

Analysis of Electromagnetic Wave Propagation

L5 Electromagnetic Radiation Module (OME Degree) - ACDC5009

Alex Lamdin

19th July 2024

Abstract

To ensure that a waveguide or antenna performs as desired, it is imperative that the characteristics of electromagnetic radiation and electromagnetic wave propagation are properly understood.

This report explores the construction and function of two electromagnetic devices, a Rectangular Waveguide and a Half-Wavelength Dipole Antenna, and evaluates the performance of two case studies to determine the optimum operating characteristics.

Table of Contents

1. Introduction
2. Task 1 – Rectangular Waveguide
 - 2.1. Method
 - 2.2. Results
 - 2.2.1. Port Field Display
 - 2.2.2. Field Vectors & Magnitudes
 - 2.2.3. Cut-Off Frequency Plot
 - 2.3. Discussion
 - 2.3.1. Task 1A (Vacuum Filled)
 - 2.3.2. Task 1B (Teflon Filled)
 - 2.3.3. Comparison
3. Task 2 – Half-Wave Dipole Antenna
 - 3.1. Method
 - 3.2. Results
 - 3.2.1. S-Parameter Plot
 - 3.2.2. Radiation Pattern
 - 3.3. Discussion
4. Conclusion
5. References

1. Introduction

This report consists of two sections, both of which explore the propagation of electromagnetic waves. In section 1, the characteristics of a rectangular waveguide are explored, including the different transmission modes, their respective cutoff frequencies and how these characteristics change when the materials used to construct the waveguide are varied. Then, section 2, evaluates the operational frequency of a Half-Wave Dipole antenna, and models the emitted radiation pattern.

-

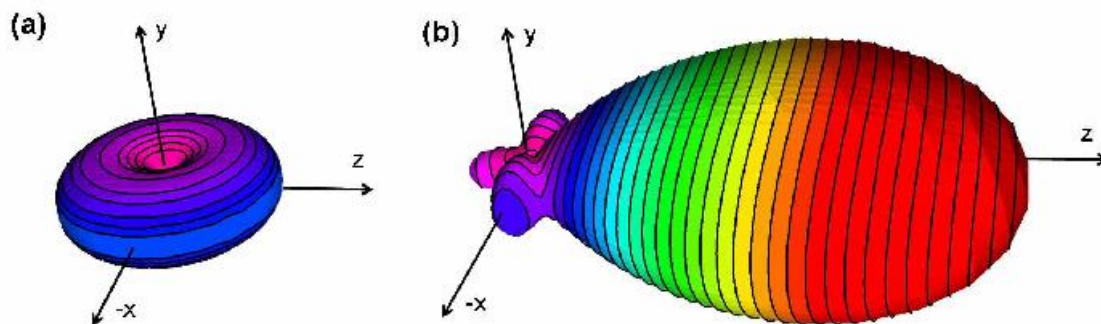
To summarise it simply, a waveguide is a device used to direct the propagation of an electromagnetic wave. It is usually used to guide the wave between two locations, such as a source and a transmitter. Waveguides can take many forms; however, they all feature a “pipe”, through which the radiation travels. This could be an optical fibre, where the EMR is visible light, or, as in our case study, a pipe constructed of a highly conductive material (often metal), with the void within containing either a vacuum or other dielectric substance. This type of waveguide is usually of circular or rectangular cross-section [1]

It is worth mentioning that other waveguide devices do exist, that are able to split, combine or multiply input frequencies. All waveguides are subject to a cutoff frequency, below which the wave will not propagate as intended.

With the modern world so reliant on EMR, it is not surprising that waveguides can be found almost everywhere, from fibre optics in data connections, to coaxial cables used for televisions, to rectangular waveguides featured in microwave ovens. [2],[3],[4]

-

A dipole antenna is one of the simplest (and quite possibly the most widely used) types of antennas used in RF communications. It consists of two conductive elements, typically wires or rods, usually of equal length that are oriented in a straight line. These elements are then fed with an RF signal at their centre point, making the structure resemble the shape of a "T" or a straight wire/rod with a gap in the middle. As used in our case study, a half-wavelength dipole antenna is a particular type of dipole antenna, where each of the two elements is half the length of the desired transmission wavelength. [5] The emission pattern of a dipole antenna is omnidirectional, being a torus or “donut” shape with the antenna at its centre. [6] This can be seen in figure (a).



Figures (a), (b)

The dipole antenna is also often seen arrayed in with passive “reflector” and “director” elements in decreasing order of size, in a format known as a Yagi-Uda (YU) antenna. This configuration offers several significant benefits, the most notable of which are high directivity, much increased signal strength and minimal lobes. [7] The layout of the elements can be seen in figure (c). In contrast to the dipole antenna, the emission pattern of the YU antenna is highly directional. This can be seen in figure (b).

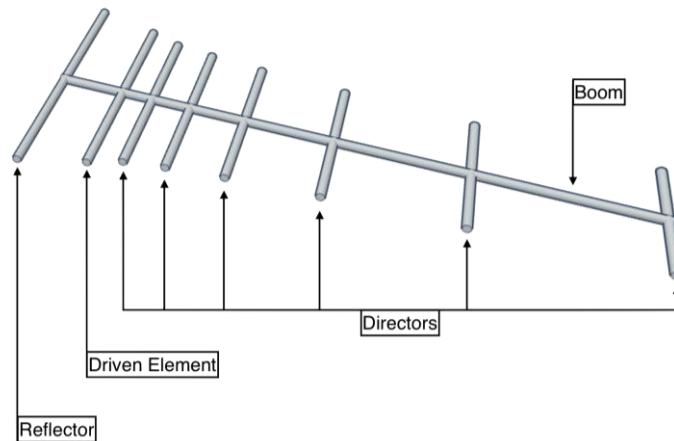


Figure (c)

Due to its operating characteristics, the YU antenna is commonly used in FM Radio, Television receiving, direction finding and military applications. [8]

-

With both rectangular waveguides and dipole waveguides used so frequently, it is important that their characteristics be properly understood so that they can be constructed correctly so that the desired frequency is propagated/transmitted in the manner expected and their output utilised effectively.

-

Both the rectangular waveguide and dipole antenna models in this report were done using the High Frequency Structure Simulation (HFSS) mode on the Ansys Electronics Student Software suite, as taught in lectures within the module.

2. Task 1 – Rectangular Waveguide

2.1 - Method

The two primary dimensions of rectangular waveguides are its width (a) and its height (b). These are usually determined to support propagation of the dominant mode. The dominant mode is the mode that has the lowest cutoff frequency; this means it is the mode that can propagate at the lowest frequency and is typically the most used mode in practical applications.

Following the task directions, the dimensions of (a) and (b) were derived from the author's student number (2217661), thus being:

(a): 22 (first two digits)

(b): 8.5 (next two digits divided by 2)

All dimensions used were in mm to allow the corresponding wavelengths and frequencies to be measured without issue. The length as given in the task was 50mm.

A rectangular waveguide with these dimensions was thus drawn up in Ansys Electronics HFSS. The model was centered upon the origin and the two end faces were assigned excitations, to function as Port 1 and Port 2. These ports were then both assigned three modes. The 4 side faces were modelled as walls consisting of "Perfect Electrical Conductor" (PEC). Finally, the waveguide was modelled as being filled with vacuum in part 1A and being filled with Teflon in part 1B.

As instructed in the task, The analysis section of the software was then set to conduct a sweep of frequencies between 2 and 30 GHz. The model and the analytical parameters were then validated, and the model was run. This model was used to gather Port Field Displays, Field Velocity and magnitude Diagrams, and cutoff frequency plots.

2.2 - Results

2.2.1 - Port Field Displays

The field patterns of different waveguide modes are distinct and depend on the mode indices m and n , where m and n denote the number of half wavelength variations in the x- and y- directions respectively. Modes are thus described as TE_{mn} or TM_{mn} .

In rectangular waveguides, the TE_{mn} and TM_{mn} modes have characteristic distributions of the electric and magnetic fields across the waveguide cross-section. For example, in a rectangular waveguide, a TE_{10} mode has one half-wavelength variation in the x-direction and no variation in the y-direction, whereas TE_{21} mode has two half-wavelength variations in the x-direction and one in the y-direction.

To determine the dominant mode of the rectangular waveguide, port field displays were recorded for the three modes from both port 1 and port 2. The first three PFDs from the vacuum filled waveguide (Task 1A) can be seen below in Figs. 1, 2, 3.

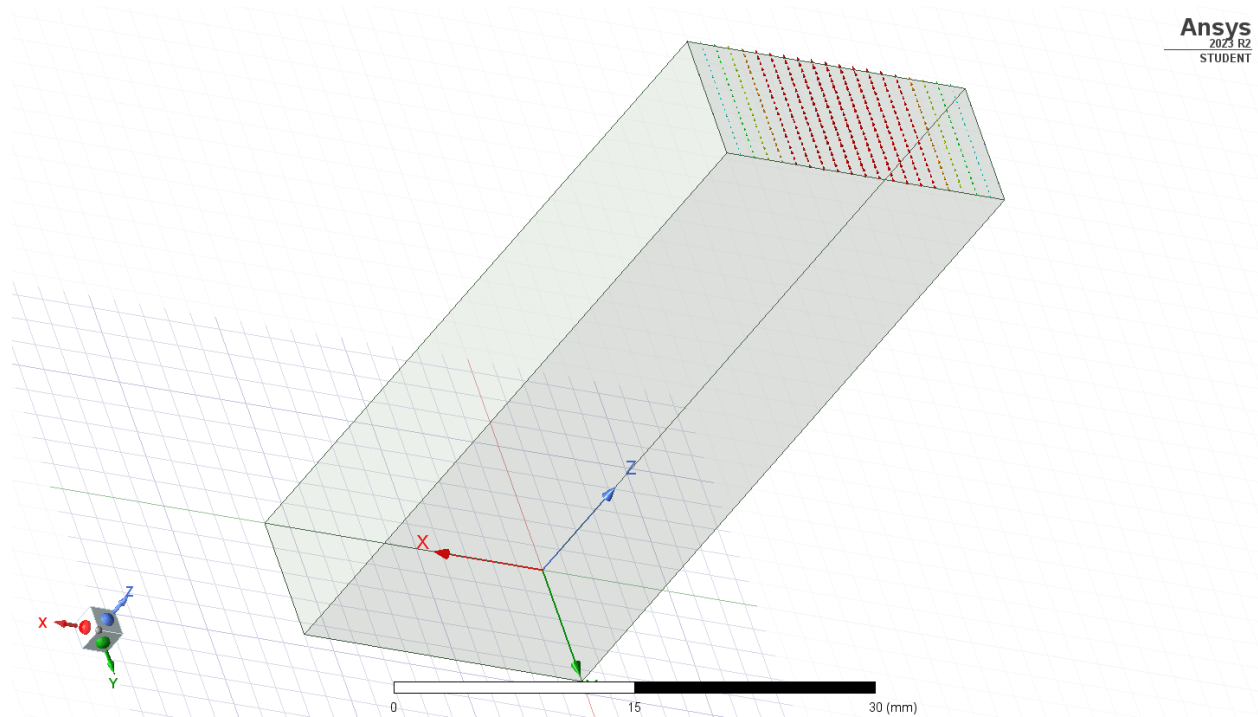


Fig. 1 – Port 1, Mode 1

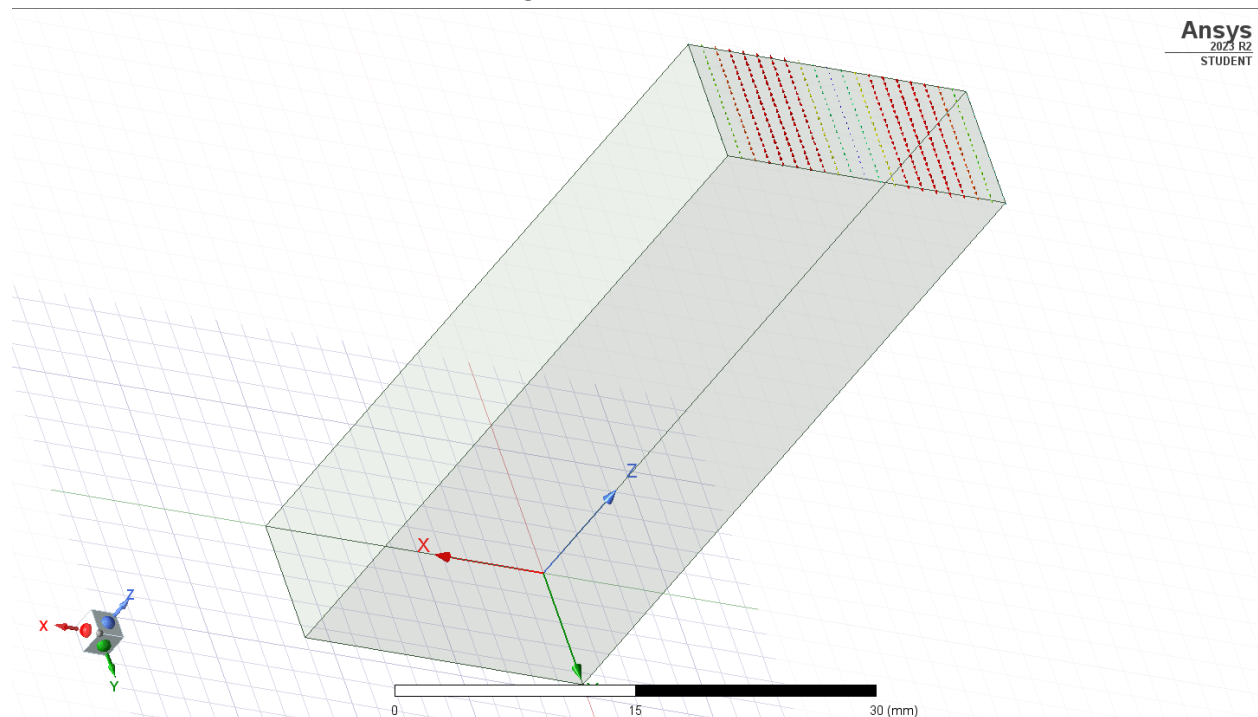


Fig. 2 – Port 1, Mode 2

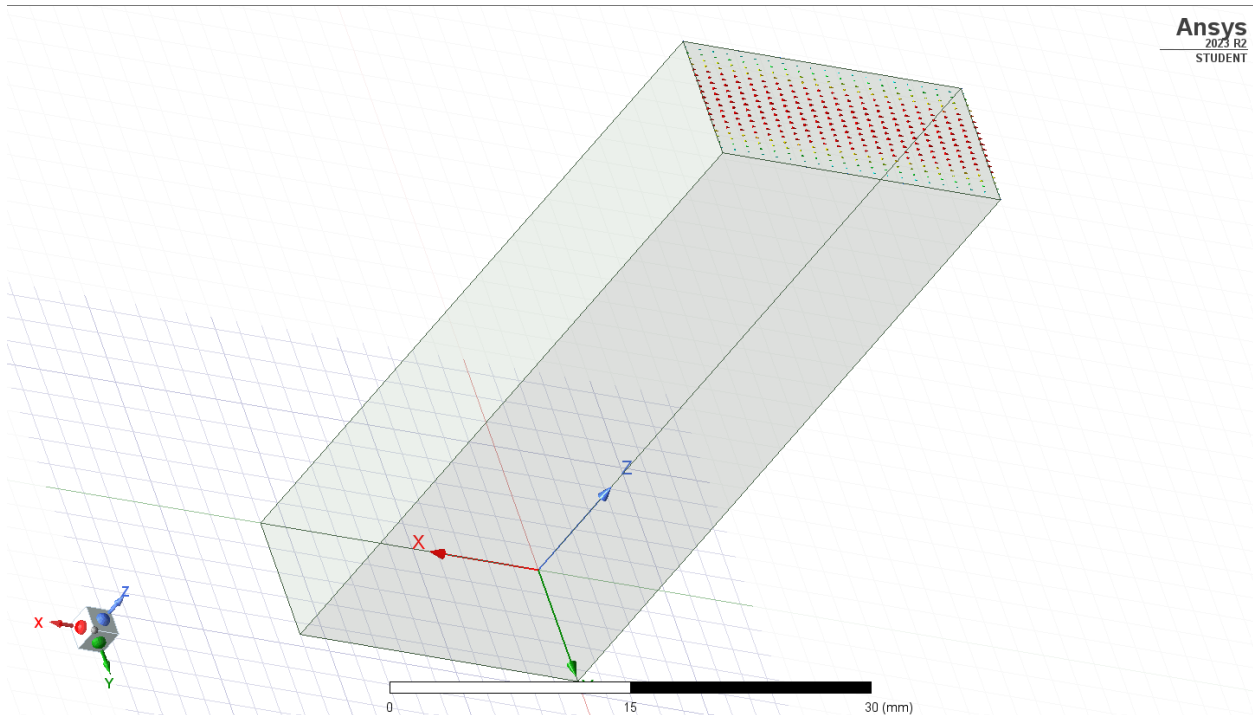


Fig. 3 – Port 1, Mode 3

By looking at these three port field diagrams, we can determine that “Mode 1” is a TE_{10} , “Mode 2” is a TE_{20} , and “Mode 3” is a TE_{01} . A further three PFDs from port 2 confirm this. These can be seen below in Figs. 4, 5, 6.

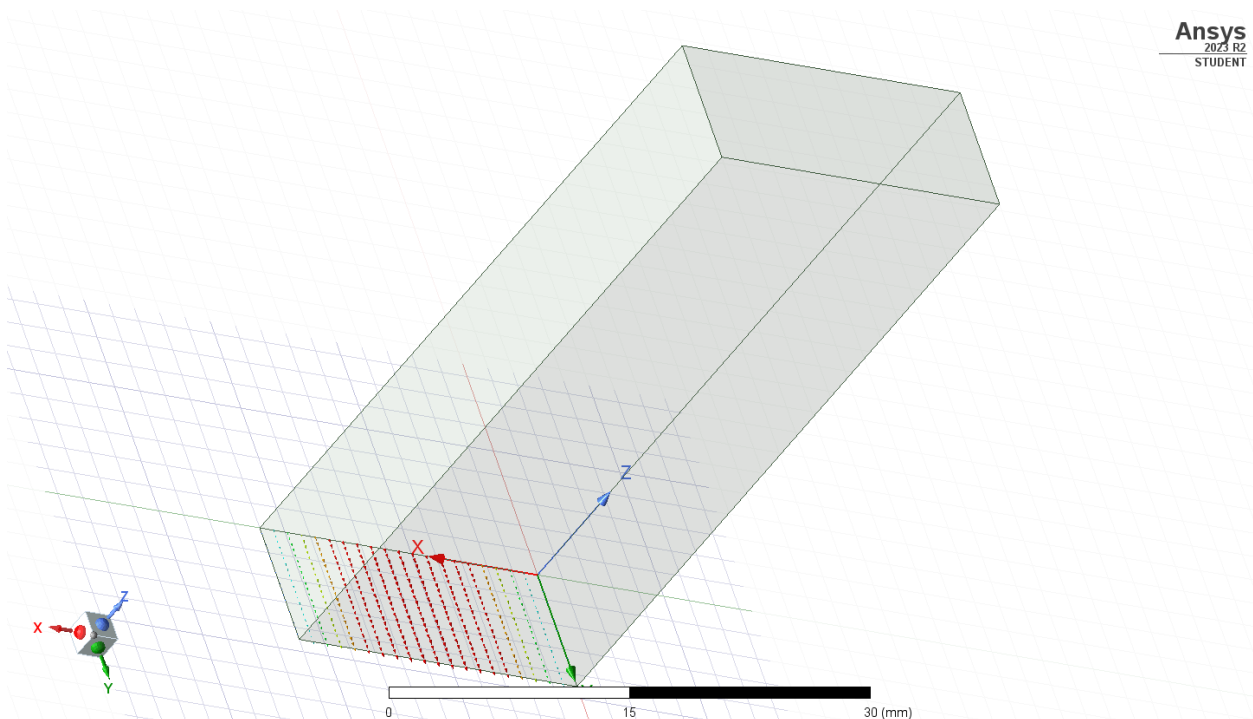


Fig. 4 – Port 2, Mode 1

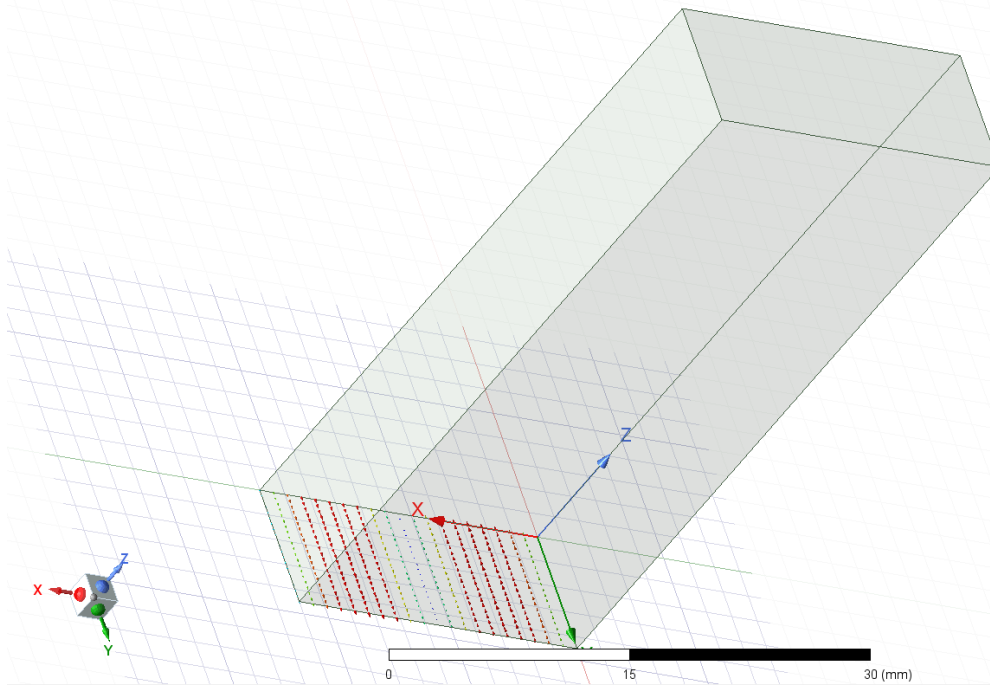


Fig. 5 – Port 2, Mode 2

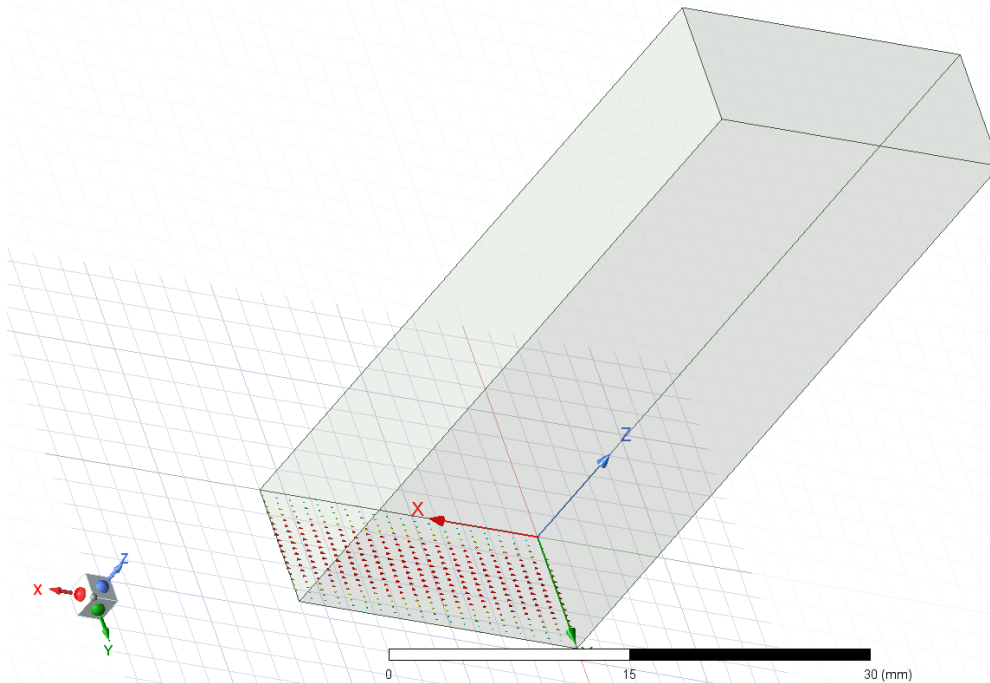


Fig. 6 – Port 2, Mode 3

Similarly, for task 1B, six port field displays were produced for the Teflon-filled waveguide, one for each mode from each of the two ports. This can be seen in Figs. 7-12.

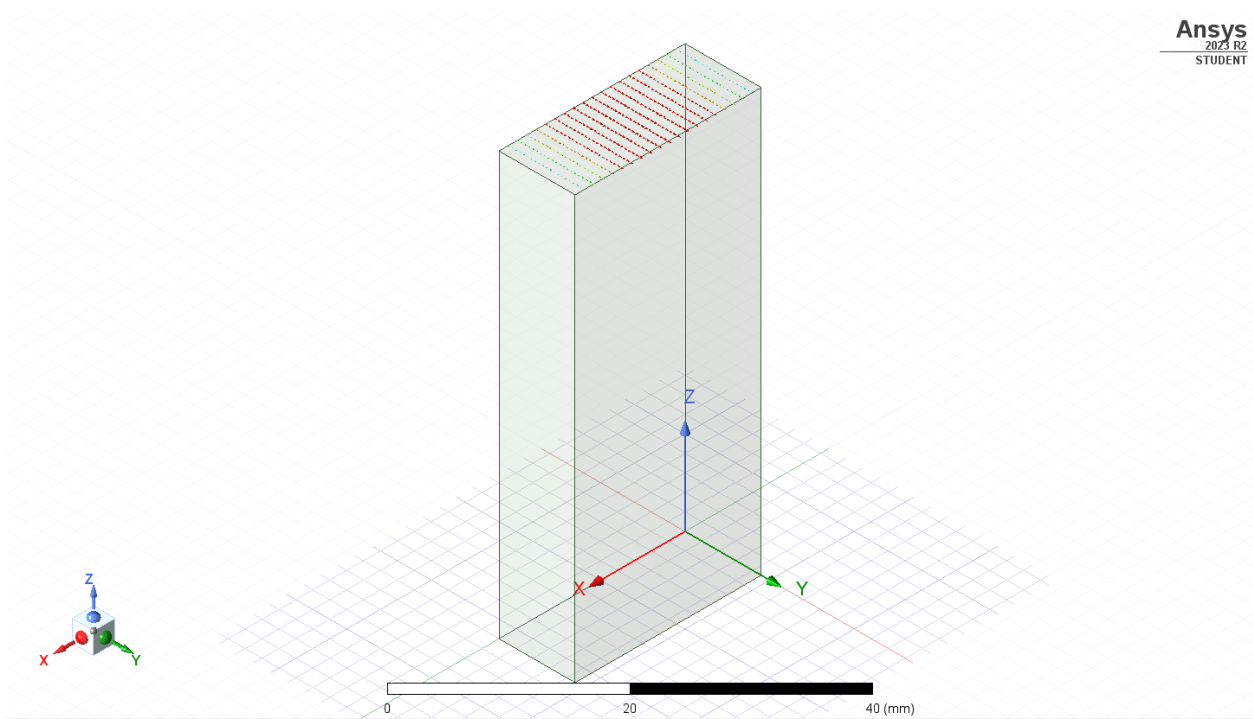


Fig. 7 – Port 1, Mode 1

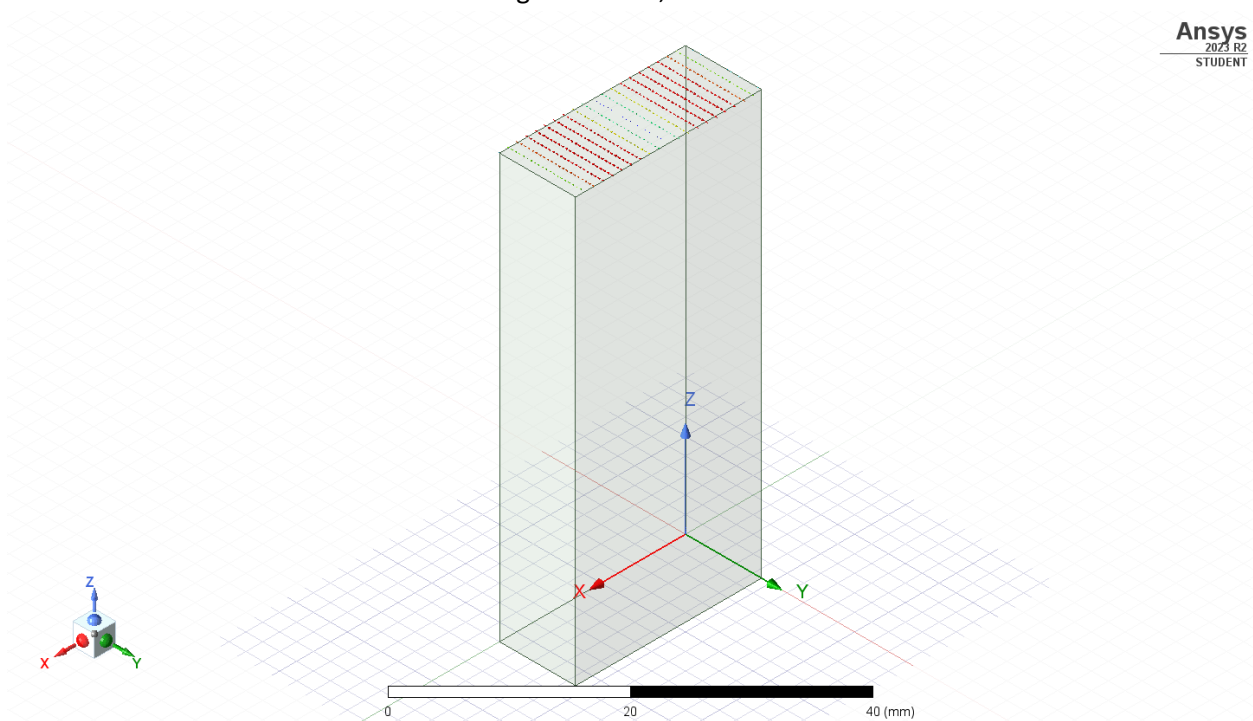


Fig. 8 – Port 1, Mode 2

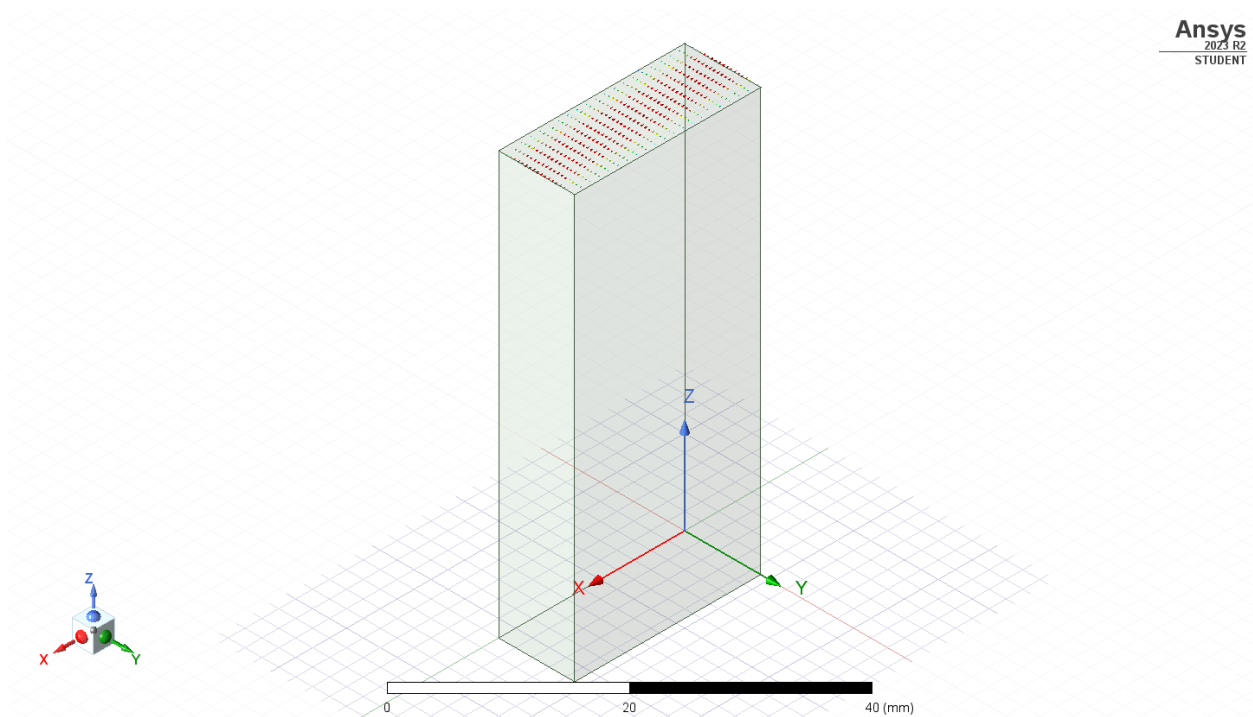


Fig. 9 – Port 1, Mode 3

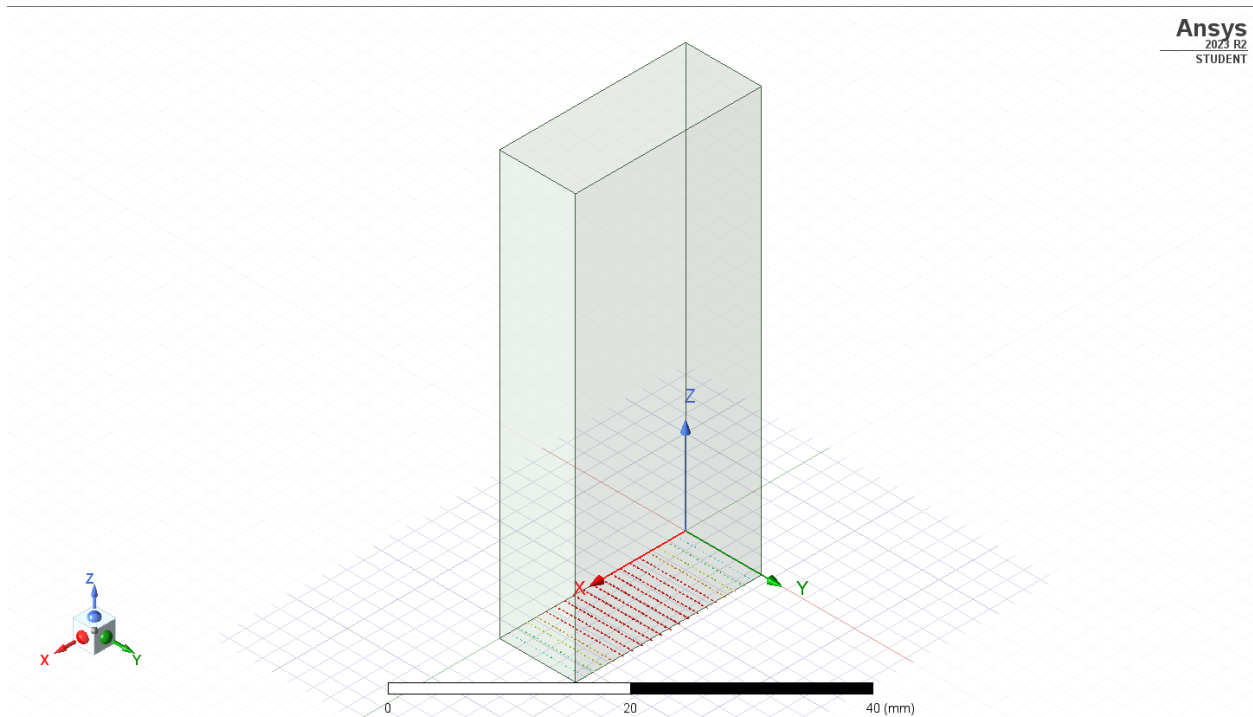


Fig. 10 – Port 2, Mode 1

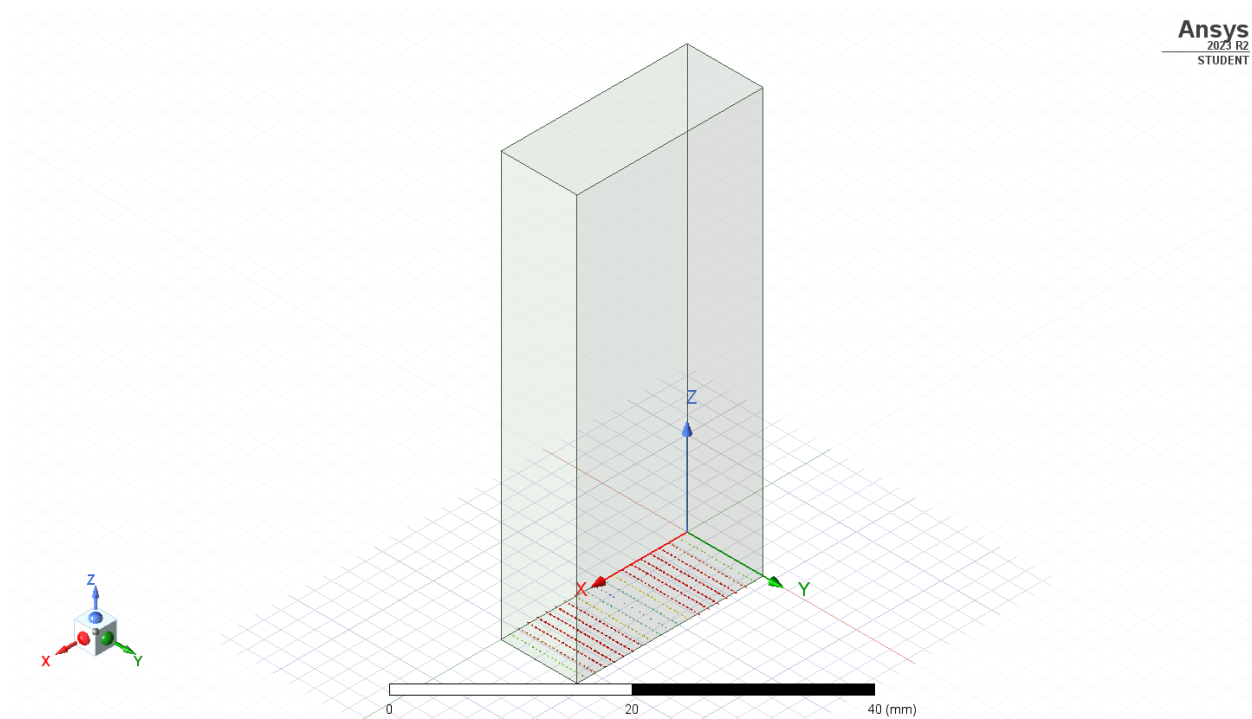


Fig. 11 – Port 2, Mode 2

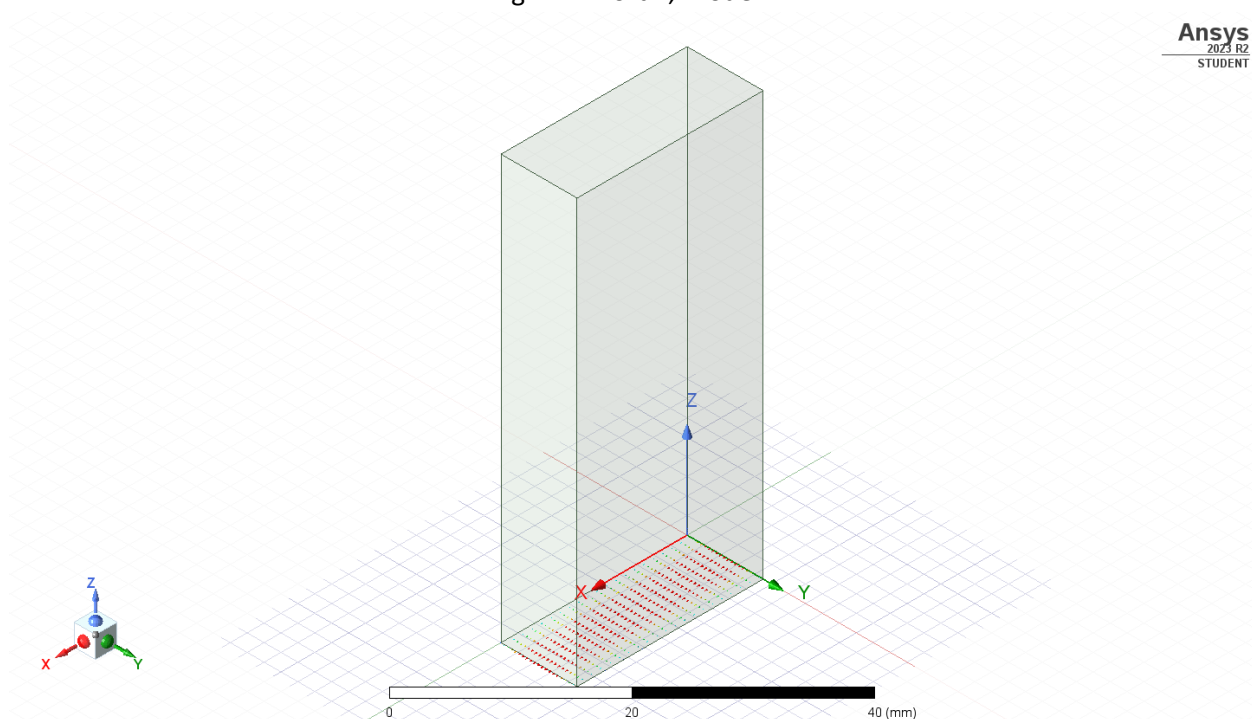


Fig. 12 – Port 2, Mode 3

Identically to the vacuum filled waveguide, by looking at these three port field diagrams, we can determine that for the Teflon-filled waveguide, “Mode 1” is a TE_{10} , “Mode 2” is a TE_{20} , and “Mode 3” is a TE_{01} .

2.2.2 - Field Vectors and Magnitudes

So that the vectors and magnitudes of the electric and magnetic fields within the waveguides could be obtained, the previous model was again used except to generate field plots, as instructed in the task. These can be seen below.

Field Magnitudes – Vacuum Filled

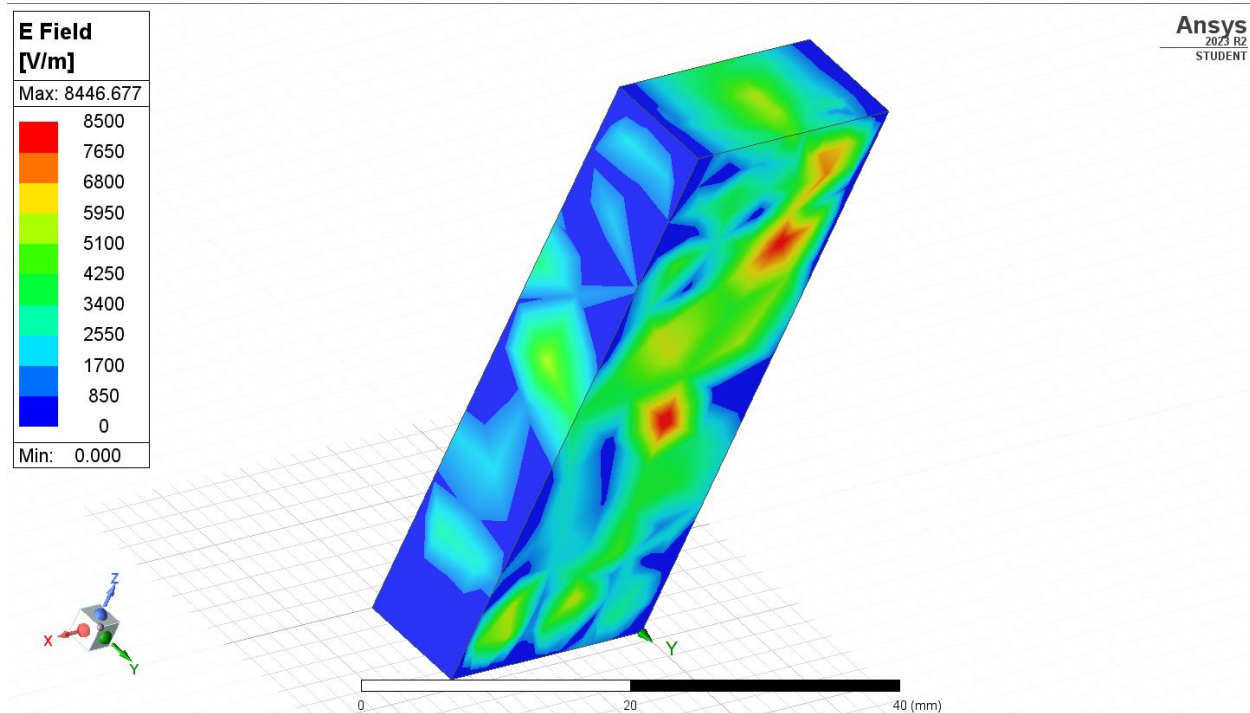


Fig. 13 – Vacuum Filled, Electric Field, Mode 1

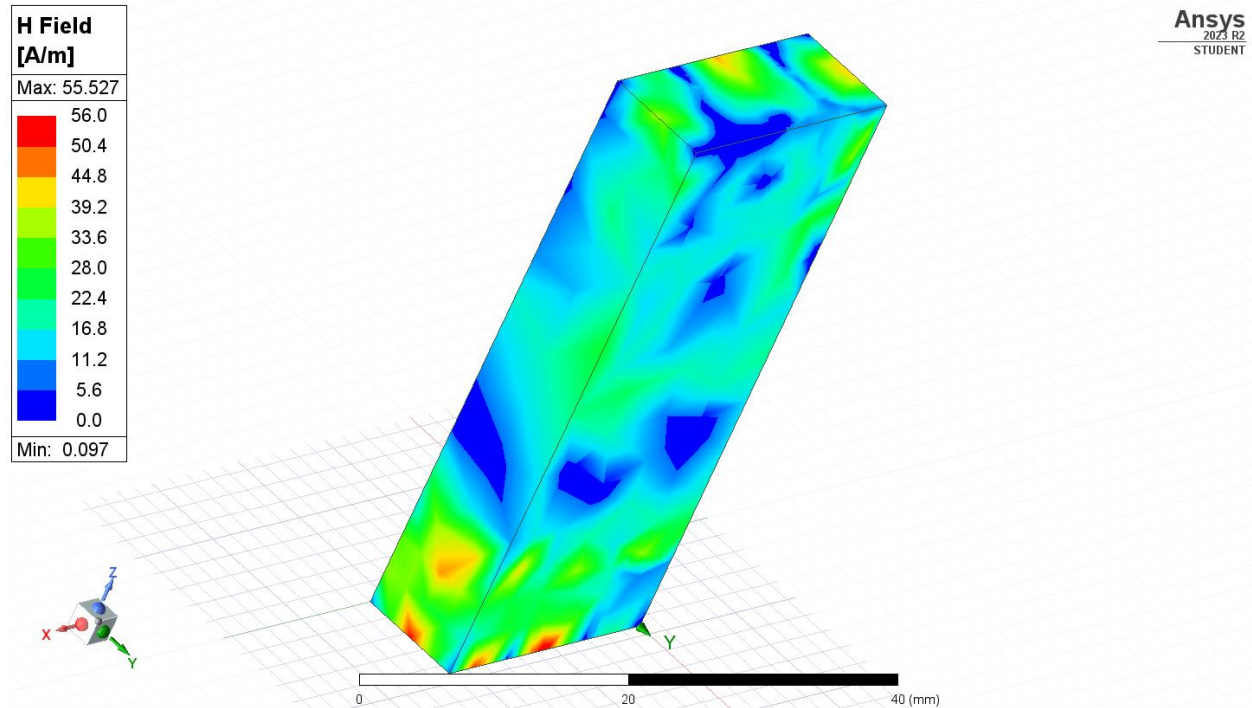


Fig. 14 – Vacuum Filled, Magnetic Field, Mode 1

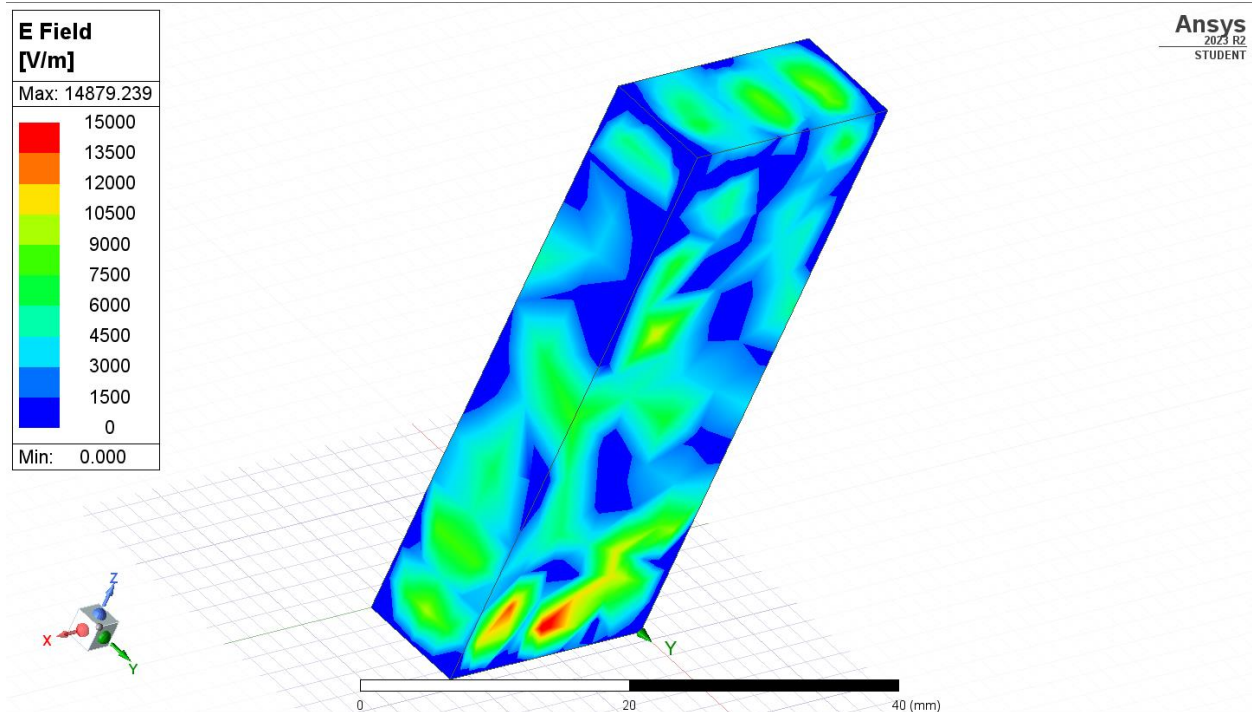


Fig. 15 – Vacuum Filled, Electric Field, Mode 2

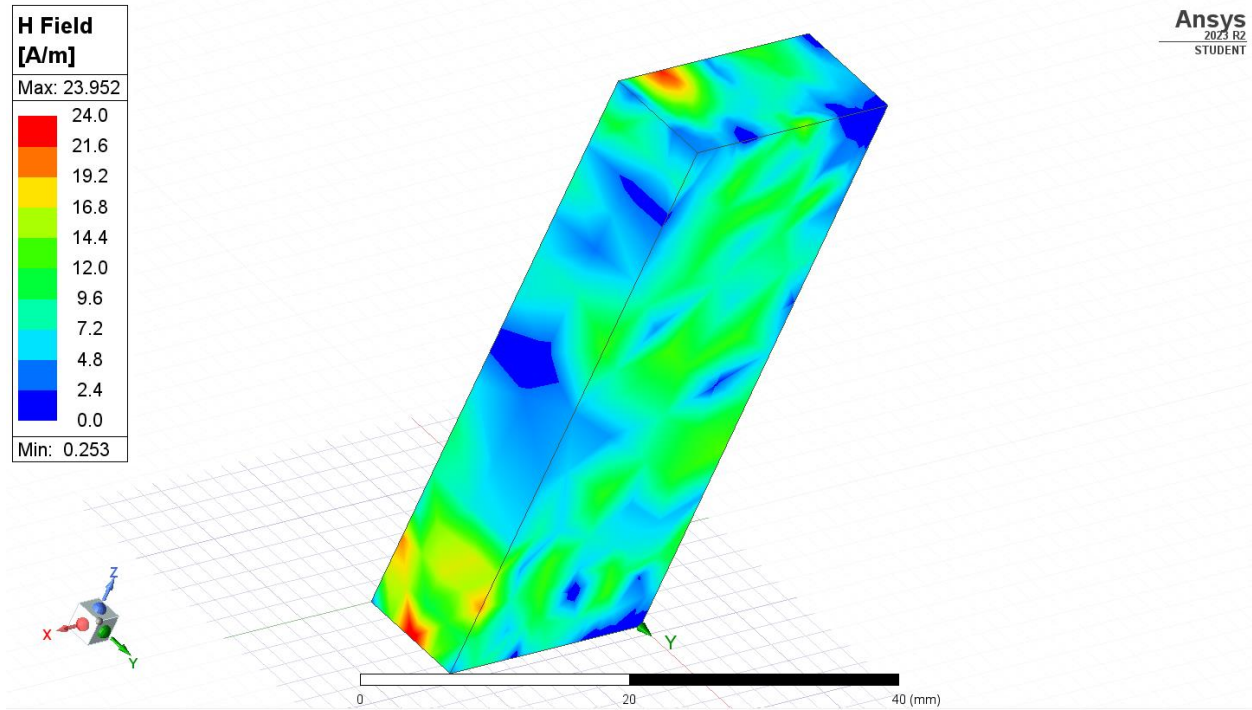


Fig. 16 – Vacuum Filled, Magnetic Field, Mode 2

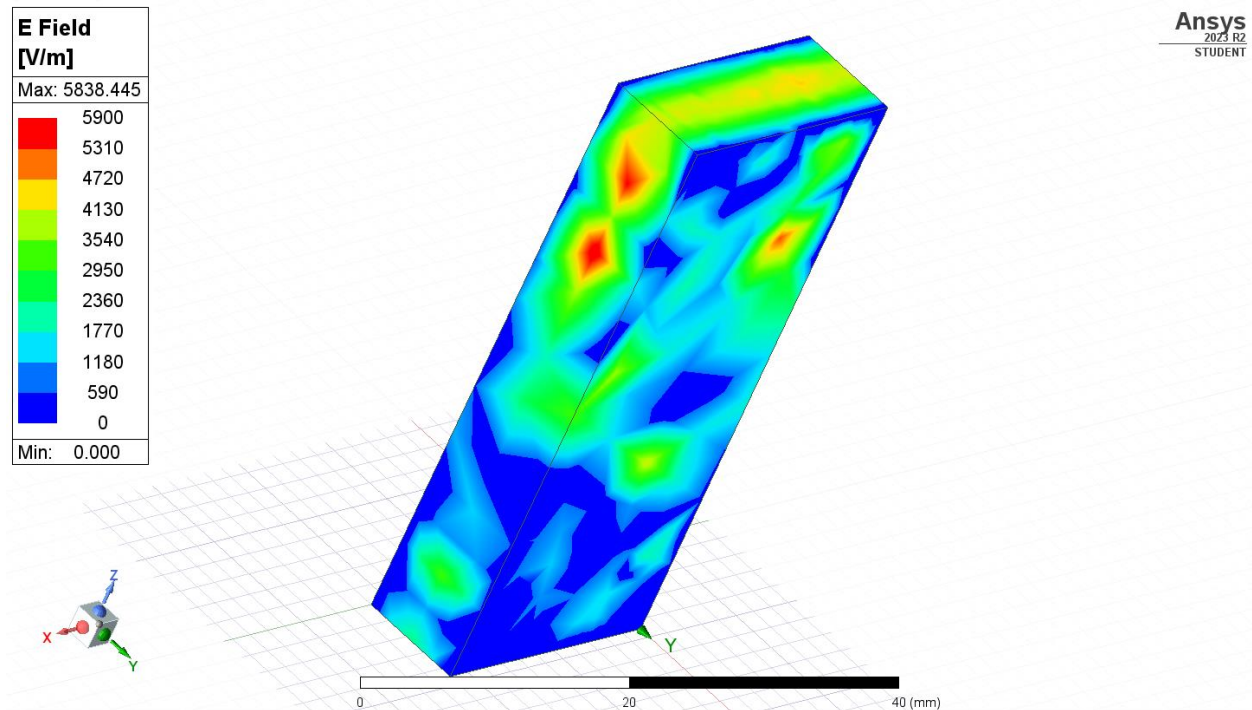


Fig. 17 – Vacuum Filled, Electric Field, Mode 3

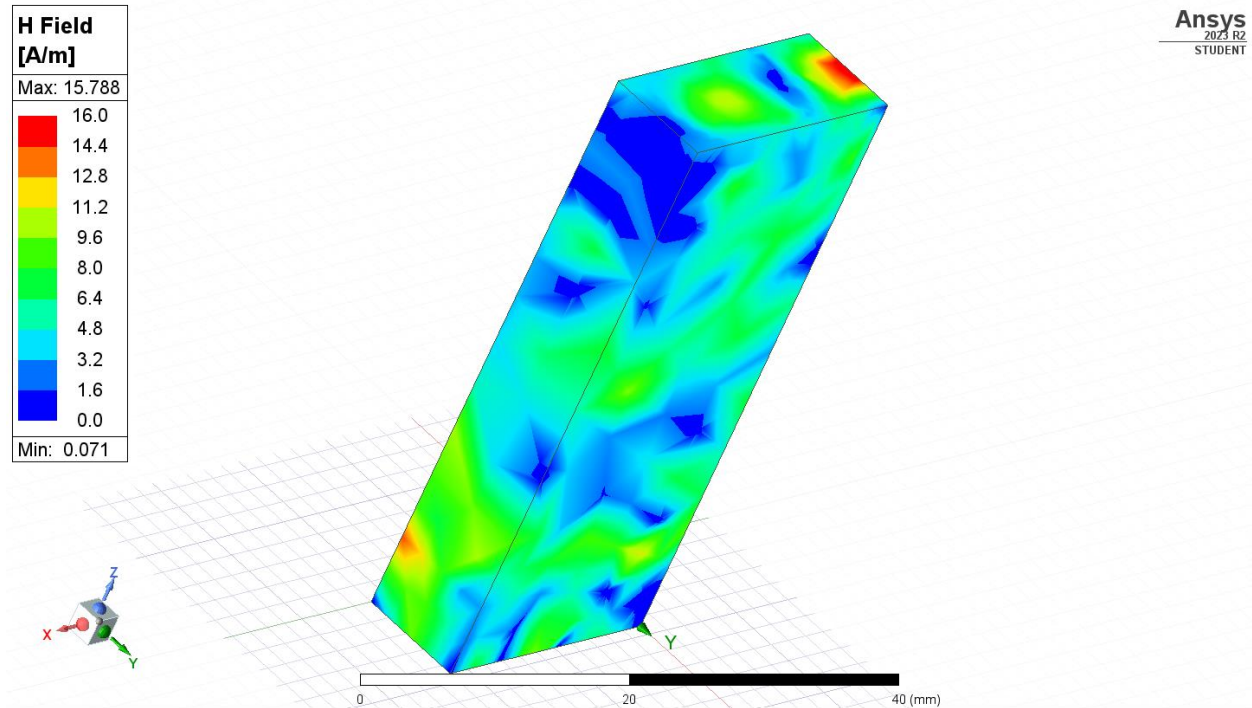


Fig. 18 – Vacuum Filled, Magnetic Field, Mode 3

Field Vectors – Vacuum-Filled

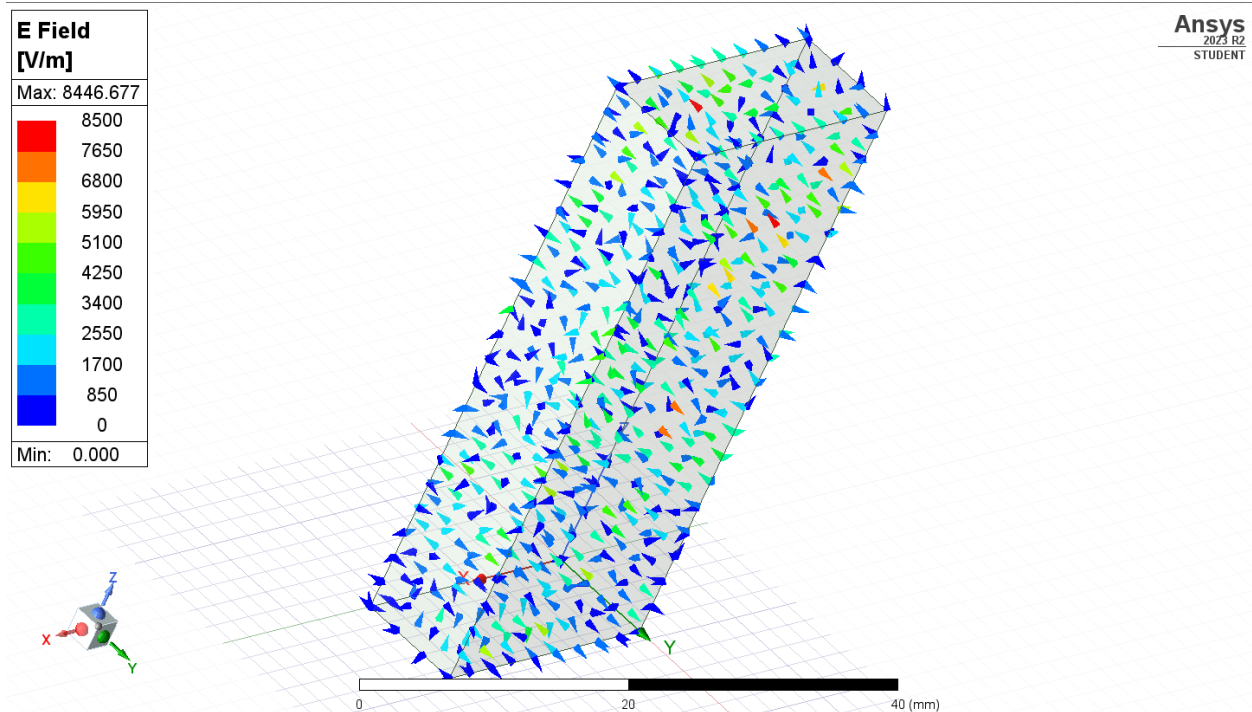


Fig. 19 – Vacuum Filled, Electric Field, Mode 1

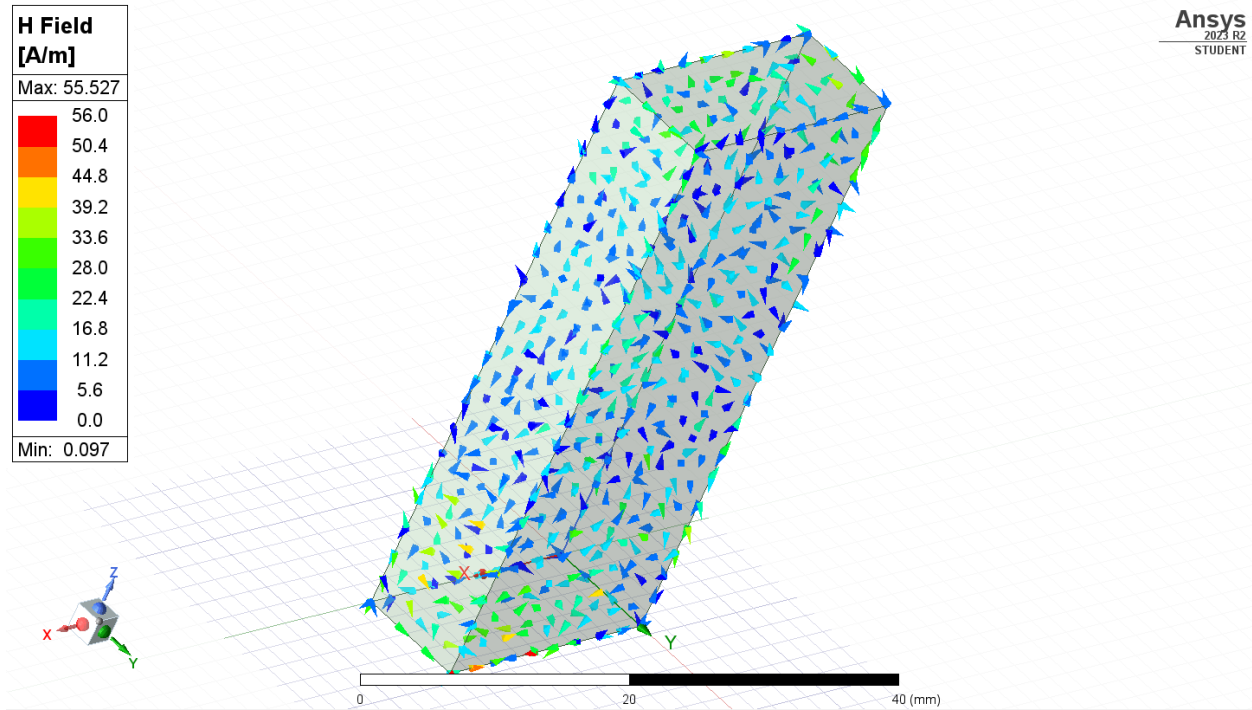


Fig. 20 – Vacuum Filled, Magnetic Field, Mode 1

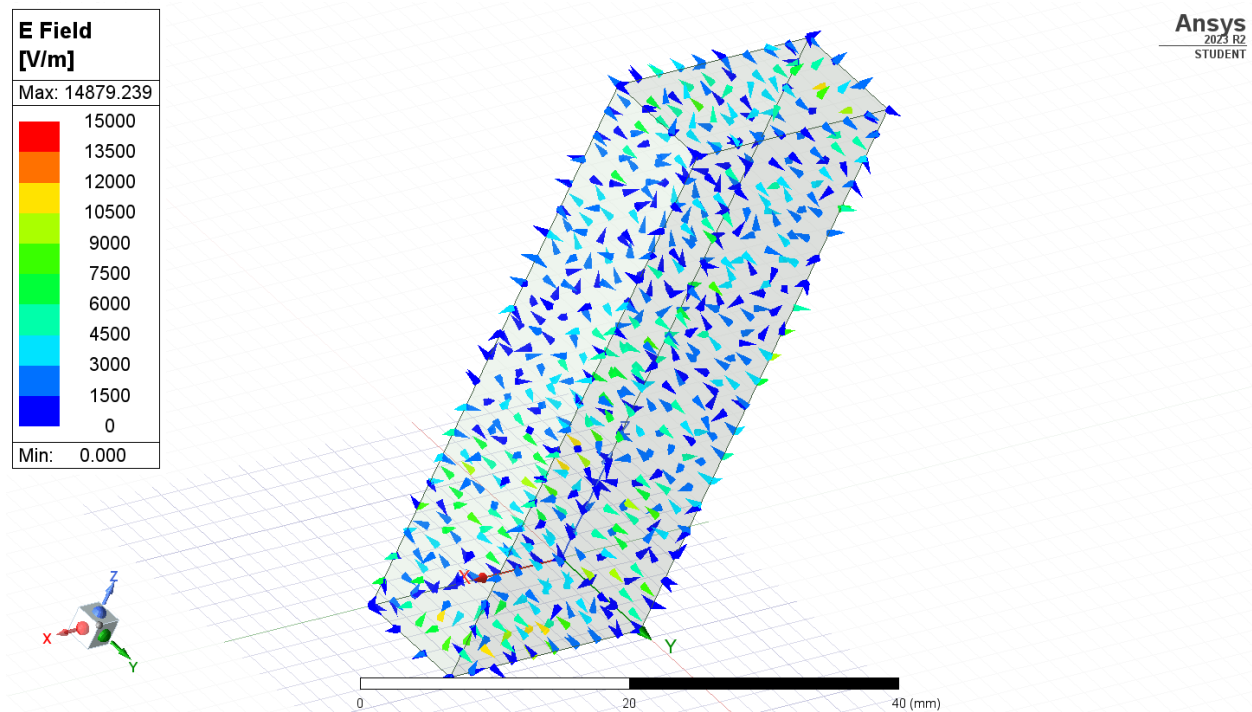


Fig. 21 – Vacuum Filled, Electric Field, Mode 2

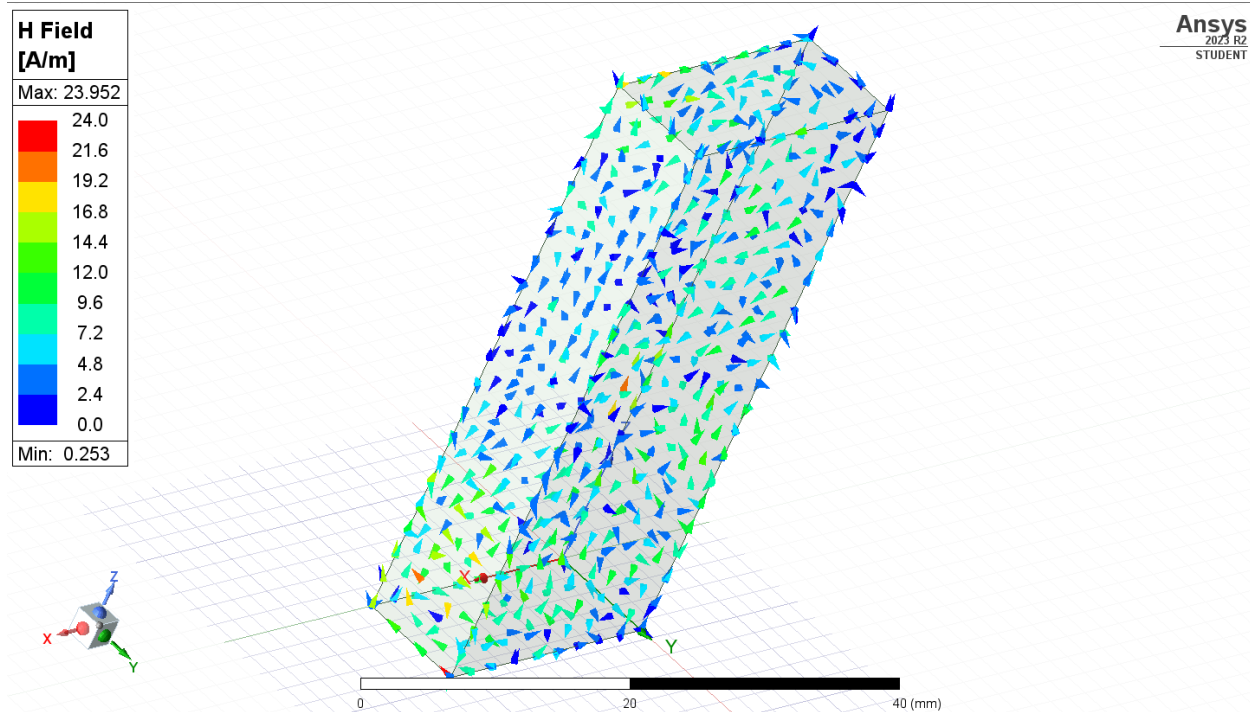


Fig. 22 – Vacuum Filled, Magnetic Field, Mode 2

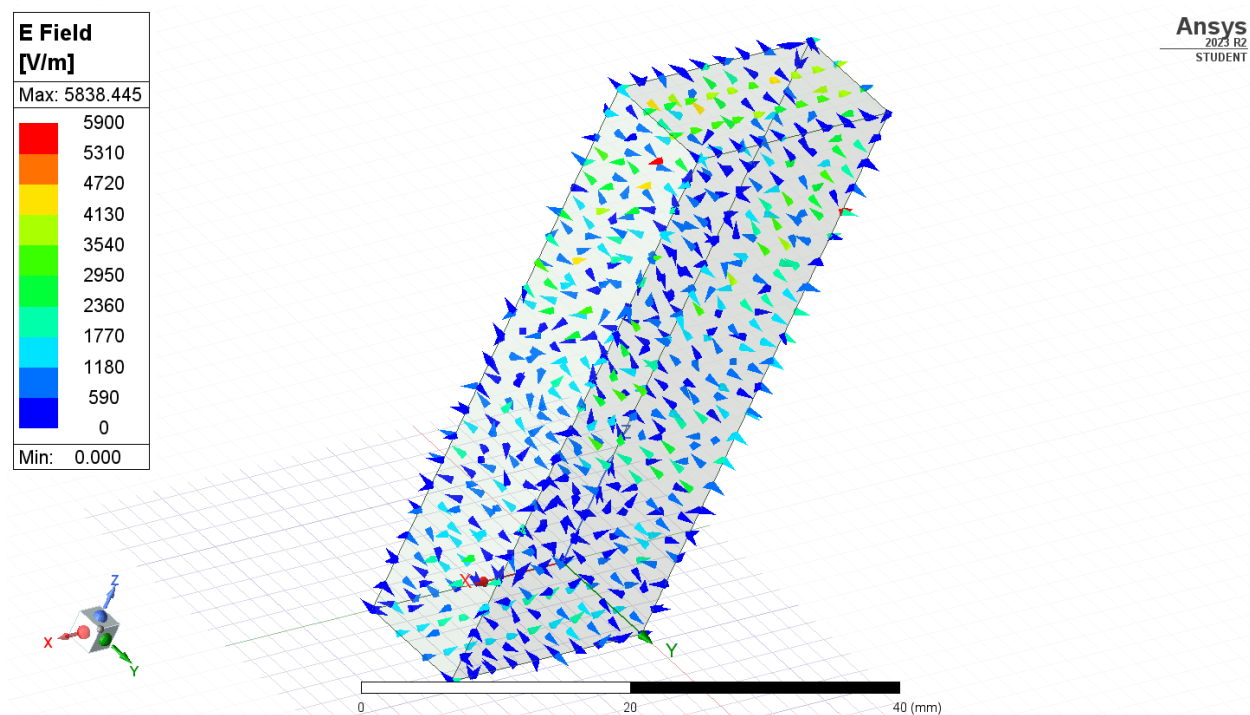


Fig. 23 – Vacuum Filled, Electric Field, Mode 3

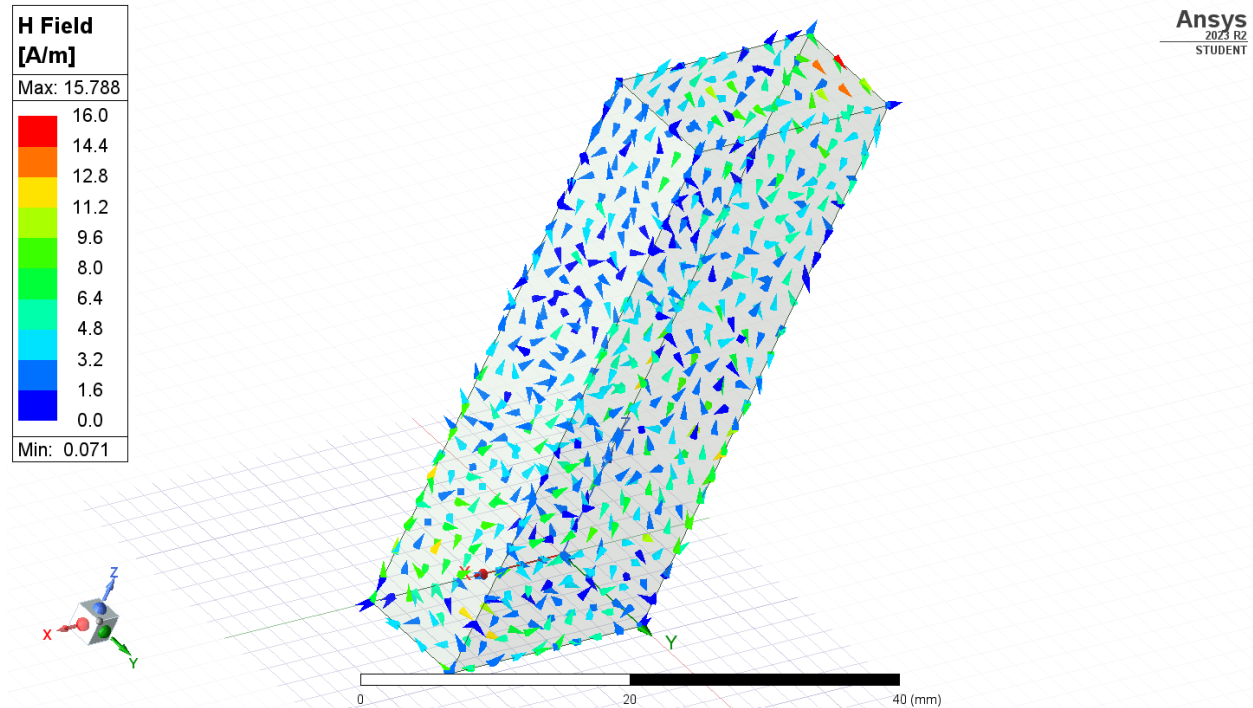


Fig. 24 – Vacuum Filled, Magnetic Field, Mode 3

Field Magnitudes – Teflon Filled

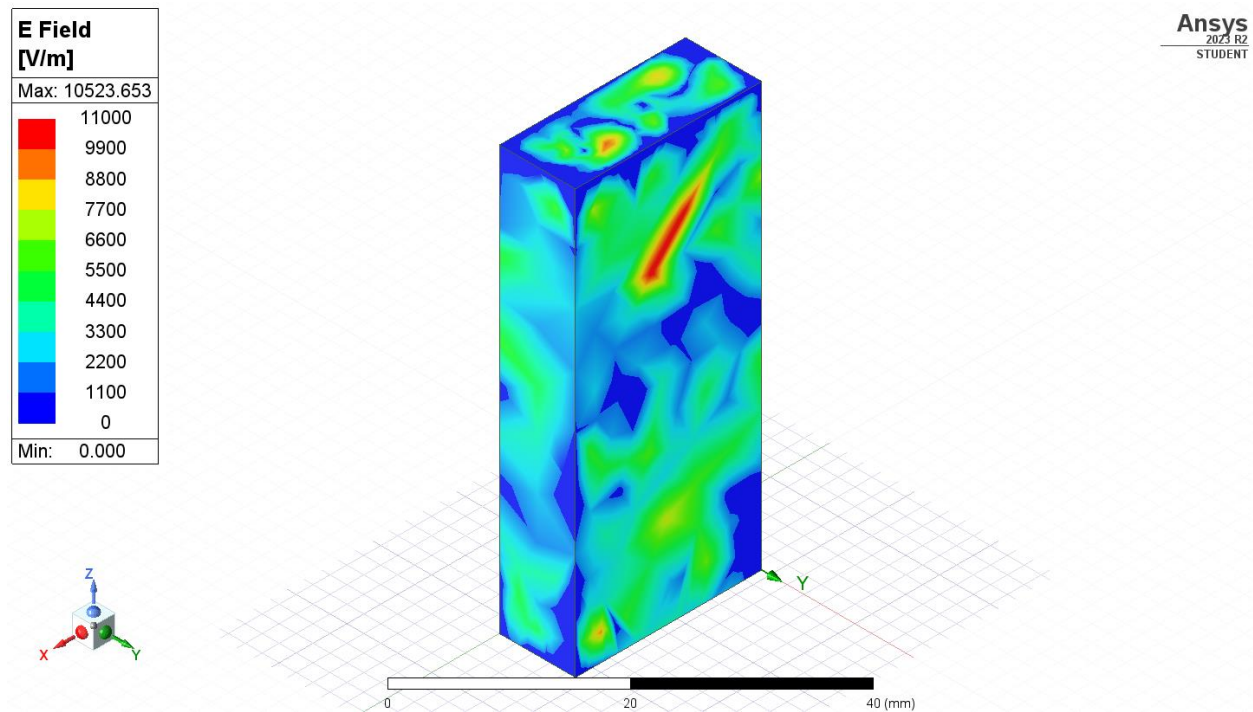


Fig. 25 – Teflon Filled, Electric Field, Mode 1

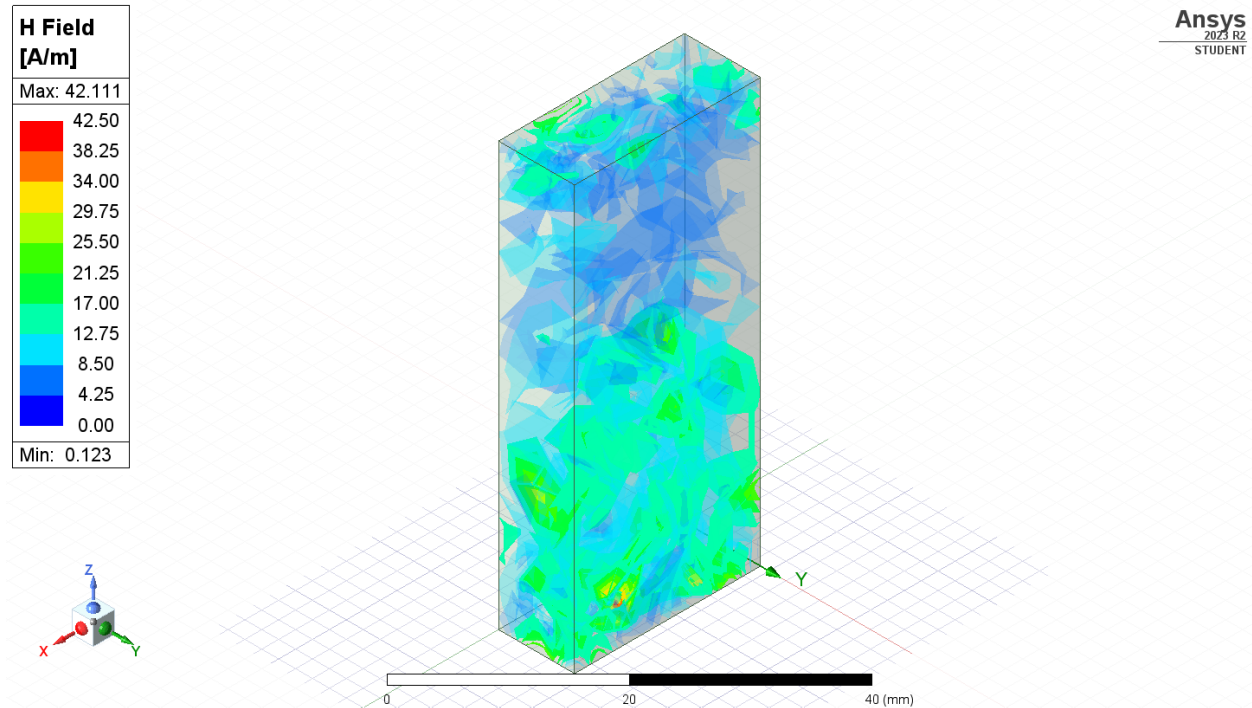


Fig. 26 – Teflon Filled, Magnetic Field, Mode 1

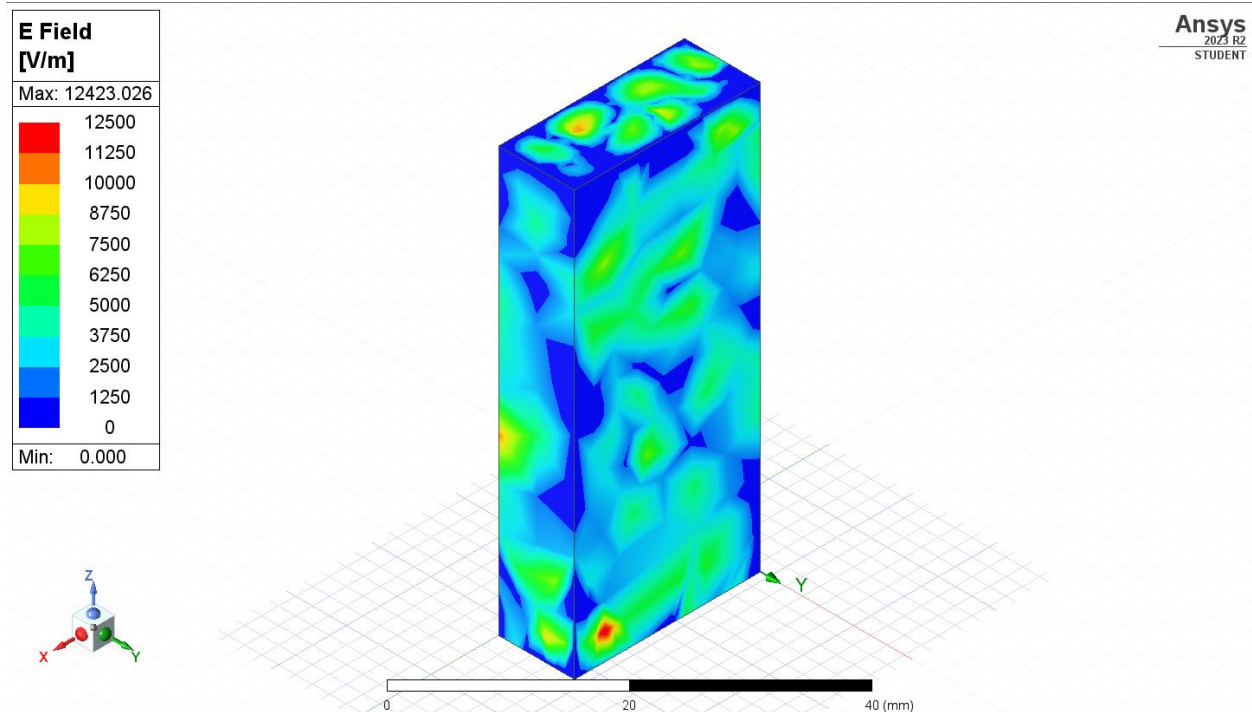


Fig. 27 – Teflon Filled, Electric Field, Mode 2

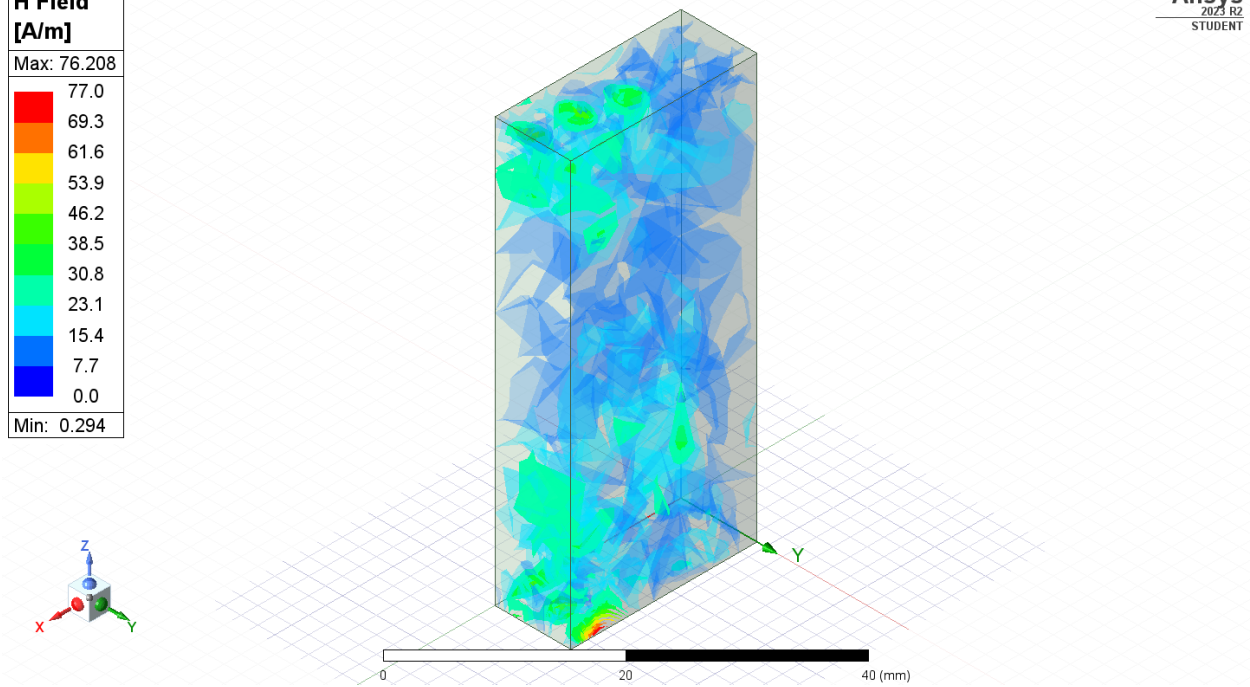
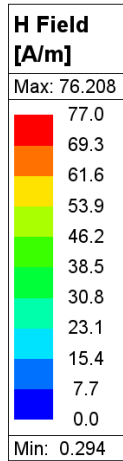


Fig. 28 – Teflon Filled, Magnetic Field, Mode 2

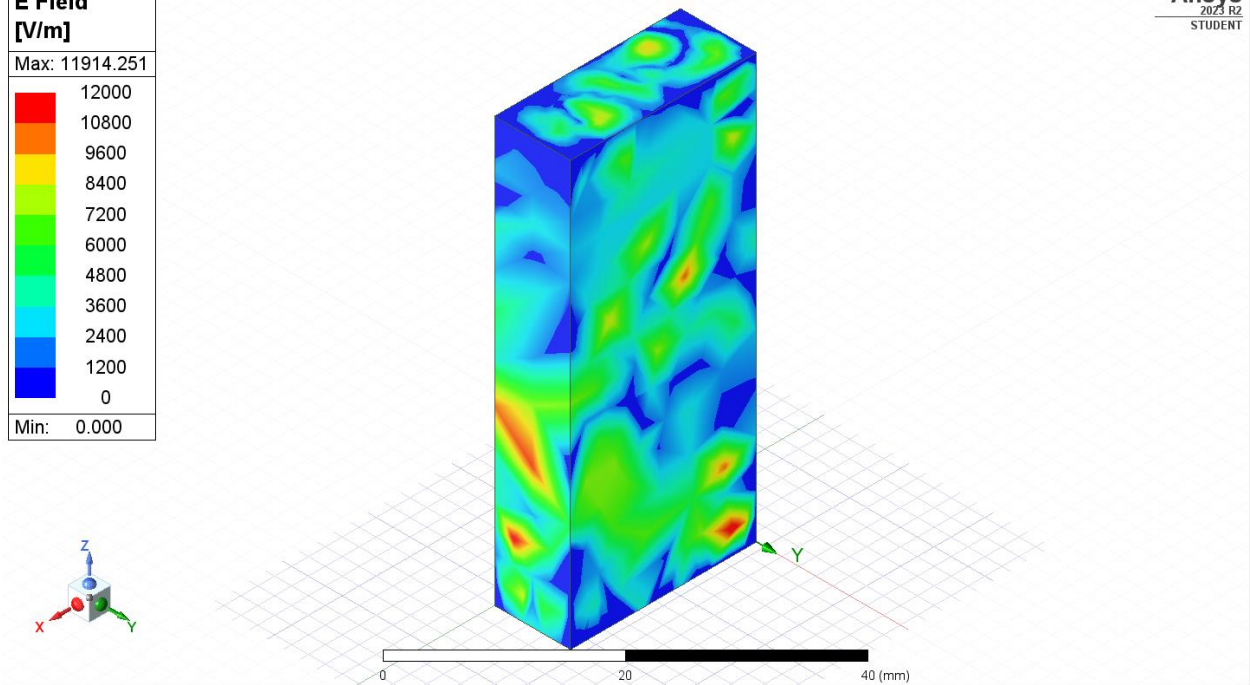
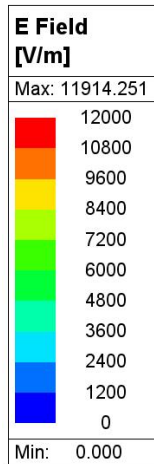


Fig. 29 – Teflon Filled, Electric Field, Mode 3

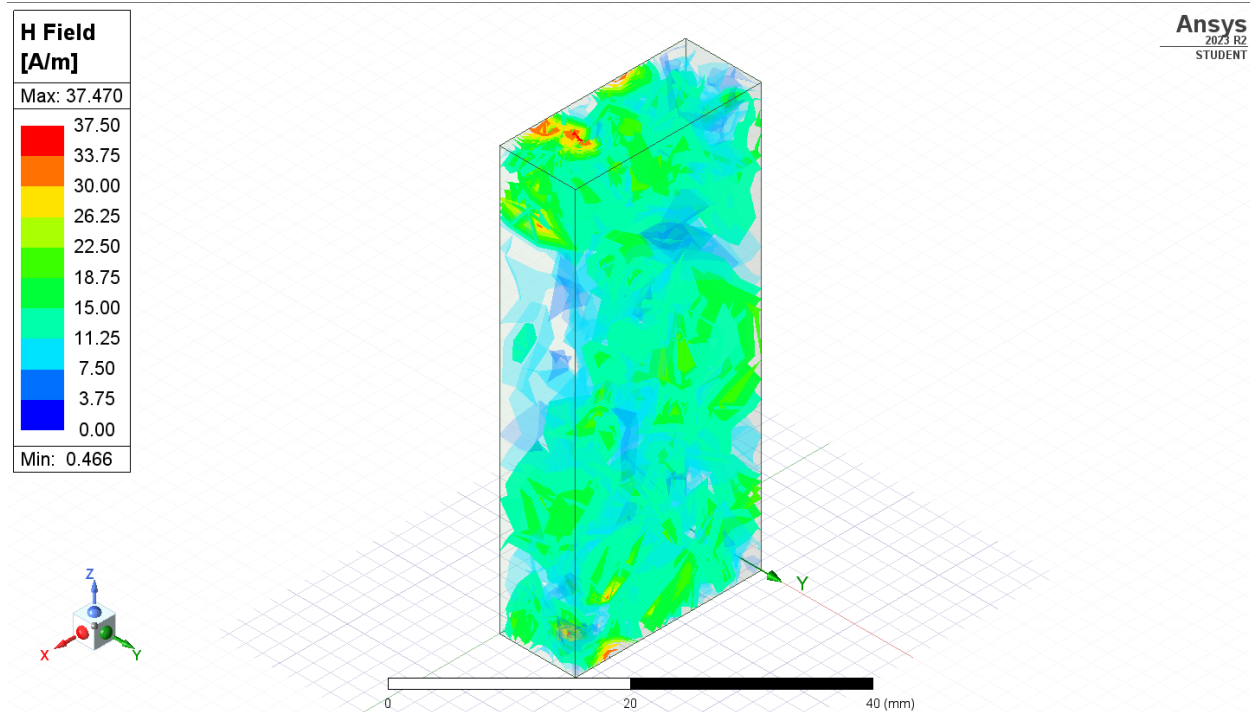


Fig. 30 – Teflon Filled, Magnetic Field, Mode 3

Field Velocities – Teflon-Filled

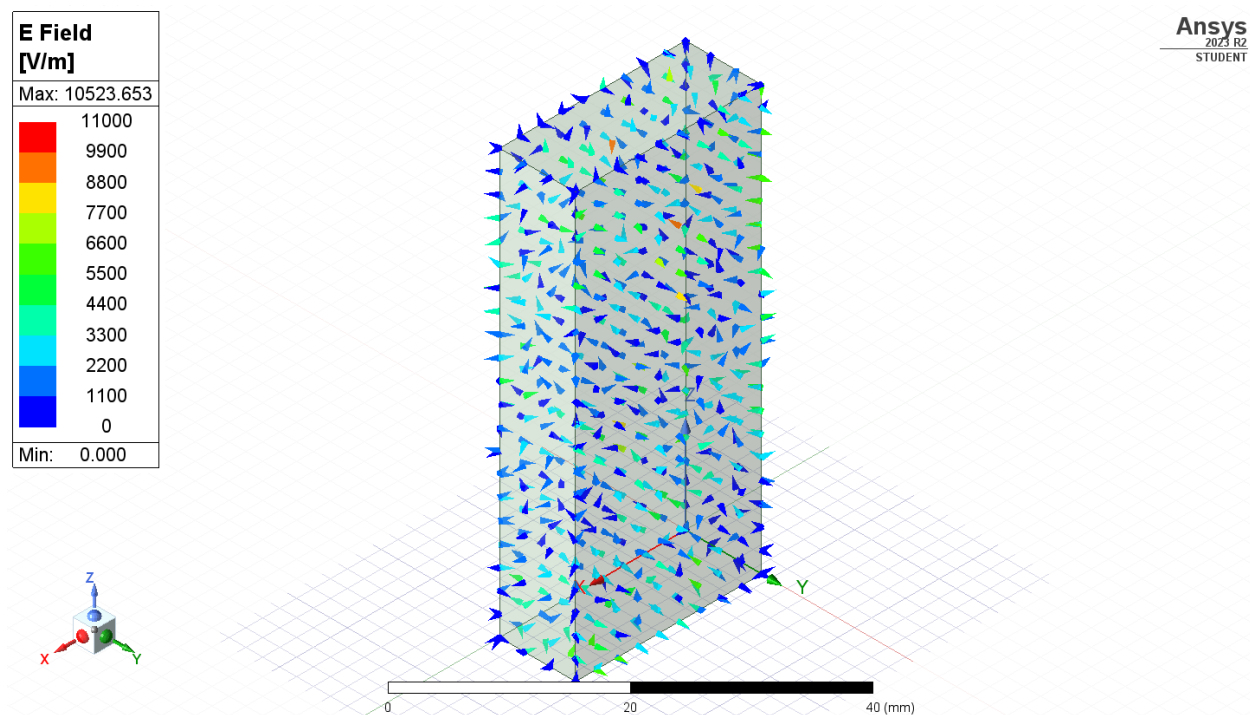


Fig. 30 – Teflon Filled, Electric Field, Mode 1

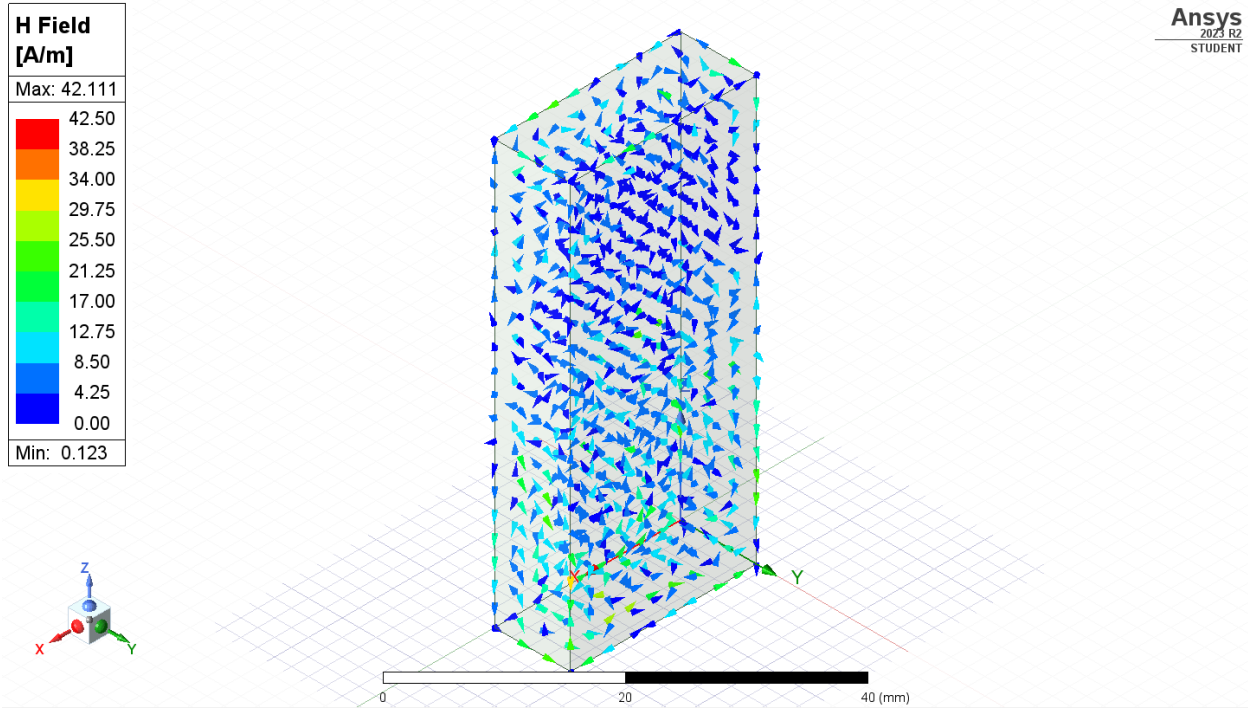


Fig. 31 – Teflon Filled, Magnetic Field, Mode 1

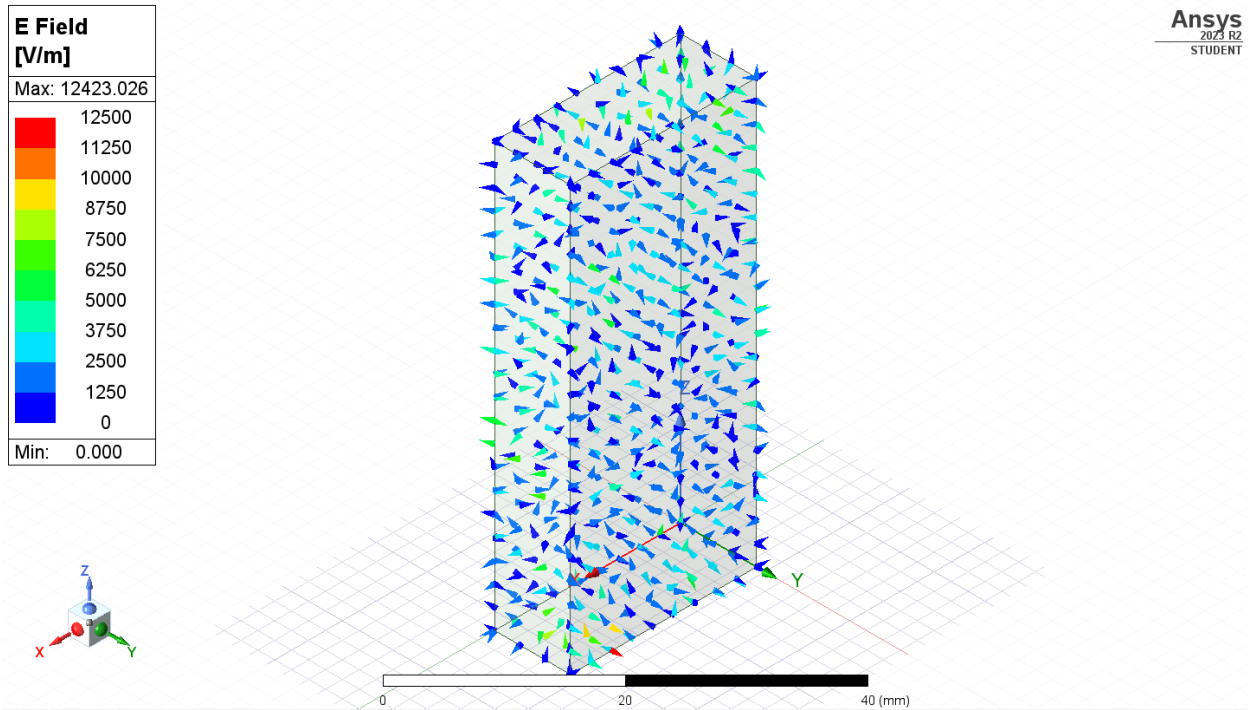


Fig. 32 – Teflon Filled, Electric Field, Mode 2

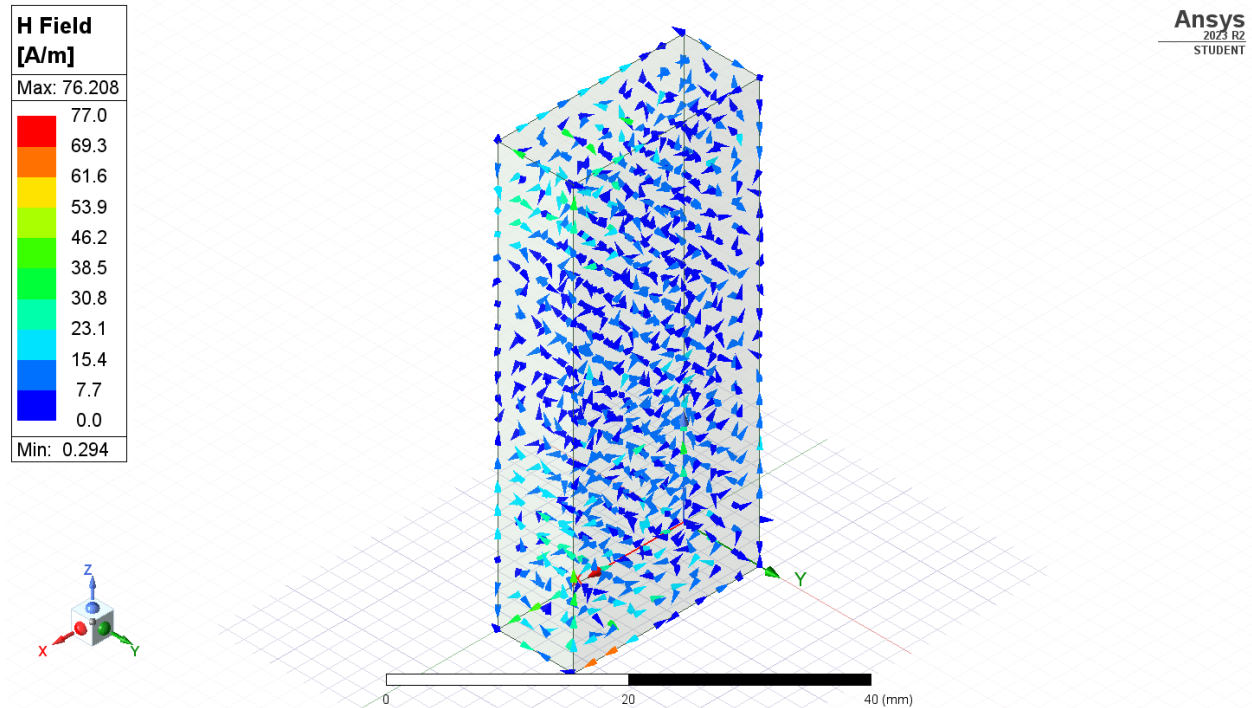


Fig. 33 – Teflon Filled, Magnetic Field, Mode 2

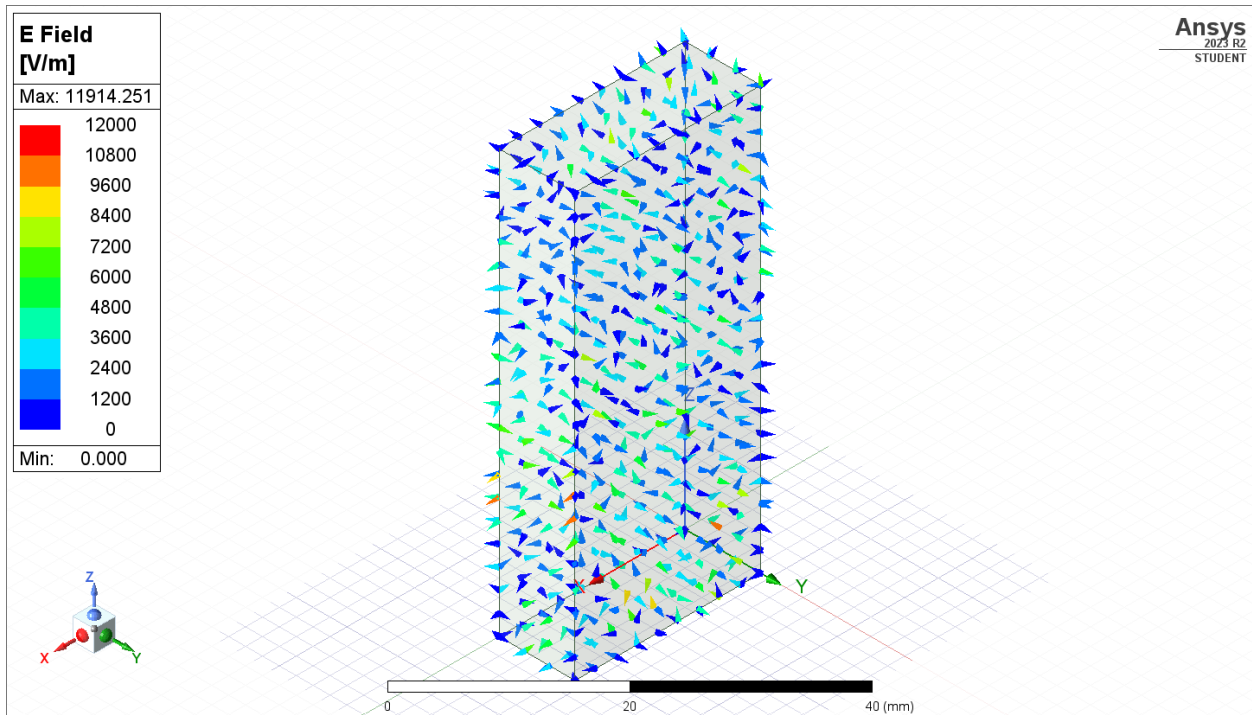


Fig. 34 – Teflon Filled, Electric Field, Mode 3

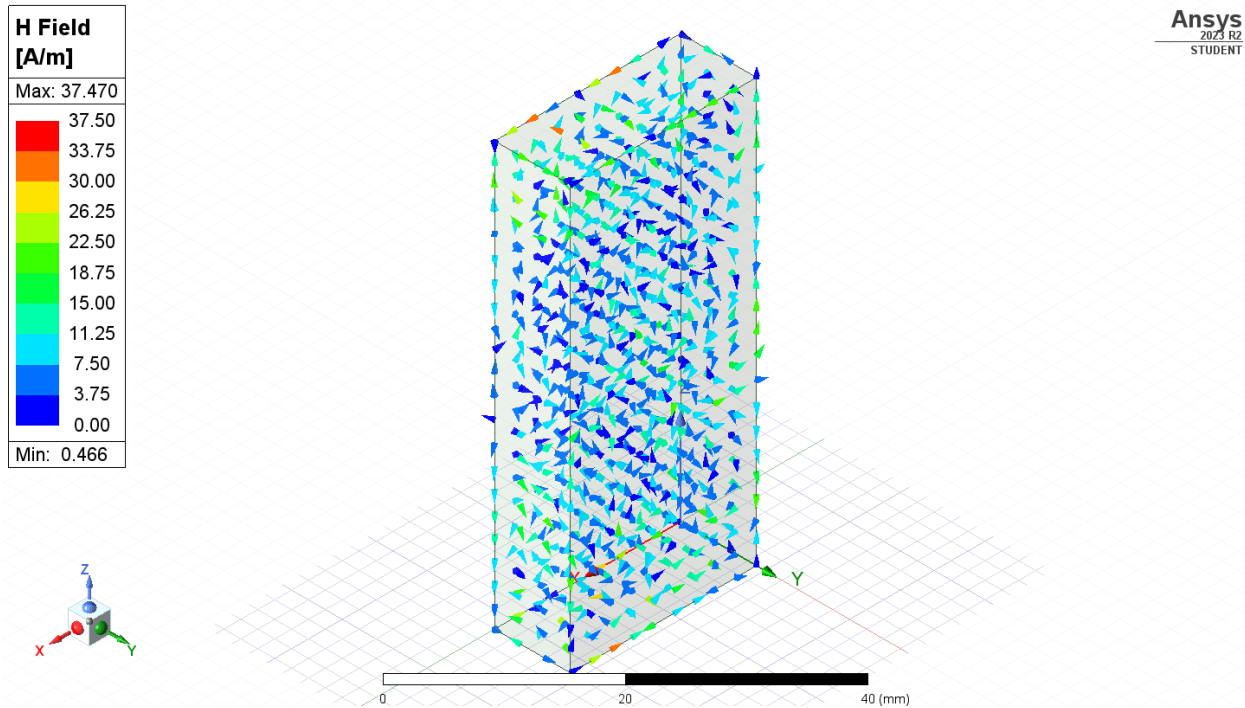


Fig. 35 – Teflon Filled, Magnetic Field, Mode 3

2.2.3 - Cut-Off Frequency Plot

The cut-off frequencies of the model were simulated and then plotted onto a graph, both for the Vacuum-Filled waveguide from Task 1A and the Teflon-Filled waveguide from Task 1B. These can be seen in figures 36 and 37

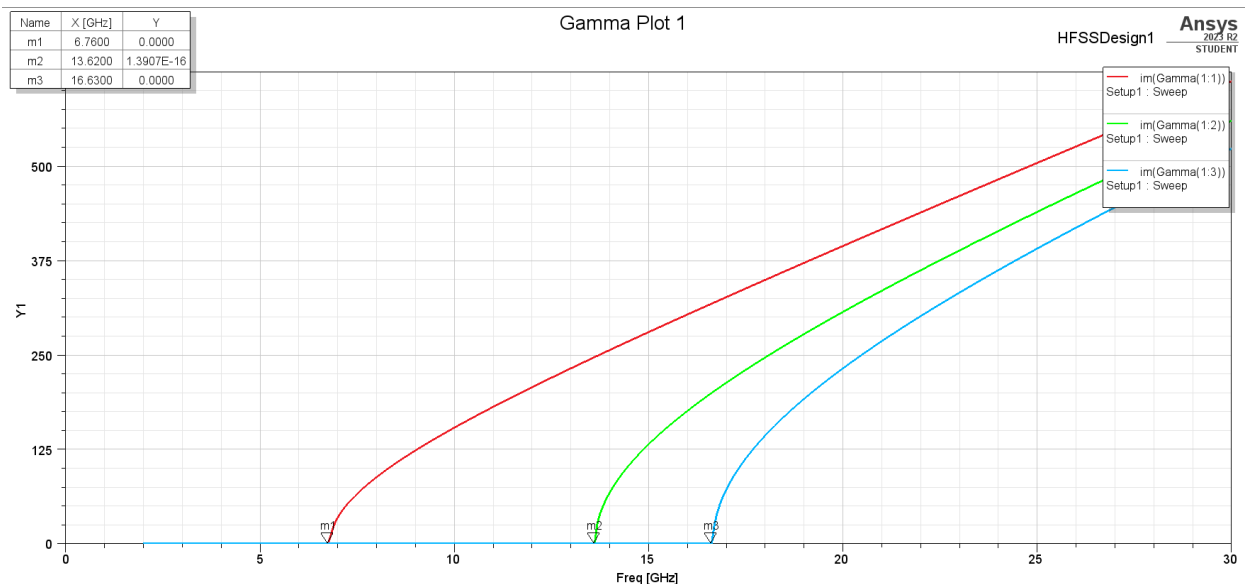


Fig. 36 - Vacuum-Filled Waveguide (Task 1A) Cut-Off Frequency Plot

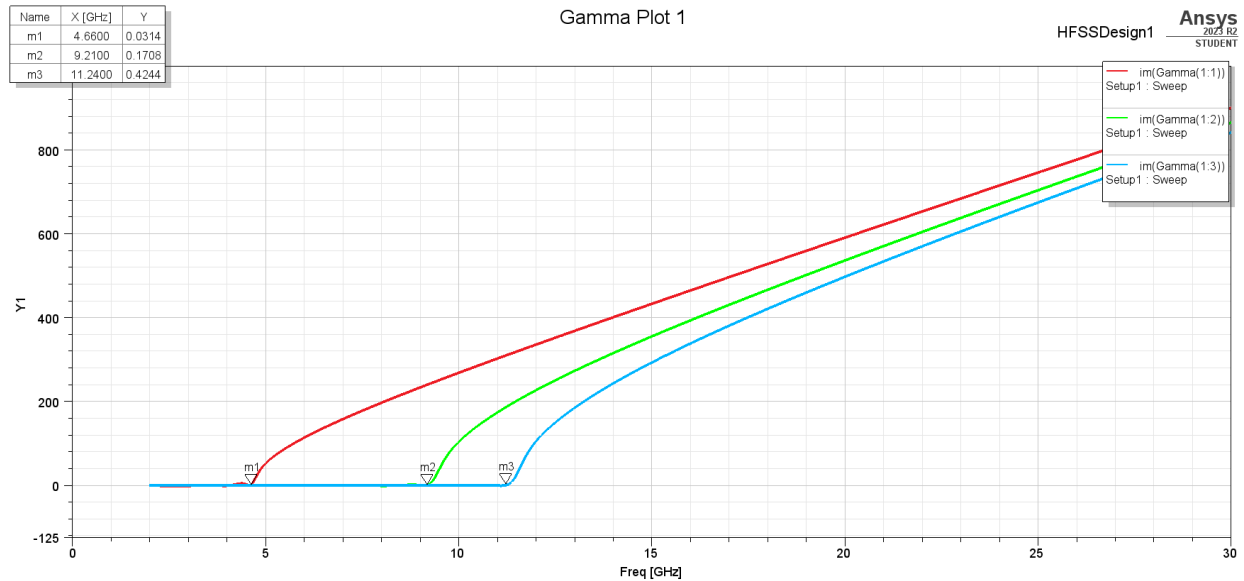


Fig. 37 - Teflon-Filled Waveguide (Task 1B) Cut-Off Frequency Plot

We can see that for the Vacuum-Filled waveguide the three modes cut off at 6.81, 13.67 and 16.65 GHz, whereas the three modes for the Teflon-Filled waveguide cut off at 4.68, 9.23 and 11.24 GHz. These will be compared to theoretical values in the discussion.

2.3 - Discussion

2.3.1 - Task 1A (Vacuum-Filled)

So that the validity of the results gained from the model can be evaluated, it is important to establish theoretical values for the Cut-Off Frequencies. For the Vacuum-Filled waveguide, this is done using the following equation:

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

For Task 1A, (a) and (b) are the values previously determined from the student number, and (m) and (n) are the parameters of the node. (c) is the speed of light. These can be seen below.

a	22		
b	8.5		
m	1	2	0
n	0	0	1
c	3×10^8		

When these numbers were used in the formula above, the following calculated results were gained:

Mode 1 (TE₁₀)	6.82 GHz
Mode 2 (TE₂₀)	13.64 GHz
Mode 3 (TE₀₁)	17.65 GHz

These calculated figures can then be compared with the results from the simulation:

	Simulated Value	Calculated Value	Difference	% Difference
Mode 1 (TE10)	6.81	6.82	0.01	0.14%
Mode 2 (TE20)	13.67	13.64	0.03	0.22%
Mode 3 (TE01)	16.65	17.65	1	5.67%

The difference between the simulated and calculated value for mode 1 and mode 2 are almost negligible, at below .25 of a percent. This is excellent. The difference between the values for the third mode, at under 6 percent, is also very close. The values can be declared effectively the same “within experimental error”

2.3.2 - Task 1B (Teflon-Filled)

As with task 1A, to evaluate the validity of the results gained from the model, it is important to establish theoretical values for the Cut-Off Frequencies. For the Teflon-Filled waveguide, this is done using the same master equation:

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

Where (a) and (b) are the values previously determined from the student number, and (m) and (n) are the parameters of the node. (c) is the speed of light. However, due to the material differences with Teflon, a new value of (c) must be calculated using the following formula:

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

Where ϵ is the relative permittivity of Teflon (2.1) and μ is the relative permeability of Teflon (1). This calculates our new value for (c) of 2.0685×10^8

Using this, for the three nodes, the variables and constants are as follows:

Variable/Constant	Mode 1 (TE10)	Mode 2 (TE20)	Mode 3 (TE01)
a	22		
b	8.5		
m	1	2	0
n	0	0	1
c	2.0685×10^8		

When these numbers were used in the formula above, the following calculated results were gained:

Mode 1 (TE10)	4.70 GHz
Mode 2 (TE20)	9.40 GHz
Mode 3 (TE01)	12.17 GHz

These calculated figures can then be compared with the results from the simulation:

	Simulated Value	Calculated Value	Difference	% Difference
--	-----------------	------------------	------------	--------------

Mode 1 (TE10)	4.68	4.70 GHz	0.02	0.43%
Mode 2 (TE20)	9.23	9.40 GHz	0.17	1.81%
Mode 3 (TE01)	11.24	12.17 GHz	0.93	7.64%

Whilst this set of results do have larger differences than for the vacuum-filled waveguide, they are also still within only a few percent of the calculated values, and similarly can also be declared the same “within experimental error”. The larger differences can, however, be noted as the Teflon-filled simulation being slightly less accurate than that for the vacuum-filled waveguide.

2.3.3 - Comparison

With the simulated result having been validated with the calculated results, they can now be used to compare the performance of vacuum- and teflon-filled waveguides who have otherwise identical characteristics. For ease of reading, the two result sets are shown below.

	Simulated COF (Vacuum Filled)	Simulated COF (Teflon Filled)
Mode 1 (TE10)	6.82 GHz	4.68 GHz
Mode 2 (TE20)	13.64 GHz	9.23 GHz
Mode 3 (TE01)	17.65 GHz	11.24 GHz

We can see that the three modes have increasing cutoff frequencies in both waveguides, and as such, for both waveguides, the dominant mode is Mode 1 (TE10). Overall, the cut-off frequencies are always higher in the vacuum filled waveguide, and therefore a teflon-filled waveguide should be considered when looking to direct the propagation of lower frequencies.

3. Task 2 – Half-Wave Dipole Antenna

3.1 - Method

The primary dimension of a half-wavelength dipole antenna is unsurprisingly its length (l). This is determined so that the length of each element is half of the wavelength. Following the task directions, the wavelength was derived from the author's student number (2217661), particularly the first three digits. As such, the wavelength that the simulated antenna was to be designed to transmit was 221mm, and the length of each element would therefore be 110.5mm.

All dimensions used were in mm to allow the corresponding wavelengths and frequencies to be measured without issue. The diameter of the elements, as given in the task, was 1mm.

A dipole antenna with these dimensions was thus drawn up in Ansys Electronics HFSS. The model was centered upon the origin and a centre lumped port was assigned an excitation with a port impedance of 50 Ohms. The antenna was modelled with a wall consisting of "Perfect Electrical Conductor" (PEC). The designed model was then placed within a rectangular radiating surface.

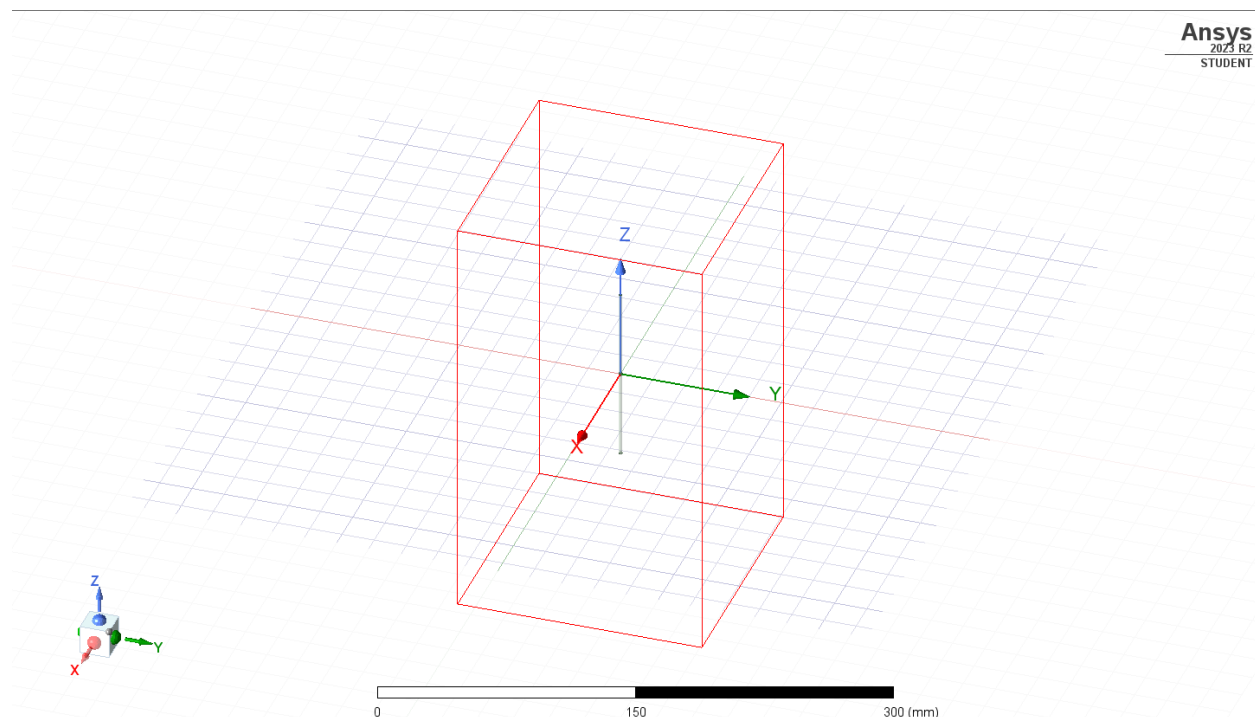


Fig. 38 Halfwave Dipole Antenna Model in Ansys HFSS

The model and the analytical parameters were then validated, and the model was run. This model was used to gather an S parameter plot and a radiation pattern.

3.2 - Results

3.2.1 - S-Parameter Plot

The Ansys HFSS suite was used to create an S-Parameter Plot from the modelled antenna. This can be seen below in figure 40.

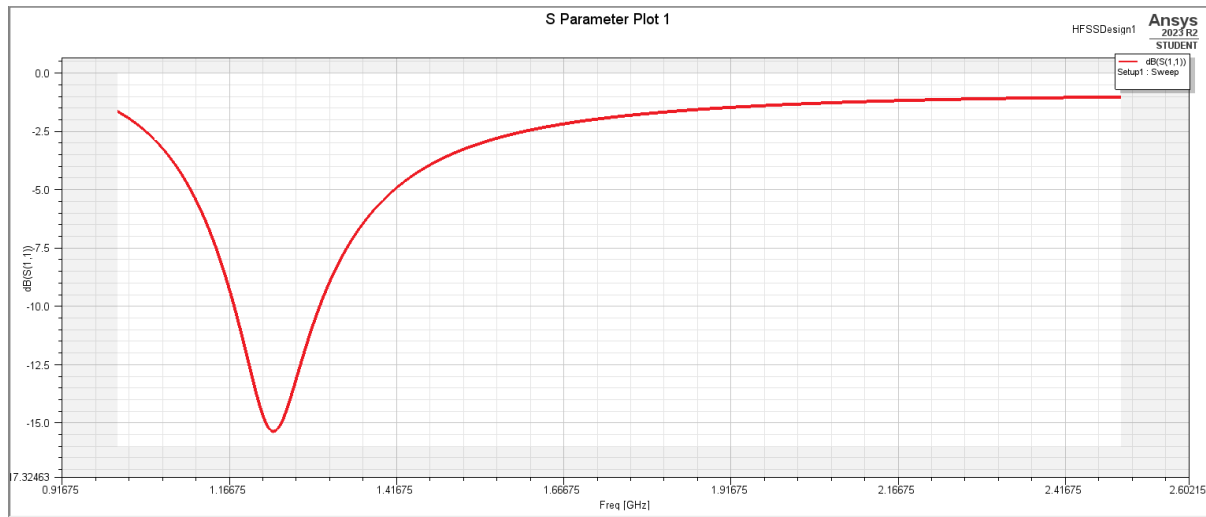


Fig. 39 – S-Parameter Plot

The clear indent in the plot indicates an operating frequency for the modelled antenna as 1.245GHz.

3.2.2 - Radiation Pattern

The Ansys HFSS suite was used to create a visual representation of the radiation pattern of the modelled antenna. This can be seen below in figure 41.

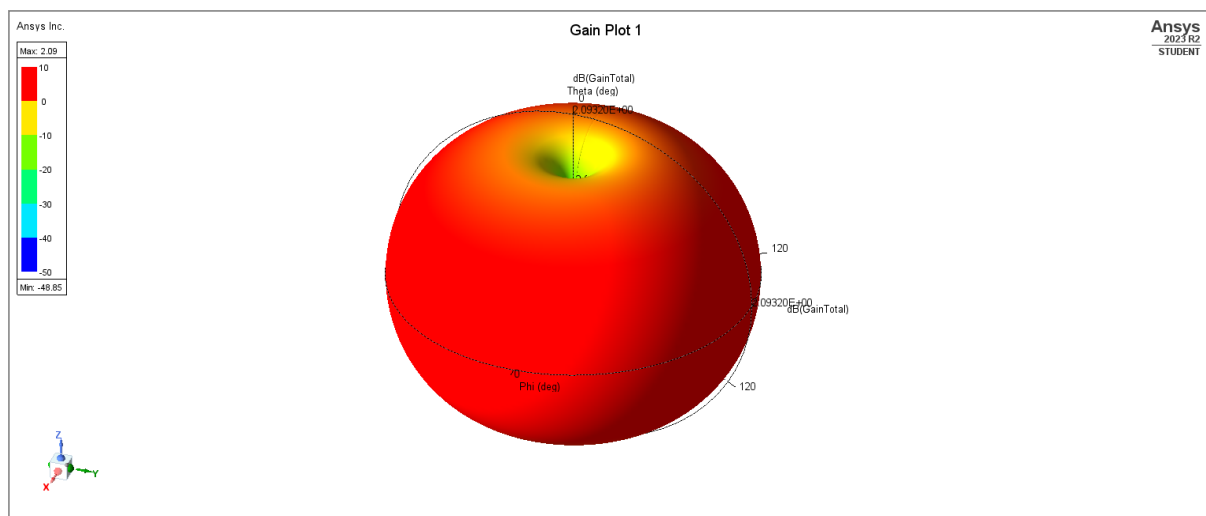


Fig. 40 – Antenna Radiation Pattern

The radiation pattern clearly shows the omnidirectional nature of the dipole antenna, when modelled as being in free space.

3.3 - Discussion

So that the validity of the results gained from the model can be evaluated, it is important to establish a theoretical value for the antenna operating frequency. Since our dipole antenna has been modelled to operate on a wavelength of 221mm (as derived earlier in this report), the theoretical frequency is calculated using the following equation:

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

Using this equation, the calculated value for the operating frequency is determined to be 1.357 GHz.

	Simulated Value	Calculated Value	Difference	% Difference
Frequency	1.245 GHz	1.357 GHz	0.112	8.25%

Since the simulated value is within, but approaching 10% from the theoretical value, the model can be declared as “reasonably accurate” and could therefore be useful in assessing the operating characteristics of speculative antenna designs.

4. Conclusion

The ability to direct and transmit wireless signals in a controlled manner is critical within modern technology, both domestic, commercial and military. It is therefore essential for any individual working in a field related to EMR to have a sound understanding of, not only how EMR propagates in free space, but also when directed within waveguides and transmitted via antennae.

This study has shown the usefulness and relative accuracy of electromagnetic modelling software, (in this case the Ansys suite) in predicting the performance of potential waveguide and antennae designs to ensure that the desired frequencies are directed/transmitted, without interference from other undesired frequencies. In today's crowded spectrum, this is becoming more and more essential.

It has particularly highlighted the potential to improve the performance of waveguides via alternative, solid fillings, as well as the efficiency of the half-wavelength dipole antenna design.

5. References

1. Unknown, "Waveguides", ScienceDirect (Academic Summary page), unknown, [Online]. Available: <https://www.sciencedirect.com/topics/materials-science/waveguide> [Accessed 17/07/2024]
2. K. Likharev, "Dielectric Waveguides, Optical Fibres and Paraxial Beams," Libretexts Physics, Unknown. [Online]. Available: [https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Essential_Graduate_Physics_-_Classical_Electrodynamics_\(Likharev\)/07%3A_Electromagnetic_Wave_Propagation/7.07%3A_Dielectric_Waveguides_Optical_Fibers_and_Paraxial_Beams](https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Essential_Graduate_Physics_-_Classical_Electrodynamics_(Likharev)/07%3A_Electromagnetic_Wave_Propagation/7.07%3A_Dielectric_Waveguides_Optical_Fibers_and_Paraxial_Beams) [Accessed 17/07/2024]
3. F. Marhauser, "Lecture: Transmission Lines and Waveguides", USPAS, 15/01/2018. [Online]. Available: <https://uspas.fnal.gov/materials/18ODU/11L%20Waveguides.pdf> [Accessed 17/07/2024]
4. Unknown, "Microwaves in Waveguides", Manchester University, Unknown. [Online]. Available: https://users.hep.manchester.ac.uk/u/rjones/Third_Year_Lab/microwaves.pdf [Accessed 17/07/2024]
5. Unknown, "The Dipole Antenna", Antenna-Theory, Unknown. [Online]. Available: <https://antenna-theory.com/antennas/dipole.php> [Accessed 17/07/2024]
6. K. Leigh-Smith, "The Theoretical Radiation Pattern of a Half-wave Dipole — Lesson 3", University of North Carolina-Charlotte, 10/08/2021. [Online]. Available: <https://www.youtube.com/watch?v=8Kq8htzbBpc> [Accessed 17/07/2024]
7. Unknown, "Understanding the Yagi Antenna: Design, Applications, and Benefits", The HAM Shack, 26/02/2024. [Online]. Available: <https://www.thehamshack.blog/understanding-the-yagi-antenna-design-applications-and-benefits/> [Accessed 17/07/2024]
8. B. Schweber, "The Yagi Antenna: Simple, Flexible and Great for DIYers, or to Buy Off the Shelf," Digikey, 14 07 2022. [Online]. Available: <https://www.digikey.co.uk/en/blog/the-yagi-antenna>. [Accessed 08 05 2024].