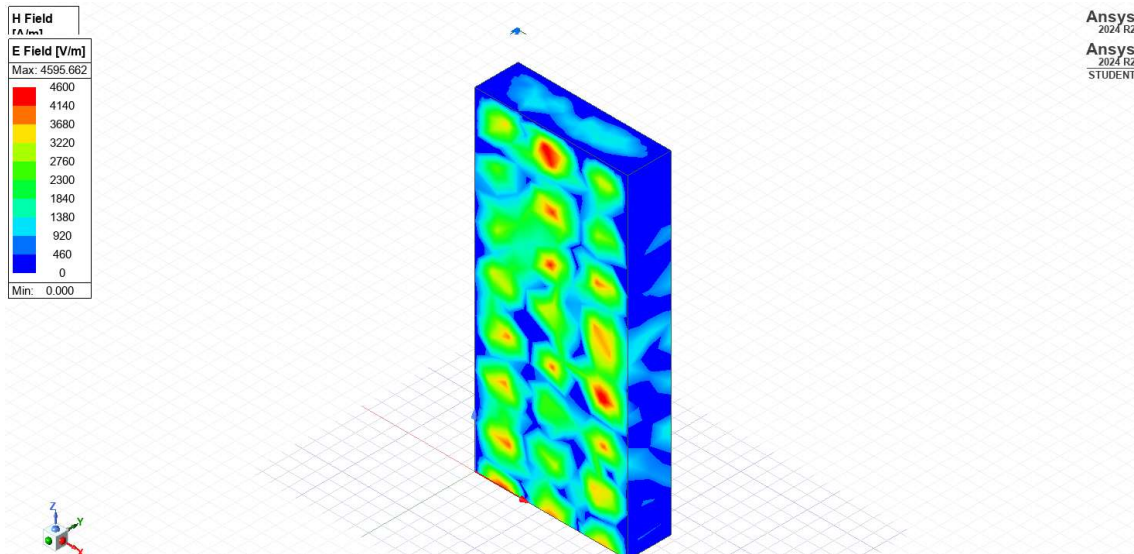


Figure 15 - Mode 3 E Field Magnitude

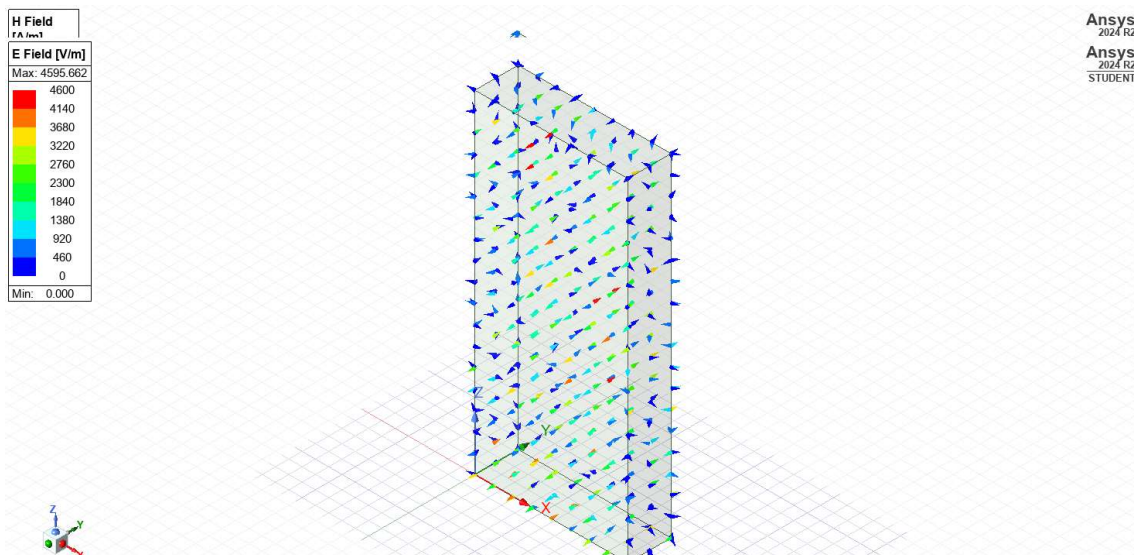


Figure 16 - Mode 3 E Field Vector

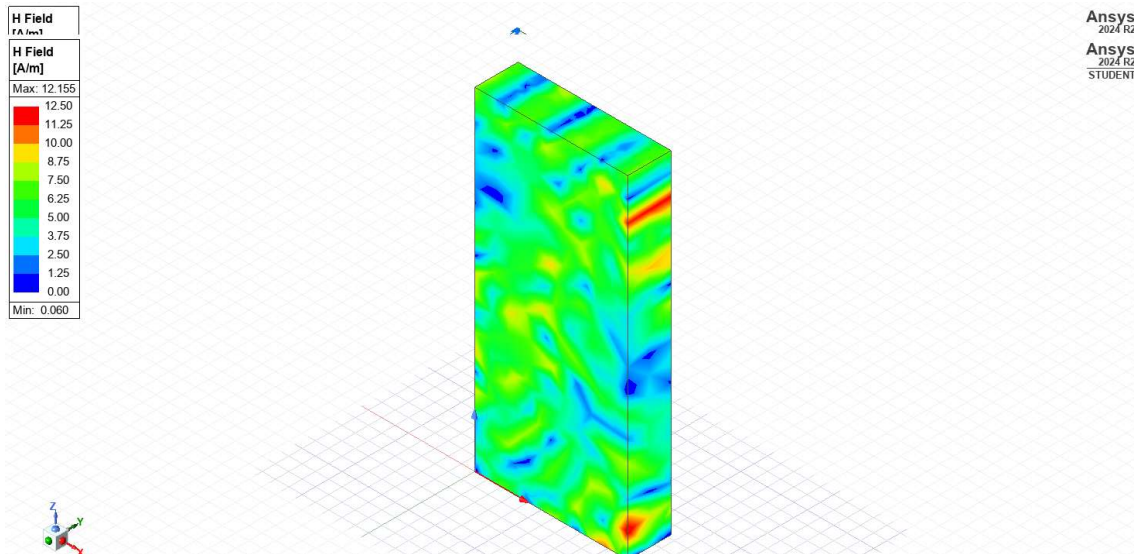


Figure 17 - Mode 3 H Field Magnitude

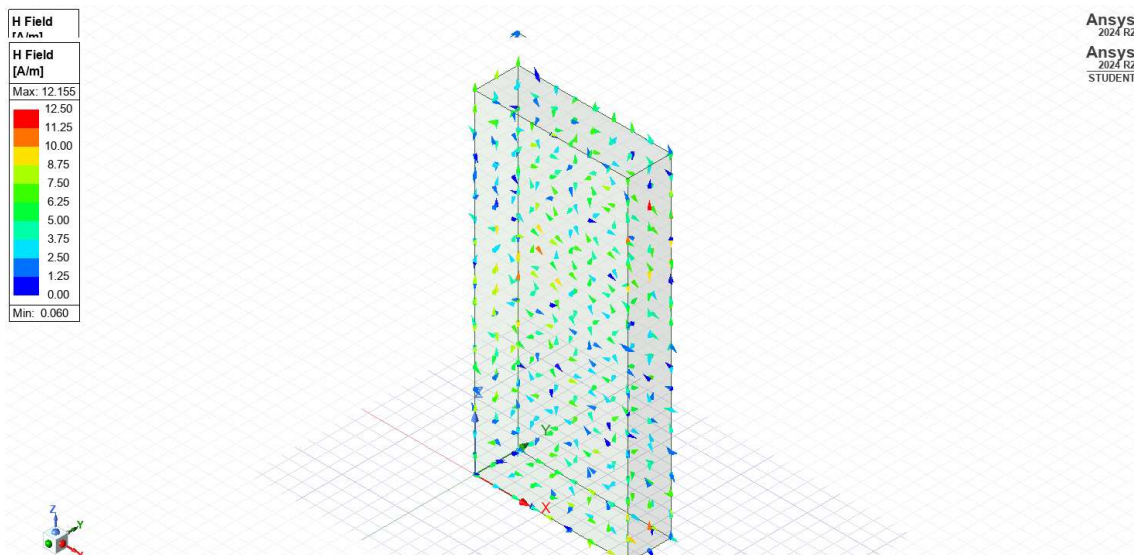
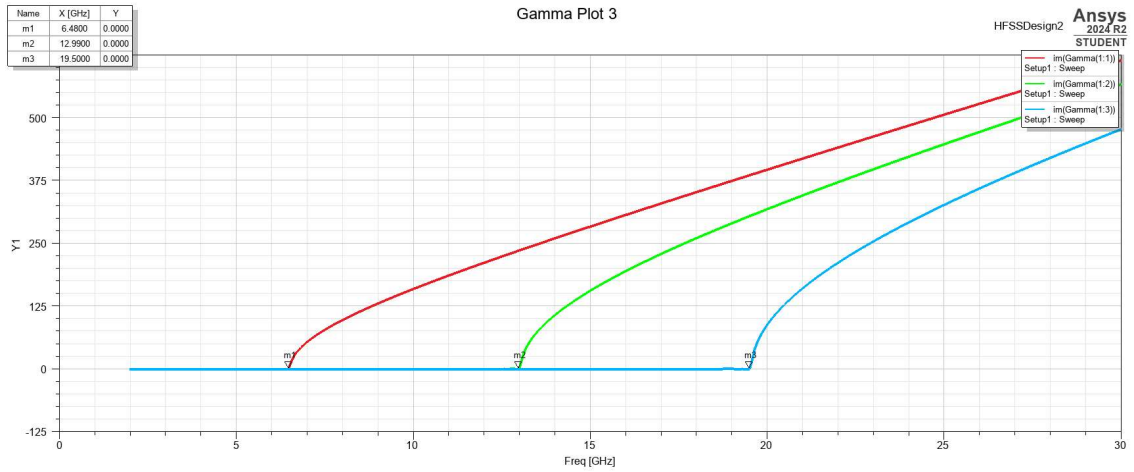


Figure 18 - Mode 3 H Field Vector



Graph 1 - Rectangular Plot Showing Cut-off Frequencies for Three Modes

Appendix B Results of Task 1b

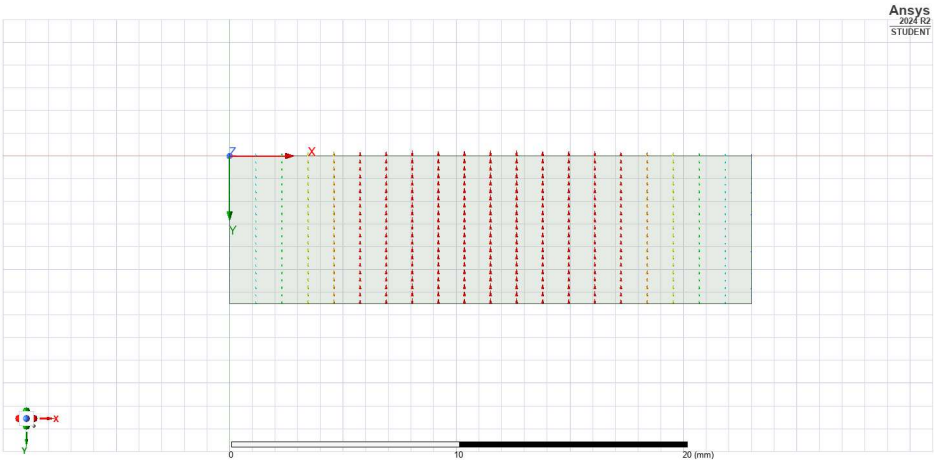


Figure 19 - Port Field Display for Mode 1

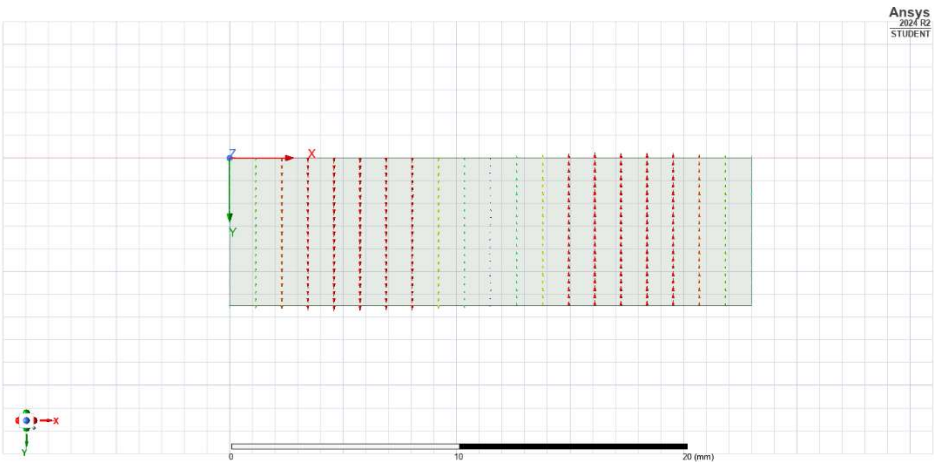


Figure 20 - Port Field Display for Mode 2

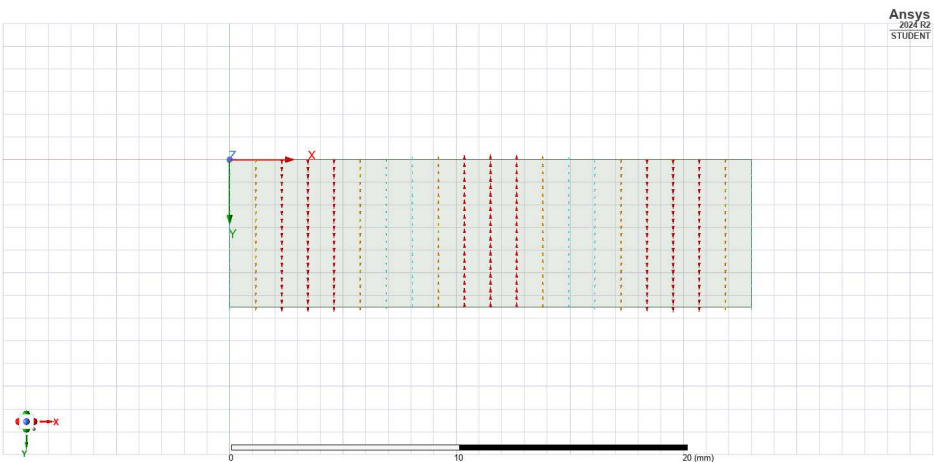


Figure 21 - Port Field Display for Mode 3

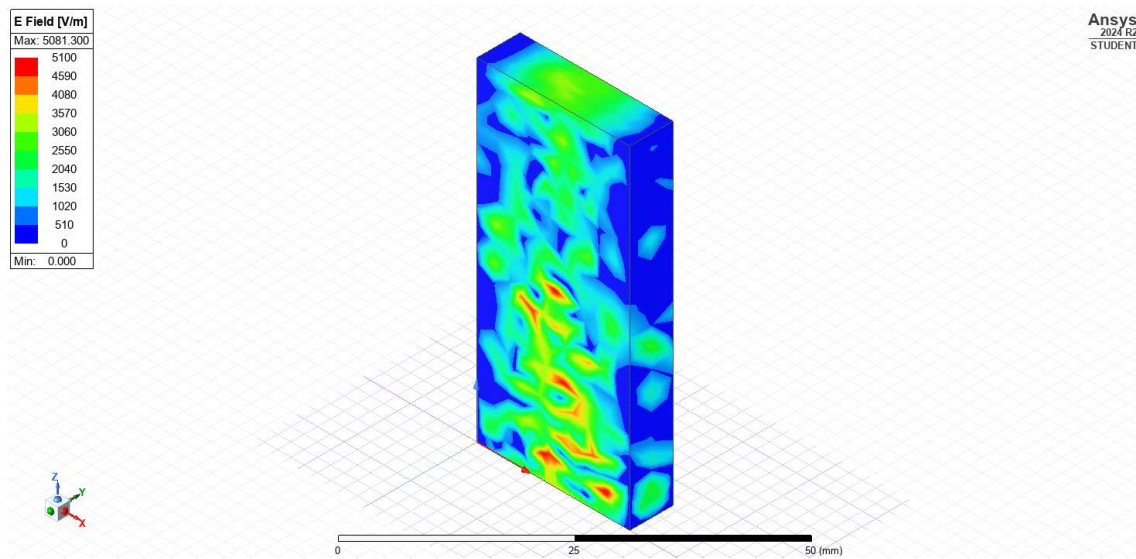


Figure 22 - Mode 1 E Field Magnitude

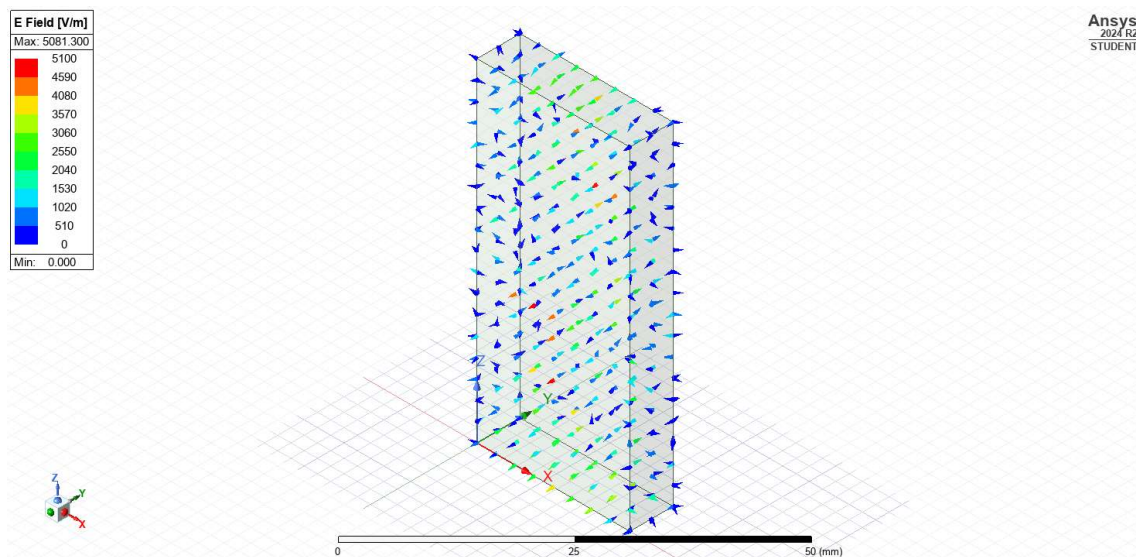
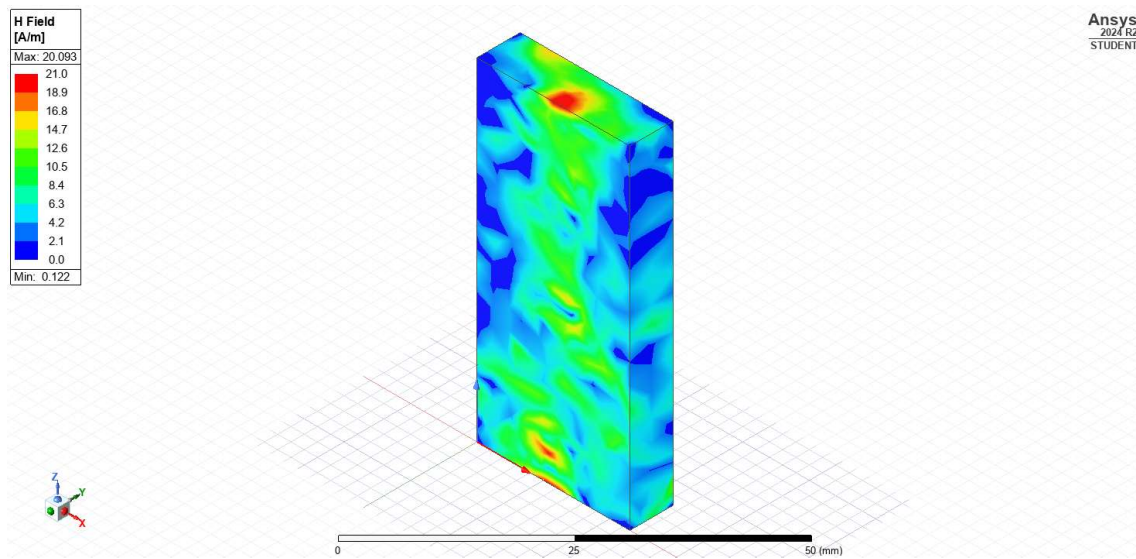
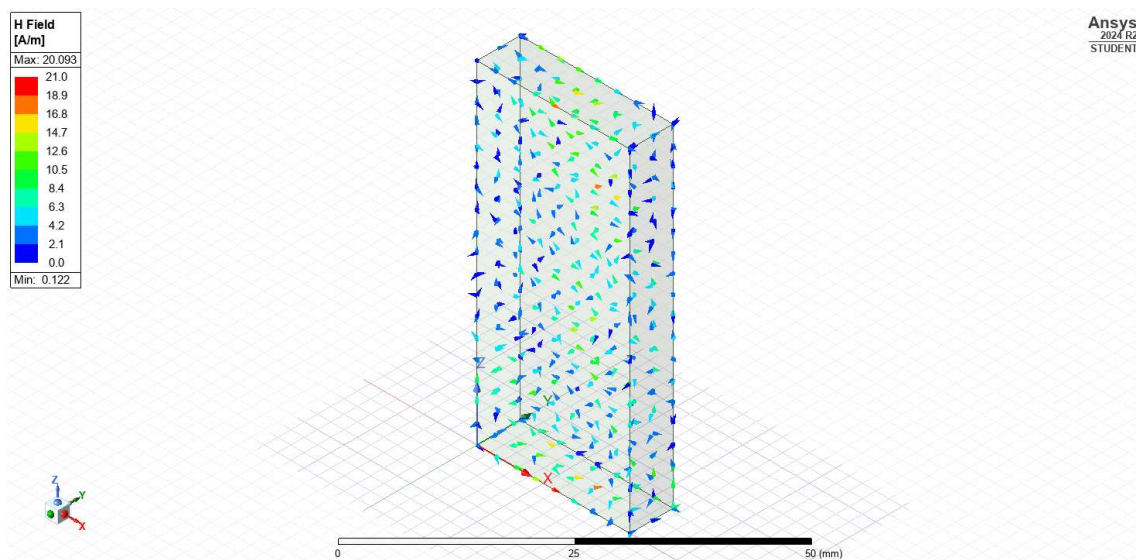


Figure 23 - Mode 1 E Field Vector



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Figure 24 - Mode 1 H Field Magnitude



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2024 R2
STUDENT

Figure 25 - Mode 1 H Field Vector

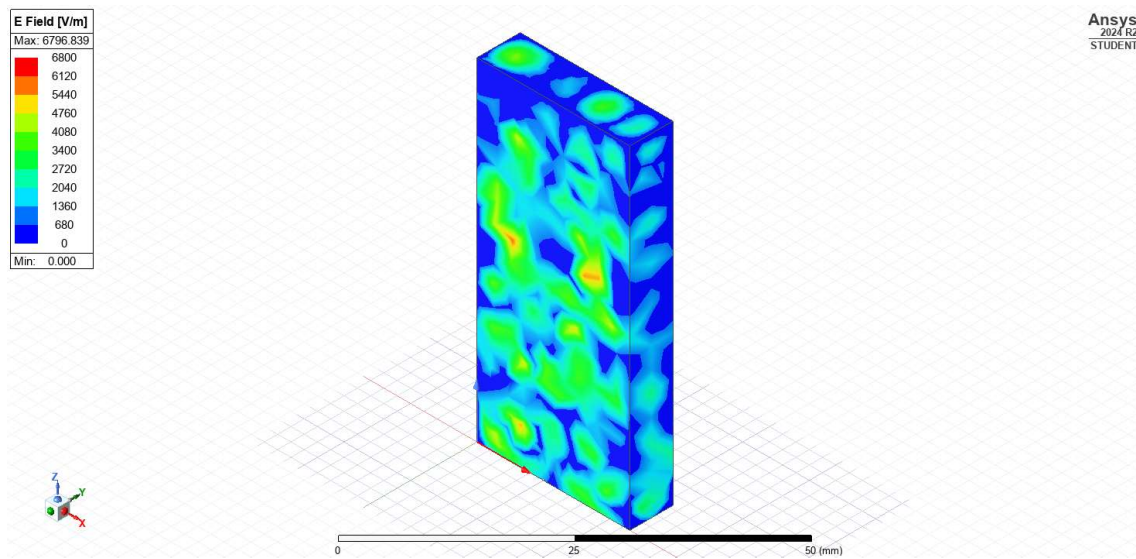


Figure 26 - Mode 2 E Field Magnitude

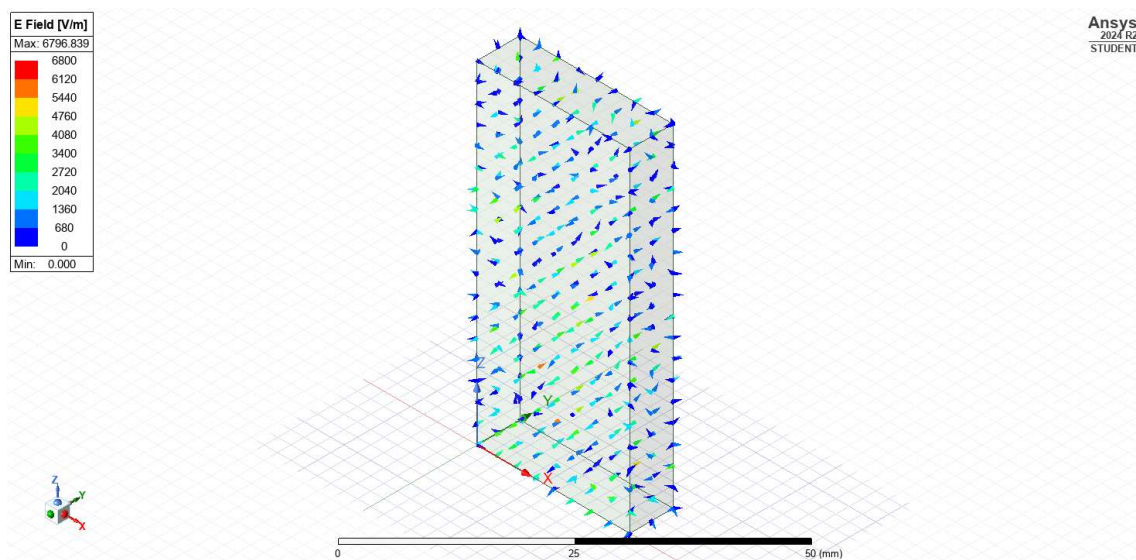


Figure 27 - Mode 2 E Field Vector

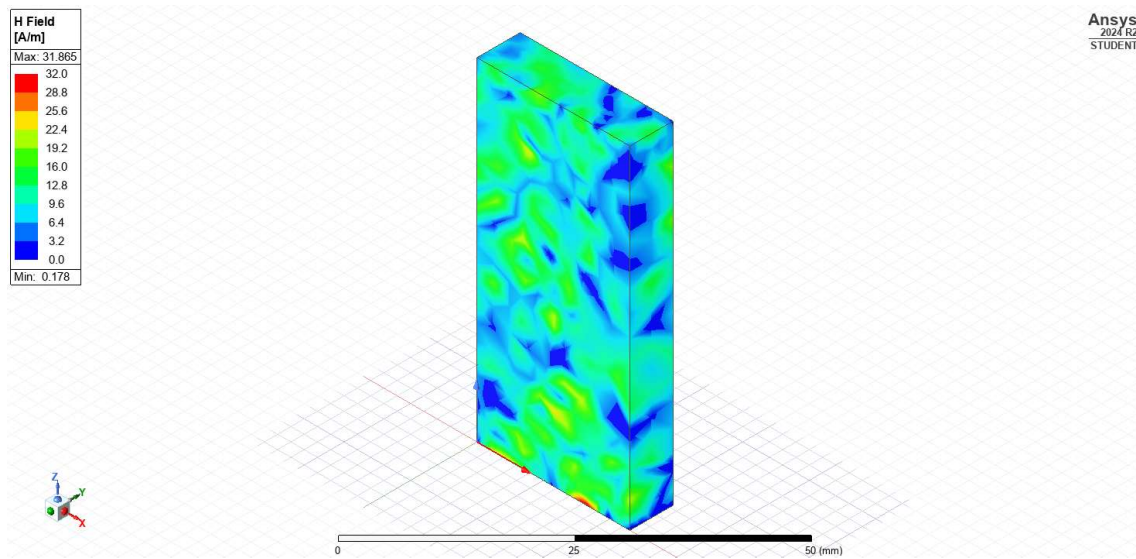


Figure 28 - Mode 2 H Field Magnitude

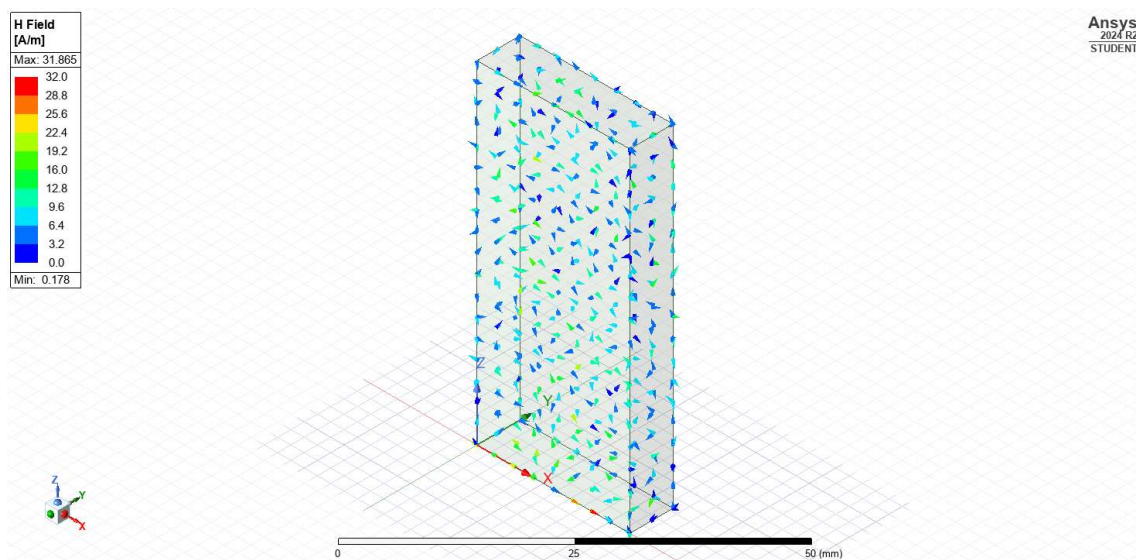


Figure 29 - Mode 2 H Field Vector

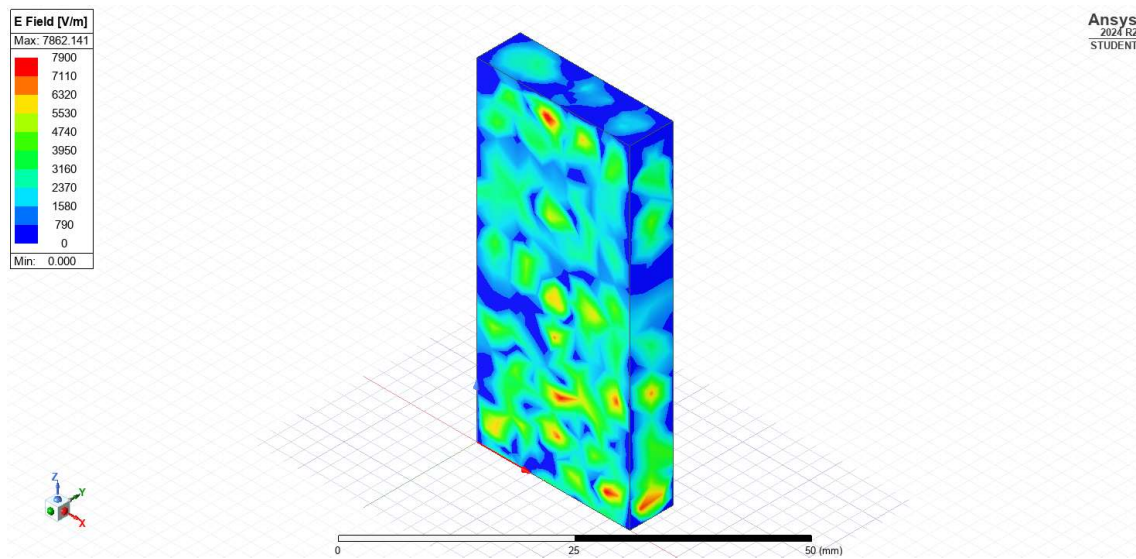


Figure 30 - Mode 3 E Field Magnitude

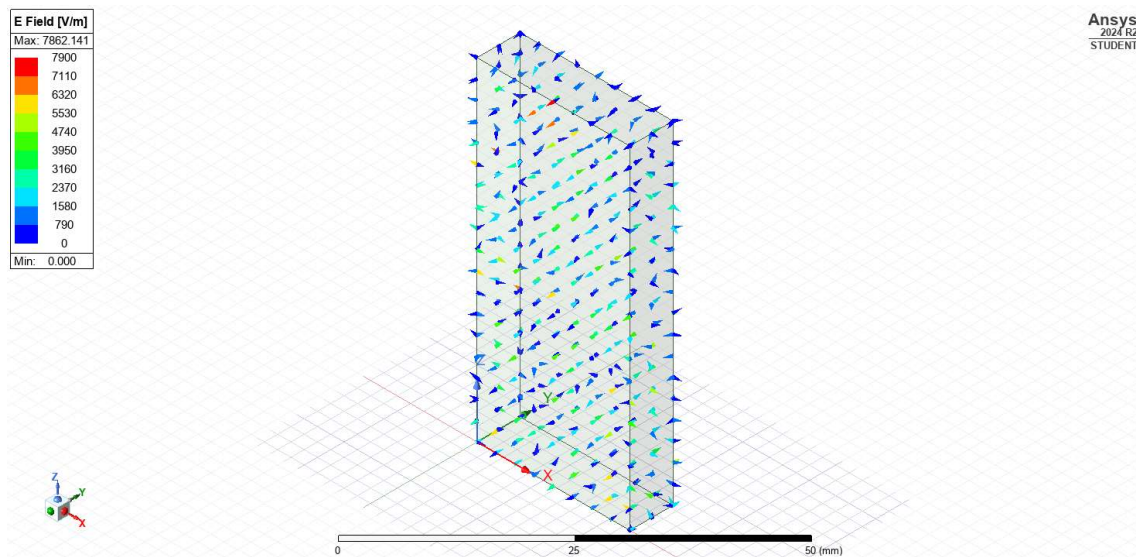
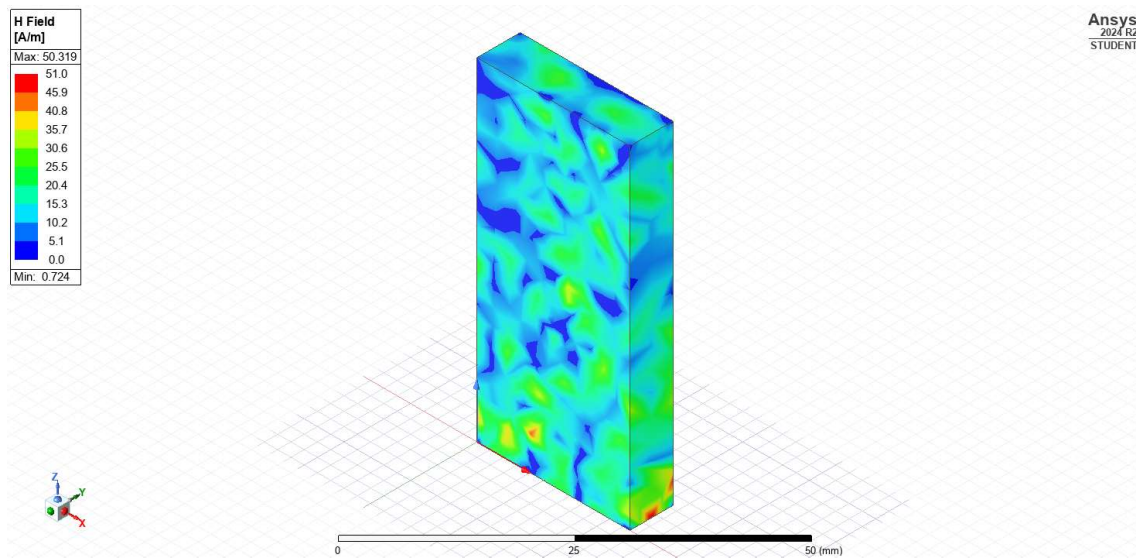
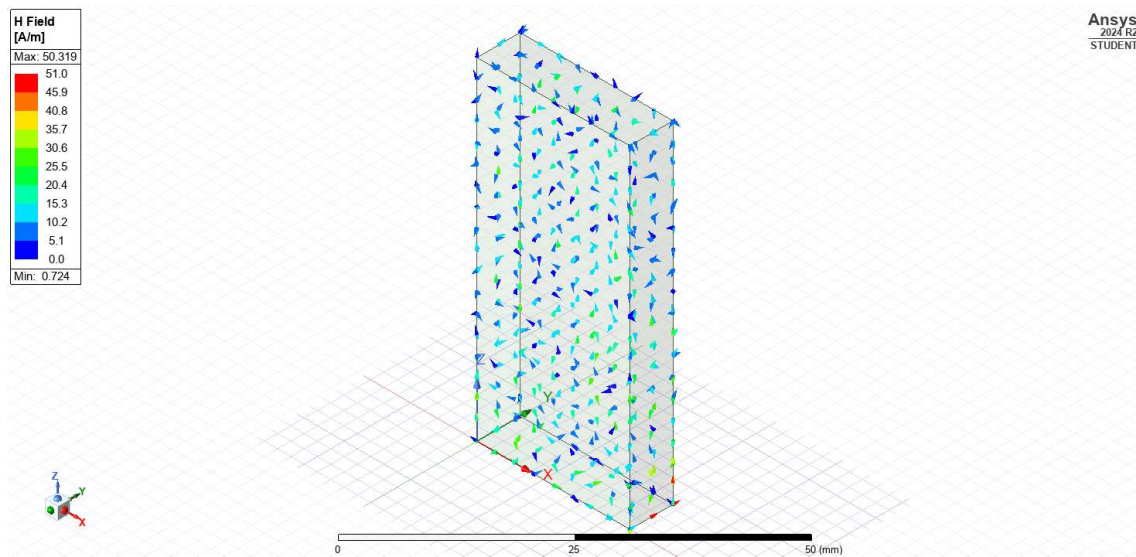


Figure 31 - Mode 3 E Field Vector



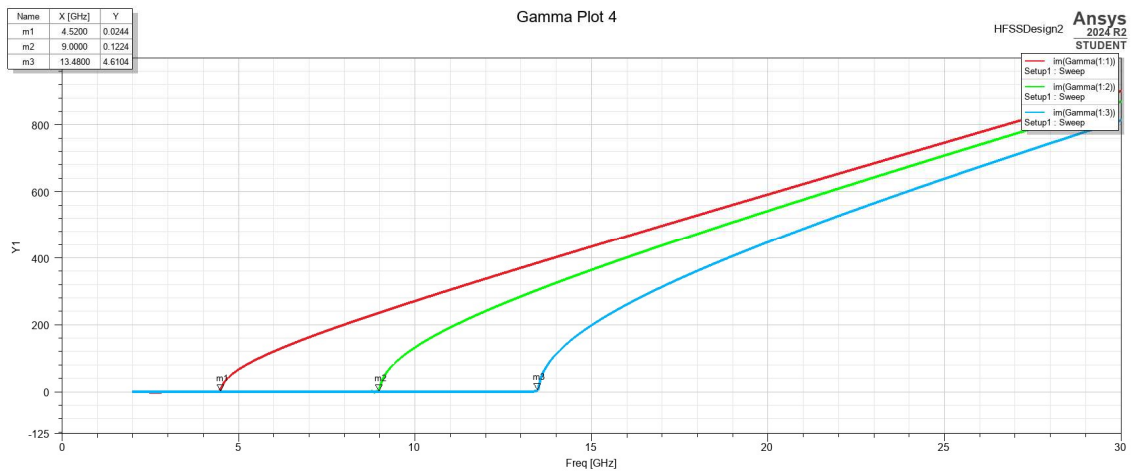
Ansys
2024 R2
STUDENT

Figure 32 - Mode 3 H Field Magnitude



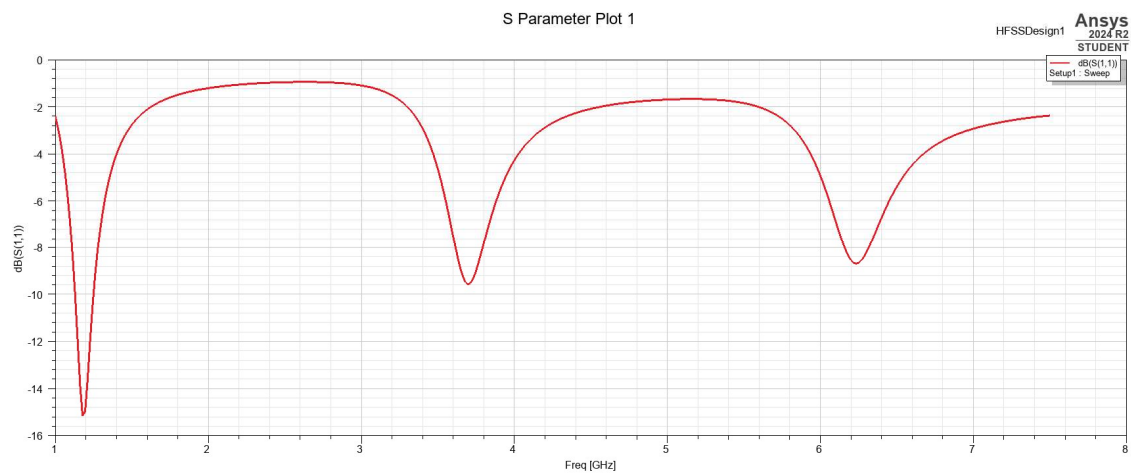
Ansys
2024 R2
STUDENT

Figure 33 - Mode 3 H Field Vector



Graph 2 - Rectangular Plot Showing Cut-off Frequencies for Three Modes

Appendix C Results of Task 2



Graph 3 - Antenna S-parameter Plot

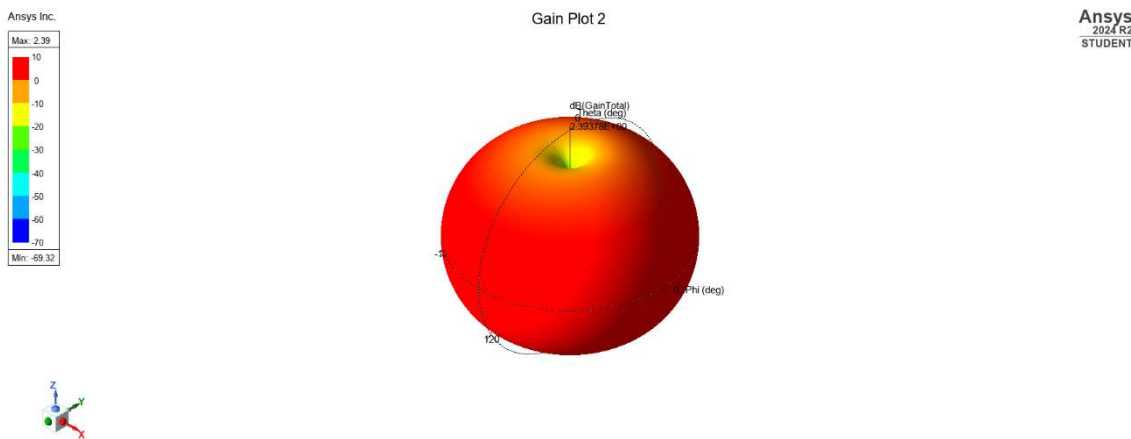


Figure 34 - Antenna Gain Plot