

Assignment

by Finn Mallon

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ELECTROMAGNETIC RADIATION

ANALYSIS OF ELECTROMAGNETIC WAVE

PROPOGATION



Mr Finn Mallon
2031021

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Abstract



Task 1a

Task 1a looks into the design and simulation of a rectangular waveguide featuring perfect electric conductor (PEC) walls, specifically optimized for operation under vacuum conditions. The waveguide dimensions include a width of 20 mm, a height of 16 mm, and a length of 50 mm along the z-axis. To analyse the propagation characteristics of electromagnetic waves within the structure, wave ports were strategically positioned at both the input and output faces, with three modes configured at each port for thorough modal analysis. A frequency sweep from 2 GHz to 30 GHz was conducted to characterize the waveguide's performance across a diverse frequency range. This in-depth frequency analysis facilitated the determination of cut-off frequencies, operational bandwidth, and modal transitions in the waveguide. The simulation results offer valuable insights into the electromagnetic performance of the waveguide across microwave and millimetre-wave bands, providing essential information for microwave engineering, communication systems, and high-frequency circuit design where accurate control of electromagnetic wave propagation is critical.

Task 1b

Task 1b looks into the design and analysis of a rectangular waveguide featuring Perfect Electric Conductor (PEC) walls and filled with Teflon dielectric material. Teflon exhibits a relative permeability of 1 and a relative permittivity of 2.1, which plays a crucial role in altering wave propagation characteristics compared to waveguides filled with air. The dimensions of the waveguide were meticulously chosen to accommodate the desired operating frequency range, and ports were established at both ends to analyse the electromagnetic wave propagation throughout the structure. A thorough frequency sweep was conducted to evaluate the waveguide's performance across multiple frequency bands, identifying critical parameters such as cut-off frequencies, propagation constants, and field distributions for various modes.

The simulation outcomes illustrate the influence of Teflon dielectric loading on the waveguide's electromagnetic behaviour, leading to a reduction of cut-off frequencies by approximately a factor of $1/\sqrt{2.1}$ compared to air-filled counterparts. This study offers significant insights for the development of dielectric-loaded waveguides in applications such as microwave filters, phase shifters, and other high-frequency components where precise control over wave propagation characteristics is vital. [1]

Task 2

Task 2 looks into the design and analysis of a half-wave dipole antenna crafted from Perfect Electric Conductor (PEC) material with a 1mm radius. The antenna dimensions were precisely calibrated to effectively radiate electromagnetic waves with a wavelength of λ mm, thereby enhancing its efficacy as a resonant radiator. The excitation process utilized a lumped port featuring a standardized impedance of 50 Ohms, ensuring alignment with typical RF systems. For accurate far-field analysis and characterization of the radiation pattern, the antenna model was situated within a defined rectangular radiation boundary. Extensive simulation results illustrate the antenna's radiation properties, encompassing directivity, gain, input impedance, and voltage standing wave ratio (VSWR). Additionally, an assessment of how conductor radius affects bandwidth and radiation efficiency was conducted, shedding light on the performance trade-offs associated with dipole antenna design. This investigation provides essential insights for applications that require efficient half-wave dipole radiators, such as wireless communications, broadcasting, and sensing systems, where reliable radiation patterns and impedance matching are crucial. [2]

Introduction



What is Electromagnetic Wave Propagation?



Electromagnetic wave propagation describes how electromagnetic waves, which consist of alternating electric and magnetic fields, move through space or various materials. Unlike sound waves, these electromagnetic waves do not need a medium to travel and can move through a vacuum at light speed. The path of their travel is perpendicular to both the electric and magnetic fields.

Key Aspects of Electromagnetic Wave Propagation

- **No medium required** - Electromagnetic waves, in contrast to sound waves, have the ability to move through a vacuum, which is essentially empty space.
- **Self-propagating** - Electromagnetic waves are able to propagate on their own due to a dynamic interplay between electric and magnetic fields. When the electric field changes, it creates a varying magnetic field, which then leads to further changes in the electric field, continuing this cycle and allowing the wave to move forward.
- **Transverse Nature** - The electric and magnetic fields move in oscillations that are perpendicular to each other as well as to the path they propagate along.

- **Interaction with matter** - When electromagnetic waves come into contact with matter, they may be absorbed, reflected, refracted, or scattered.
- **Propagation modes** – Ground Waves, Space Waves and Sky Waves
- **Speed of light** - In a vacuum, electromagnetic waves move at the speed of light, which is roughly 299,792,458 meters per second.

Method

This section will describe the methods from Task 1 of creating both the Rectangular Waveguide model filled with vacuum and the Rectangular Waveguide model filled with Teflon. It will also describe the method from Task 2 creating a Half Wave Dipole Antenna intended to radiate Electromagnetic waves. Each of the models were created using given measurements and parameters. All models were created using Ansys Electronic software.

Task 1a Method

Before any of the software was used to create the Rectangular Waveguide the dimensions needed to be calculated. These included the width (a), the height (b) and the length (c). The Length (c) was a given value = 50mm meaning only the width (a) and the height (b) needed to be calculated using the following principles.

(a) = first two numbers of student ID number

(b) = $\frac{\text{3rd and 4th number of student ID number}}{2}$ (rounded to the nearest integer)

In this case, the student ID number was: 2031021

Therefore, (a) = 20 and (b) = $\frac{31}{2} = 15.5$ rounded to 16

Meaning, (a) = 20mm, (b) = 16mm and (c) = 50mm.

Once all of the initial calculations were complete to figure out the dimensions of the rectangular waveguide model, these dimensions could be used to create the model in Ansys.

Firstly, a new project was started and a HFSS design was created. The units that were to be used for the dimensions were set to mm and a HFSS Modal solution was selected as the required model design. A rectangular waveguide was then drawn and the dimensions previously calculated were added. The X-axis dimensions corresponded to the width (a), in this case it was 20mm. The Y-axis dimensions corresponded to the height (b), in this case it was 16mm. Finally, the Z-axis dimensions corresponded to the length (c), in this case it was 50mm.

Once the correct measurements had been allocated to the rectangular waveguide a name was added, the desired materials were allocated (Task 1a it was vacuum and for Task 1b it was Teflon) and the transparency was adjusted to around 0.8. The design needed to have perfect electric conductor walls therefore these needed to be added. All four of the sides of the rectangle were selected and the Perfect E boundary was assigned, all four sides of the rectangle then displayed a pattern ensuring the PEC walls had been added.

Now it was time to create the excitation at the ports also known as the openings of the waveguide. This excitation was a wave port, this was assigned by selecting one of the faces of the rectangular waveguide and assigning a wave port (modal). The number of modes then needed to be assigned and the full port impedance was set. In this case it was 3 modes and the default full port impedance was set to 50 ohms. Another excitation was created at the second port and the same steps as previous were followed. 3 modes were also assigned to the second excitation and as before the default full port impedance was set to 50 ohms.

Next, was to apply the solution setup frequency to the model, this needed to be close to the operating frequency or expected cut-off frequency. The maximum number of passes which is basically the refinement steps when the mesh is created in the software needs to be set at 99 or less simply for simulation efficiency allowing the system to run as smoothly as possible. The frequency sweeps then needed be altered to a starting frequency of 2GHz and an end frequency of 30GHz.

After creating the model, the simulation needed to be ran to obtain the results. After a short amount of time the simulation should have finalised, at this point the cut-off frequencies needed to be checked. These can be viewed by creating a terminal solution data report in this case a rectangular plot. To view the cut-off frequencies on the rectangular plot data report three markers needed to be added for each mode, these will be labelled as m1, m2 and m3. These results will be displayed and discussed within the Results section of the report. [3]

The cut-off frequencies can also be calculated using the following formula:

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

Where:

- f_c : Cut-off frequency (Hz)
- c : Speed of light in vacuum (3×10^8 m/s)
- a : Width of the waveguide (in meters, along x-axis)
- b : Height of the waveguide (in meters, along y-axis)
- m, n : Mode indices (non-negative integers)
 - For TE modes: $m, n \geq 0$, but not both zero
 - For TM modes: $m, n > 0$

In this example:

$$a = 20\text{mm} = 2\text{cm} = \underline{0.02\text{m}}$$

$$b = 16\text{mm} = 1.6\text{cm} = \underline{0.016\text{m}}$$

Task 1b Method

The method for Task 1b is exactly the same as the method for Task 1a. However, it has some subtle differences. These include, the PEC wall will be filled with Teflon instead of Vacuum like Task 1a, the relative permeability is set to 1 and the relative permittivity is set to 2.1. The relative permeability is simply the difficulty of how easy a magnetic field can pass through a material. The relative permittivity is simple how much electric field is reduced inside a material and how well a material stores electric energy.

The cut off frequencies are calculated the same way however the results will be slightly different because of the subtle changes within the modelling of the rectangular waveguide. The relative permeability and relative permittivity will affect the cut off frequencies for the 3 modes. The following calculations can distinguish the difference that the relative permeability and permittivity have on the cut off frequencies:

The calculation for the cut-off frequency for a mode in a rectangular waveguide is:

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

Or in terms of relative permeability and permittivity:

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

Assuming:

- $\mu_r = 1$ for non-magnetic materials (which in this scenario is true for both vacuum and Teflon)
- Only ϵ_r changes

Comparing the Vacuum PEC wall and Teflon PEC wall:

- The cut-off frequency in vacuum ($\epsilon_r = 1$): $f_{c, \text{vacuum}} = \frac{c}{2a}$
- The cut-off frequency in Teflon ($\epsilon_r = 2.1$): $f_{c, \text{Teflon}} = \frac{c}{2a\sqrt{2.1}} = \frac{f_{c, \text{vacuum}}}{\sqrt{2.1}}$
-

The Teflon waveguide has a lower cut-off frequency than the vacuum filled PEC wall by a factor of:

$$\frac{f_{c, \text{Teflon}}}{f_{c, \text{vacuum}}} = \frac{1}{\sqrt{2.1}} = 0.69$$

Ultimately meaning whatever the cut-off frequency is for the vacuum filled PEC wall the cut-off frequency for the Teflon filled PEC wall will be 69% of that for each mode.

Task 2 Method

Before any of the software was used to create the Half Wave Dipole Antenna with a radius of 1mm and a wavelength of λ mm the parameters needed to be determined.

- The λ = the first three numbers of student ID number

In this case the student ID number was: 2031021

Therefore, the $\lambda = 203\text{mm}$

- The length of the dipole antenna = $L = \frac{\lambda}{2} = \frac{203}{2} = 101.5$ rounded to 102mm = 0.102m

Once all of the determinations were complete to figure out the dimensions of the Half Wave Dipole Antenna, the software could now be used to create the model.

Firstly, a new project was started and a HFSS design was created. The units that were to be used for the dimensions were set to mm and a HFSS Modal solution was selected as the required model design. A cylinder was then drawn with any dimension. The properties of the cylinder were then adjusted to fit the intended model design of the chosen parameters at the start. The Z axis was made the main axis point of the model, the radius was set to 1, the height was set to 102mm. For the centre position the Z coordinate was set to half of the height in this case -51mm so half of the cylinder was below the zero line. The material was changed to PEC, transparency was set close to 0.8.

A gap in the centre of the cylinder was then created meaning another smaller cylinder was to be created in-between. The parameters of the second cylinder were adjusted. The radius was set to 1 again, the height was set to 1mm. Just like the first cylinder the centre position for the Z coordinate was set to half the height in this case -0.5mm. The transparency of this smaller cylinder was set to 0.8 again.

The second cylinder then needed to be subtracted from the long cylinder creating a gap in-between the long cylinder at the centre. A lumped port was then created by selecting the smaller centre cylinder and the YZ section was selected. The full port impedance was then set too 50 ohms and the

number of modes was set to 1. Next an open region needed to be created, the operating frequency was left at 1GHz and the boundary was changed to PML. By pressing Excitation, this allows to check that the lumped port has been created, if it has been created correctly a pattern will show on the centre cylinder.

Solution setup then needs to be created, the frequency is set to a frequency close to the operating frequency, in this case it can be calculated as:

The basic dipole formula: $L = \frac{c}{2f}$

Rearranging to solve for frequency: $f = \frac{c}{2L}$

Where:

C = Speed of light = 3×10^8 m/s

f = frequency in (Hz)

L = total dipole length in (m)

$$f = \frac{3 \times 10^8}{2 \times 0.102}$$

$$f = 1.47\text{GHz}$$

The number of passes is set to 99. The frequency sweep is edited to allow the operating frequency to fall within the range. In this case the operating frequency was 5GHz therefore, the frequency sweep was set from 1GHz to 7.5GHz. After creating the model, the simulation needed to be ran to obtain the results. After a short amount of time the simulation should have finalised.

Results

Task 1a Results

The results in this section will discuss the modelling of the rectangular waveguide with PEC walls made from vacuum. The calculations of the cut-off frequencies will be calculated using theoretical formula and will be compared to the cut off frequency results from the simulation.

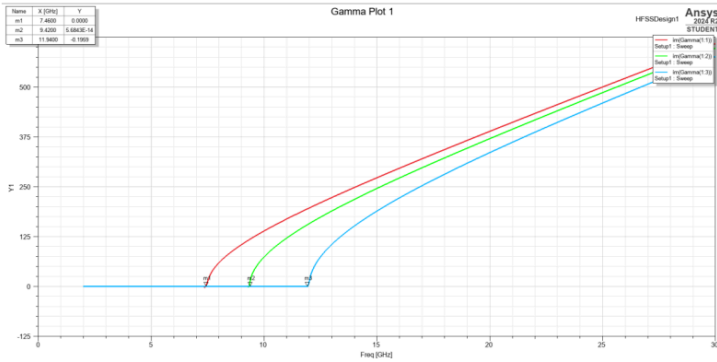


Figure 1 - Task 1a Results

Figure 1 above from completing Task 1a shows the rectangular plot which shows the three cut off frequencies for the three modes. The cut off frequencies from the simulation were as follows:

Mode 1: 7.46 GHz

Mode 2: 9.42 GHz

Mode 3: 11.94 GHz

To check that the modelling and simulation has been completed successfully the cut off frequencies can be calculated using the following theoretical formula mentioned previously:

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

Where:

- f_c : Cut-off frequency (Hz)
- c : Speed of light in vacuum (3×10^8 m/s)
- a : Width of the waveguide (in meters, along x-axis)
- b : Height of the waveguide (in meters, along y-axis)
- m, n : Mode indices (non-negative integers)
 - For TE modes: $m, n \geq 0$, but not both zero
 - For TM modes: $m, n > 0$

In this example:

$$a = 20\text{mm} = 2\text{cm} = 0.02\text{m}$$

$$b = 16\text{mm} = 1.6\text{cm} = 0.016\text{m}$$

The modes that were used for the modelling were, TE₁₀, TE₀₁ and TE₁₁. These modes are typically used for this type of simulation within Ansys.

Calculating the cut-off frequencies:

$$\text{Mode 1 – TE}_{10} \text{ Mode: } f_{c,10} = \frac{c}{2a} = \frac{3 \times 10^8}{2 \times 0.02} = 7.5 \text{ GHz}$$

$$\text{Mode 2 – TE}_{01} \text{ Mode: } f_{c,01} = \frac{c}{2b} = \frac{3 \times 10^8}{2 \times 0.016} = 9.38 \text{ GHz}$$

$$\text{Mode 3 – TE}_{11} \text{ Mode: } f_{c,11} = \frac{c}{2} \sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2}$$

$$f_{c,11} = \frac{3 \times 10^8}{2} \sqrt{\left(\frac{1}{0.02}\right)^2 + \left(\frac{1}{0.016}\right)^2} = \frac{3 \times 10^8}{2} \times 8 = 12 \text{ GHz}$$

As can be seen from the calculations, both of the answers for the cut-off frequencies for all three modes are very similar between the ones calculated using the formula and the ones calculated from the simulation.

Task 1b Results

The results in this section will discuss the modelling of the rectangular waveguide with PEC walls made from Teflon. The calculations of the cut-off frequencies will be calculated using theoretical formula and will be compared to the cut off frequency results for the same rectangular waveguide with PEC walls made from Teflon.

As previously stated, The relative permeability and relative permittivity will affect the cut off frequencies for the 3 modes. The following calculations can distinguish the difference that the relative permeability and permittivity have on the cut off frequencies:

The calculation for the cut-off frequency for a mode in a rectangular waveguide is:

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

Or in terms of relative permeability and permittivity:

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

Assuming:

- $\mu_r = 1$ for non-magnetic materials (which in this scenario is true for both vacuum and Teflon)
- Only ϵ_r changes

Comparing the Vacuum PEC wall and Teflon PEC wall:



- The cut-off frequency in vacuum ($\epsilon_r = 1$): $f_c, \text{vacuum} = \frac{c}{2a}$
- The cut-off frequency in Teflon ($\epsilon_r = 2.1$): $f_c, \text{Teflon} = \frac{c}{2a\sqrt{2.1}} = \frac{f_c, \text{vacuum}}{\sqrt{2.1}}$
-

The Teflon waveguide has a lower cut-off frequency than the vacuum filled PEC wall by a factor of:

$$\frac{f_{c, \text{Teflon}}}{f_{c, \text{vacuum}}} = \frac{1}{\sqrt{2.1}} = 0.69$$

Ultimately meaning whatever the cut-off frequency is for the vacuum filled PEC wall the cut-off frequency for the Teflon filled PEC wall will be 69% of that for each mode.

Therefore, the average cut-off frequencies for Task 1a were:

- 7.48 GHz
- 9.40 GHz
- 11.97 GHz

Baring this in mind ,this means the cut off frequencies for the same rectangular waveguide with different material for the PEC walls are:

- $7.48 \times 0.69 = 5.16 \text{ GHz}$
- $9.40 \times 0.69 = 6.49 \text{ GHz}$
- $11.97 \times 0.69 = 8.26 \text{ GHz}$

The reason that the cut off frequencies are lower for PEC walls with Teflon compared to vacuum is because of the permittivity. As the vacuum has a permittivity of 1 and the Teflon has a permittivity of 2.1 which means the electromagnetic waves move into the material slower. In simple terms:

Teflon – has a higher permeability – meaning a slower wave – longer wavelength inside – needs frequency to excite the mode – the cut-off frequency drops.

Task 2 Results

This results section will discuss the modelling of the half wave dipole antenna. Figure 2 below shows the S-parameter plot of the results.

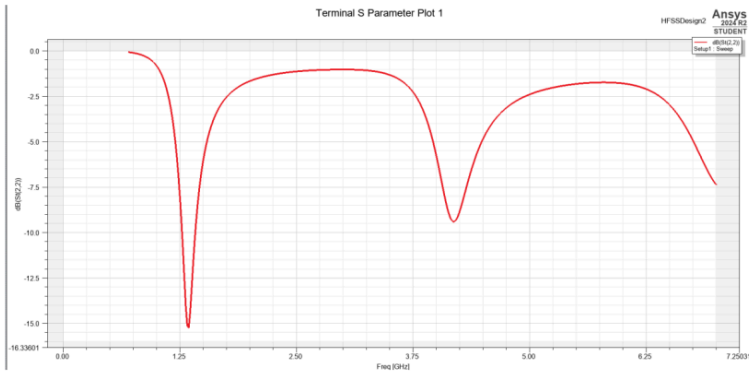


Figure 2 - Figure 2 Results

Figure 2 above shows the S-parameter plot for the half wave dipole antenna.

Conclusion

Rectangular Waveguides behave the way they do because of how electromagnetic waves interact with boundaries. In this case it is the PEC walls made from both vacuum and Teflon. The waves can be reflected or confined which ultimately changes the results of the cut off frequencies. As previously discussed the permittivity has an effect on how the waves interact with the boundaries, i.e. the PEC walls. This means the higher the permittivity the lower the cut off frequency as it is more difficult for the waves to pass into the materials.

Half wave dipole antennas behave the way they are resonant structures. They are created to support standing electromagnetic waves at certain frequencies. This occurs due to three main physical reasons:

- Resonance
- Current and Voltage Distribution
- Radiation Mechanism

A simple summary of why half wave dipole antennas work the way they do is, think of a half-wave dipole like a swing:

- When you push a swing at the right natural rhythm, it moves back and forth efficiently.

- Same with a dipole: When the frequency matches its natural "swinging" (resonant) frequency, it radiates power very efficiently into space.

The modelling and simulations carried out for both tasks were both accurate with results obtained from using theoretical formulas. This proves that modelling and simulation is a great tool to use and the results obtained are accurate to equation sources used.

References



- [[Online]. Available:
 1 [https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_\(Steer\)/06%3A_Waveguides/6.04%3A_Rectangular_Waveguide](https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_(Steer)/06%3A_Waveguides/6.04%3A_Rectangular_Waveguide).
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- [[Online]. Available: <https://rsgb.org/main/get-started-in-amateur-radio/antennas/your-first-antenna-the-half-wave-dipole/>.
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 3 <https://www.keysight.com/used/tw/en/knowledge/glossary/oscilloscopes/cutoff-frequency#:~:text=Cutoff%20frequency%2C%20or%20corner%20frequency,magnitude%20of%20the%20input%20signal.&text=Cutoff%20frequency%2C%20a%20fundamental%20concept,and%20interact%20wi>.
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Assignment

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

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PAGE 1



Comment 1

Good Work,
the first page or the tile page of the report should have the name, student ID,
Module Name, Module code, Title of the Coursework, programme of study. Most of
these are in the title page, but however few are missing.

PAGE 2



Comment 2

Good work

PAGE 3



Comment 3

he abstract should be shorter and limited to one page, summarising all tasks.

PAGE 4



Comment 4

It is better to start from a fresh page



Comment 5

It is better to number each heading

PAGE 5

PAGE 6



Comment 6

It is better to number each page

PAGE 7

PAGE 8

**Comment 7**

the wave guide design screen short is missing

**Comment 8**

Good Work

**Comment 9**

Electric and Magnetic field vectors and magnitude screen shorts are missing

**Comment 10**

The dipole antenna, and radiation pattern screen shorts are missing

**Comment 11**

It is better to include more references

GRADING FORM: EMR-MAY 2025 OME

FINN MALLON

48.85

ENGAGEMENT WITH LITERATURE

Marks will be awarded based on the extent of research and/or own reading, selection of credible sources, application of appropriate referencing conventions. You MUST include evidence of sources that you have discovered yourself during the course of your own student centred work.



Poor engagement with essential reading. No evidence of wider reading. . Heavily reliant on information gained through class contact. Weak use of referencing. Each paragraph discussing a concept or definition should be supported with a citation. Use latest engineering articles or IEEE

3.5

papers to enhance technical credibility and demonstrate engagement with current research.

KNOWLEDGE AND UNDERSTANDING

Marks will be awarded for the accuracy of your description of the concepts and principles of EMW and how this relates to the design used.



Knowledge is reasonably detailed and accurate, with a good critical understanding of well-established concepts and principles of electromagnetic radiation. Shows sound understanding of waveguide theory, cutoff frequency, and the impact of materials. Could elaborate further on field distributions and mode shapes. A deeper explanation of why a higher dielectric constant lowers the cutoff frequency would strengthen the analysis. Cutoff frequency calculations are not supported by screenshots of the port field display.

13.75

COGNITIVE AND INTELLECTUAL

Marks will be awarded for the quality and validity of your interpretation of the experimental results gathered. You should consider the differences between the simulated and theoretical and explain possible causes for them.



Limited critical evaluation of electromagnetic radiation concepts, with a tendency toward description. Theoretical and simulated results are compared logically with reasonable accuracy, and formulas are applied consistently with supporting numerical evidence. However, there is no quantitative error analysis. Parts of the conclusion are descriptive. Radiation pattern, mode screenshots, and electric/magnetic field plots (vector and magnitude) are missing.

11

PRACTICAL SKILLS

Marks will be awarded for the use of the available tools, models and techniques to explain your results and their relationship to the theory of the concepts.



An adequate awareness and mostly appropriate application of established methods, materials, tools and techniques. Correct use of PEC boundaries, wave ports, and lumped ports. No mention of mesh settings, solver convergence, or computational considerations. Consider adding field plots or gain charts for the antenna. the waveguide design screen shorts and antenna design screen shorts are missing

8.6

TRANSFERABLE SKILLS FOR LIFE

This section will be assessed based on the employability skills gained, written and presentational quality of the report. Style, structure, grammar, spelling etc..



Communicates well, consistently using a medium suitable for the intended audience. The report is mostly well-organised, with clear sectioning and logical flow. Mathematical formatting is clean and legible. The introduction is too long. Section titles and structure are clear. Proper alignment and thorough proofreading, proper caption for the figures would have improved the overall quality of the report.

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