

Design and Analysis of Electromagnetic Systems

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Abstract

This report covers the simulation, via ANSYS [1], of two rectangular wave-guides - each with the same dimensions but different material inside - and a half-wave dipole. The theoretical characteristics are compared to those produced by the simulation and reasoning provided for any discrepancies that occur.

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1 Introduction

Wave-guides and dipole antennas are key components used to propagate electro-magnetic waves. Due to the complexity of the wave propagation, theory can only go so far to teach how these components work. Applying the theory through practical experimentation and analysis shows how these components interact with the real-world.

2 Wave-guide

A wave-guide is a metal pipe that carries electromagnetic waves between various components, such as to and from antennas and transmitters and/or receivers. Wave-guides typically come in one of two shapes: circular or rectangular.

2.1 Specification

The specification dictates that the first two digits of our student number is the width, a , of the rectangular wave-guide, which gives 23 mm, the height, b , is the third and fourth digits divided by 2, which gives 6 mm, and the length is 50 mm. The walls of the wave-guide is constructed of Perfect Electric Conductor (PEC).

2.2 Propagation Modes

The waves travelling through a wave-guide can propagate in various forms. The characteristics of the wave-guide and the wave determine the mode. The two propagation modes that occur in rectangular wave-guides are transverse electric (TE) and transverse magnetic (TM).

The propagation mode takes the forms TE_{mn} and TM_{mn} where m is the number of standing waves across the width, a , and n is the number of standing waves across the height, b . For TM mode, n and m cannot be 0 [2].

The dominant propagation mode is therefore TE_{10} . Since $a > 2b$, the next propagation mode is TE_{20} , and, since $a > 3b$ the following propagation mode is TE_{30} . Only the first three propagation modes are being tested in the simulation. The first six are shown in Figure 1.

Propagation Mode
TE_{10}
TE_{20}
TE_{30}
TE_{01}
TE_{11}
TM_{11}

Figure 1: First six Propagation Modes for this Rectangular Wave-guide

The propagation mode of a wave through a wave-guide is determined by the frequency of the wave. Each mode has a cutoff frequency, f_c , below which the wave cannot propagate in that mode. The equation for the cutoff frequency of a particular TE or TM mode is

$$f_c = \frac{c_0}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (1)$$

where μ_r is relative permeability and ϵ_r is relative permittivity.

2.3 Simulation

The rectangular wave-guides were simulated using ANSYS [1].

Throughout designing the wave-guide in ANSYS, every step of the process was checked multiple times to verify each step was performed correctly. Before any analysis was performed on the wave-guide, the model was validated using tools in ANSYS. This identified mistakes and missing components needed to perform the analysis.

Alongside the verification, the model was designed to be as modular as possible. This would allow the model to be easily adjusted when modifications were made. To accomplish this, multiple properties were used to describe the wave-guide length (l), height (h), and width (w). The final values for each property is show in Figure 2.

Property	Value
l	50 mm
h	6 mm
w	23 mm

Figure 2: Properties used to characterise the wave-guide.

2.4 Vacuum

The first rectangular wave-guide simulated was filled with a vacuum.

2.4.1 Theoretical Characteristics

With a relative permeability, μ_r , of 1, and a relative permittivity, ϵ_r , of 1, the cutoff frequency, f_c for the first three modes is shown in Figure 3.

Propagation Mode	f_c
TE_{10}	6.517 GHz
TE_{20}	13.034 GHz
TE_{30}	19.552 GHz

Figure 3: First three Cutoff Frequencies this Rectangular Wave-guide when filled with a Vacuum

2.4.2 Fields

The port field displays for the first the three modes, shown in Figures 4, 5, and 6, confirm that the first three propagation modes are TE_{10} , TE_{20} , and TE_{30} respectively.

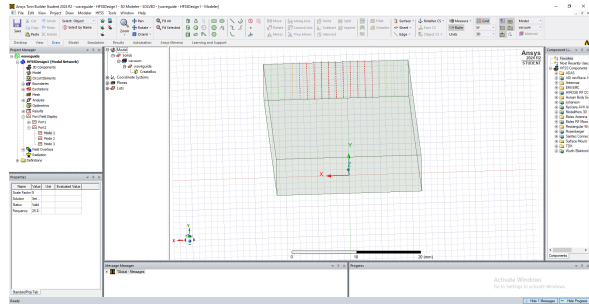
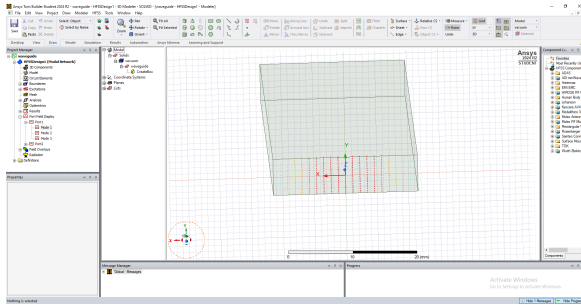


Figure 4: Port Field Displays for Mode 1 of the Rectangular Wave-guide filled with a Vacuum

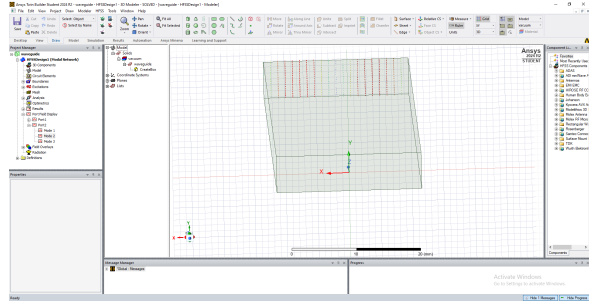
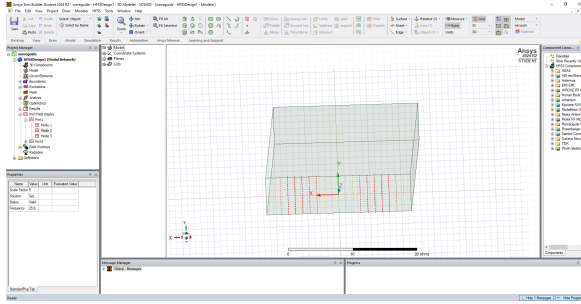


Figure 5: Port Field Displays for Mode 2 of the Rectangular Wave-guide filled with a Vacuum

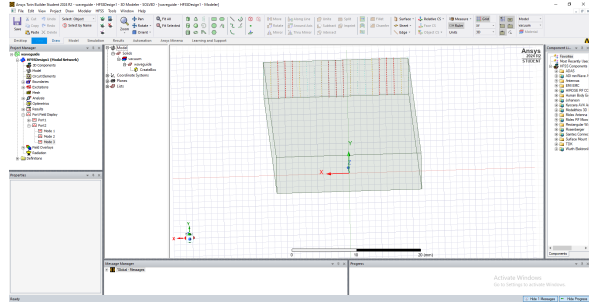
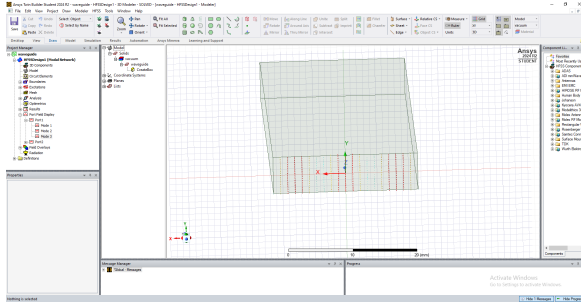


Figure 6: Port Field Displays for Mode 3 of the Rectangular Wave-guide filled with a Vacuum

The magnitude and vector plots of the electric and magnetic fields, Figures 7 and 8, also suggest that the only propagation modes are TE.

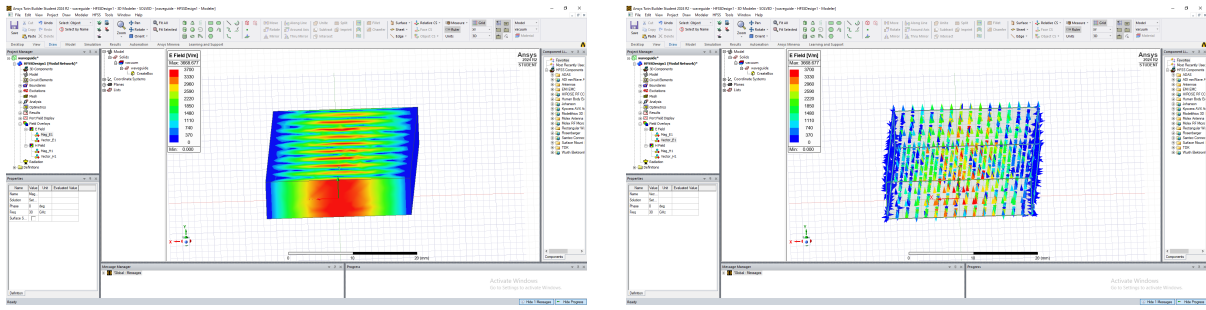


Figure 7: Magnitude and Vector Plots for the Electric Field of the Rectangular Wave-guide filled with a Vacuum

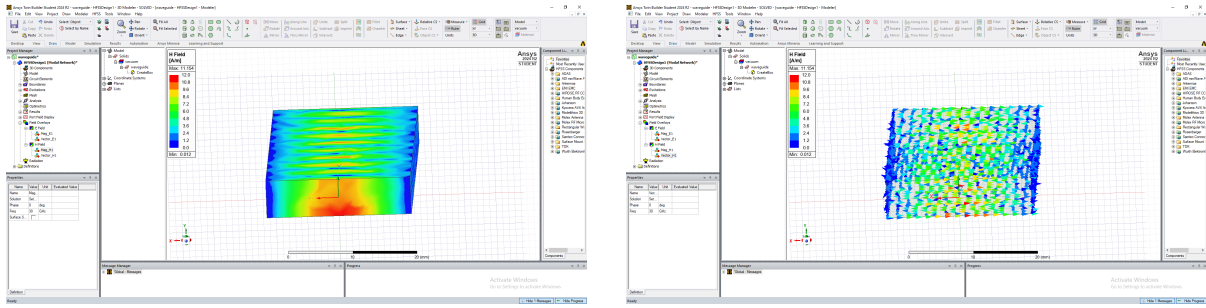


Figure 8: Magnitude and Vector Plots for the Magnetic Field of the Rectangular Wave-guide filled with a Vacuum

2.4.3 Complex Propagation Constant

The complex propagation constant plot in Figure 9, shows that the simulated cutoff frequencies are almost identical to those calculated using theory.

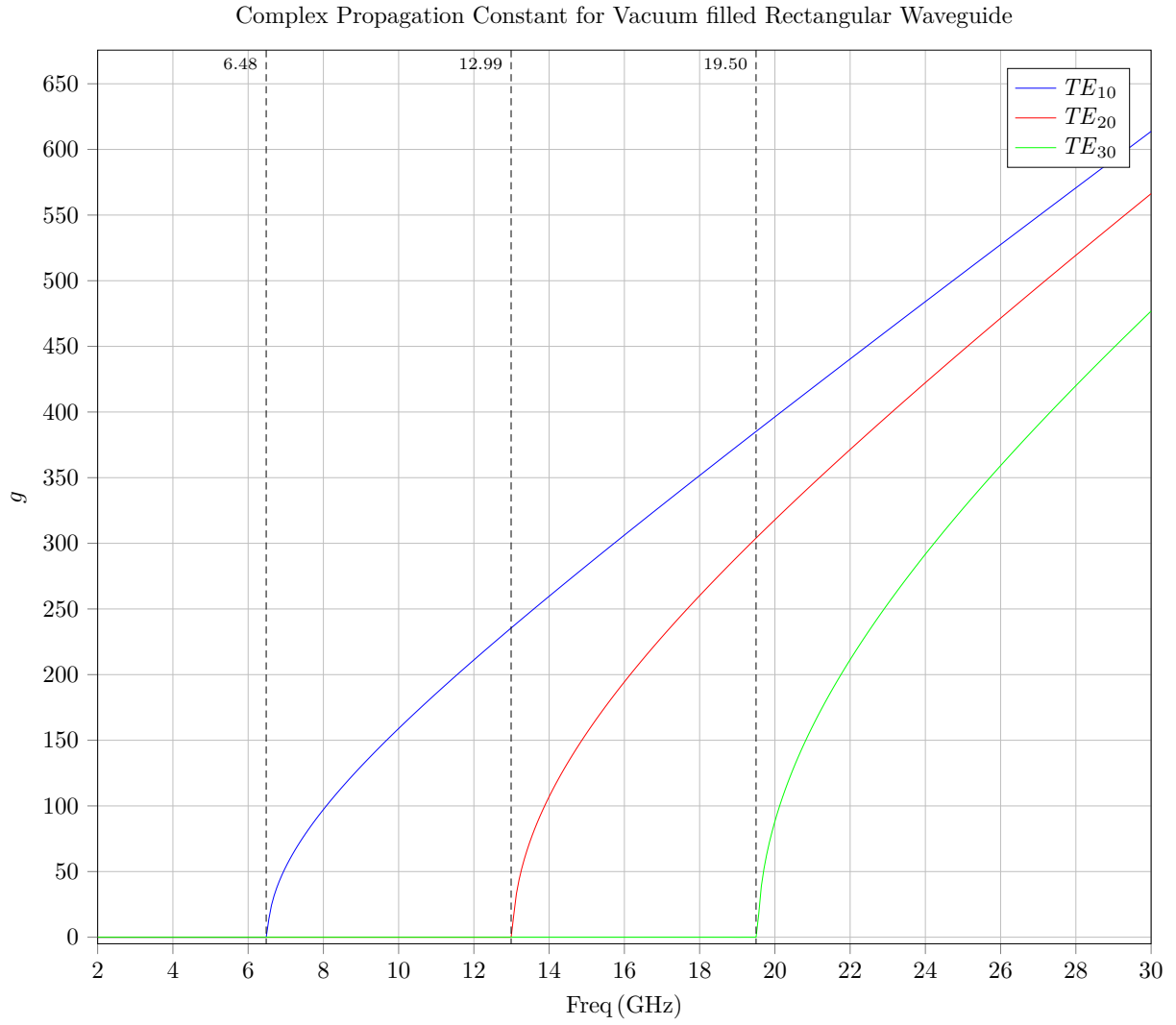


Figure 9: Complex Propagation Constant for the Rectangular Wave-guide filled with a Vacuum

2.5 Teflon

The second rectangular wave-guide simulated was filled with Teflon.

2.5.1 Theoretical Characteristics

With a relative permeability, μ_r , of 1, and a relative permittivity, ϵ_r , of 2.1, the cutoff frequency, f_c , for the first three modes is shown in Figure 10.

Propagation Mode	f_c
TE_{10}	4.497 GHz
TE_{20}	8.995 GHz
TE_{30}	13.491 GHz

Figure 10: First three Cutoff Frequencies this Rectangular Wave-guide when filled with Teflon

2.5.2 Fields

The port field displays for the first the three modes, shown in Figures 11, 12, and 13, confirm that the first three propagation modes are TE_{10} , TE_{20} , and TE_{30} respectively.

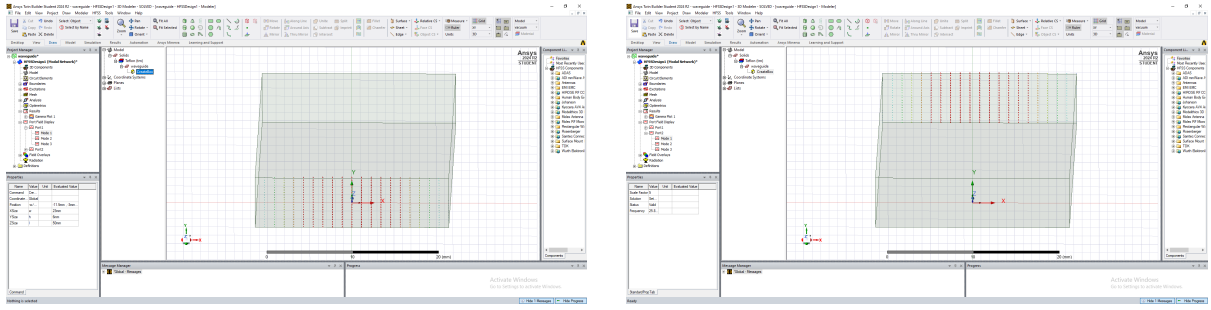


Figure 11: Port Field Displays for Mode 1 of the Rectangular Wave-guide filled with Teflon

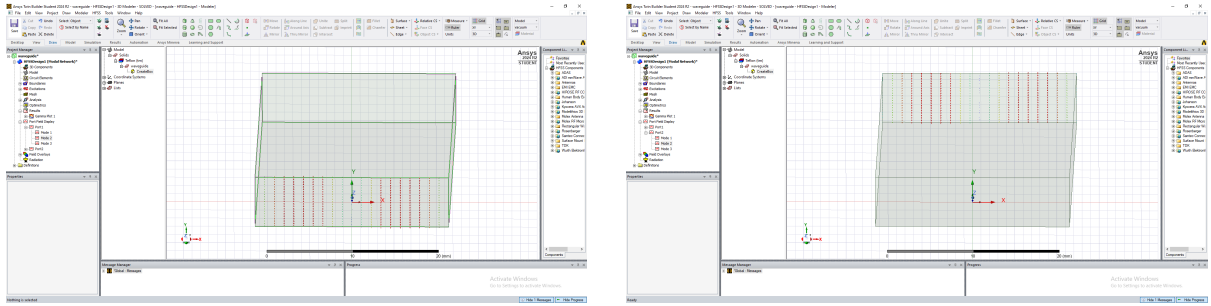


Figure 12: Port Field Displays for Mode 2 of the Rectangular Wave-guide filled with Teflon

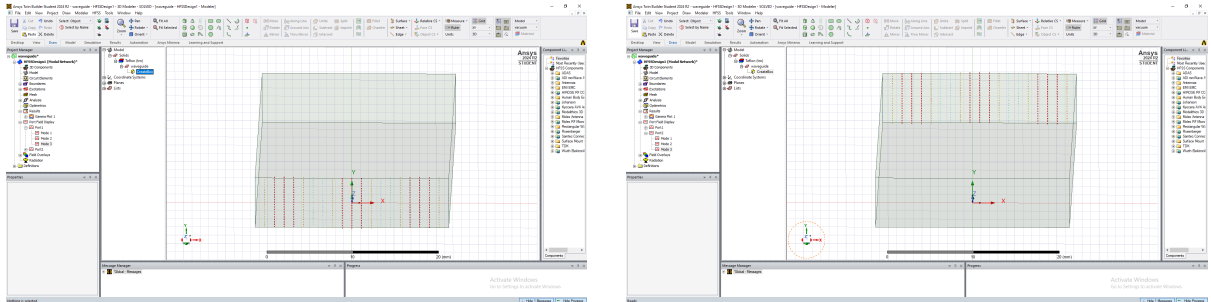


Figure 13: Port Field Displays for Mode 3 of the Rectangular Wave-guide filled with Teflon

The magnitude and vector plots of the electric and magnetic fields, Figures 14 and ??, also suggest that the only propagation modes are TE.

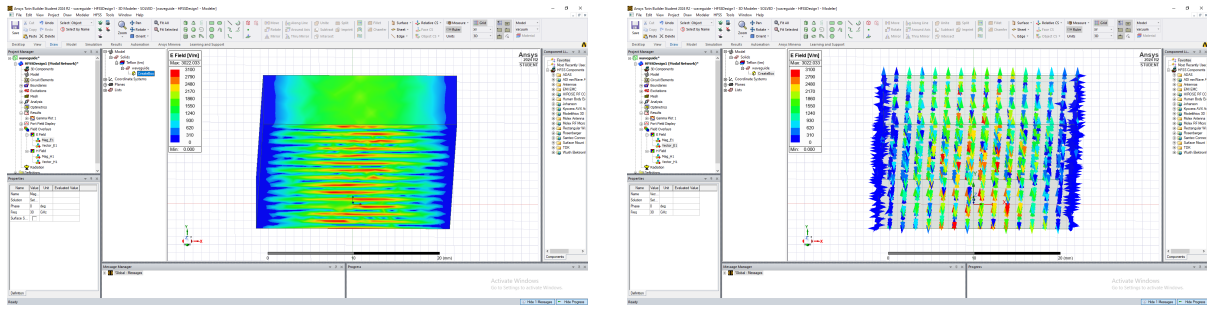


Figure 14: Magnitude and Vector Plots for the Electric Field of the Rectangular Wave-guide filled with Teflon

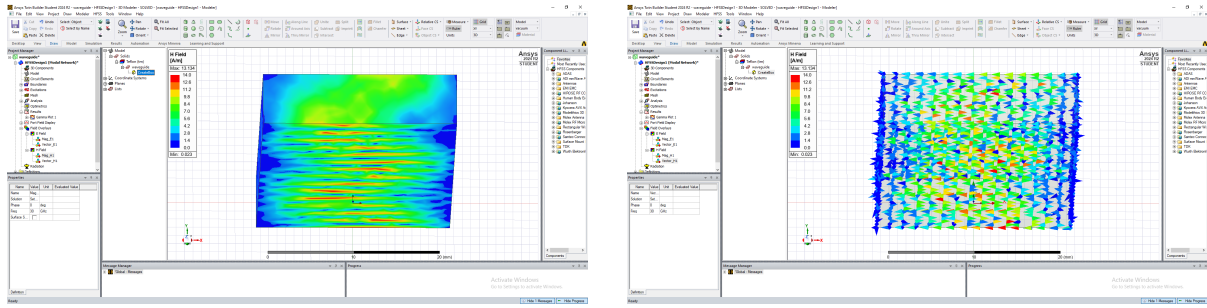


Figure 15: Magnitude and Vector Plots for the Magnetic Field of the Rectangular Wave-guide filled with Teflon

2.5.3 Complex Propagation Constant

The complex propagation constant plot in Figure 16, shows that the simulated cutoff frequencies are almost identical to those calculated using theory.

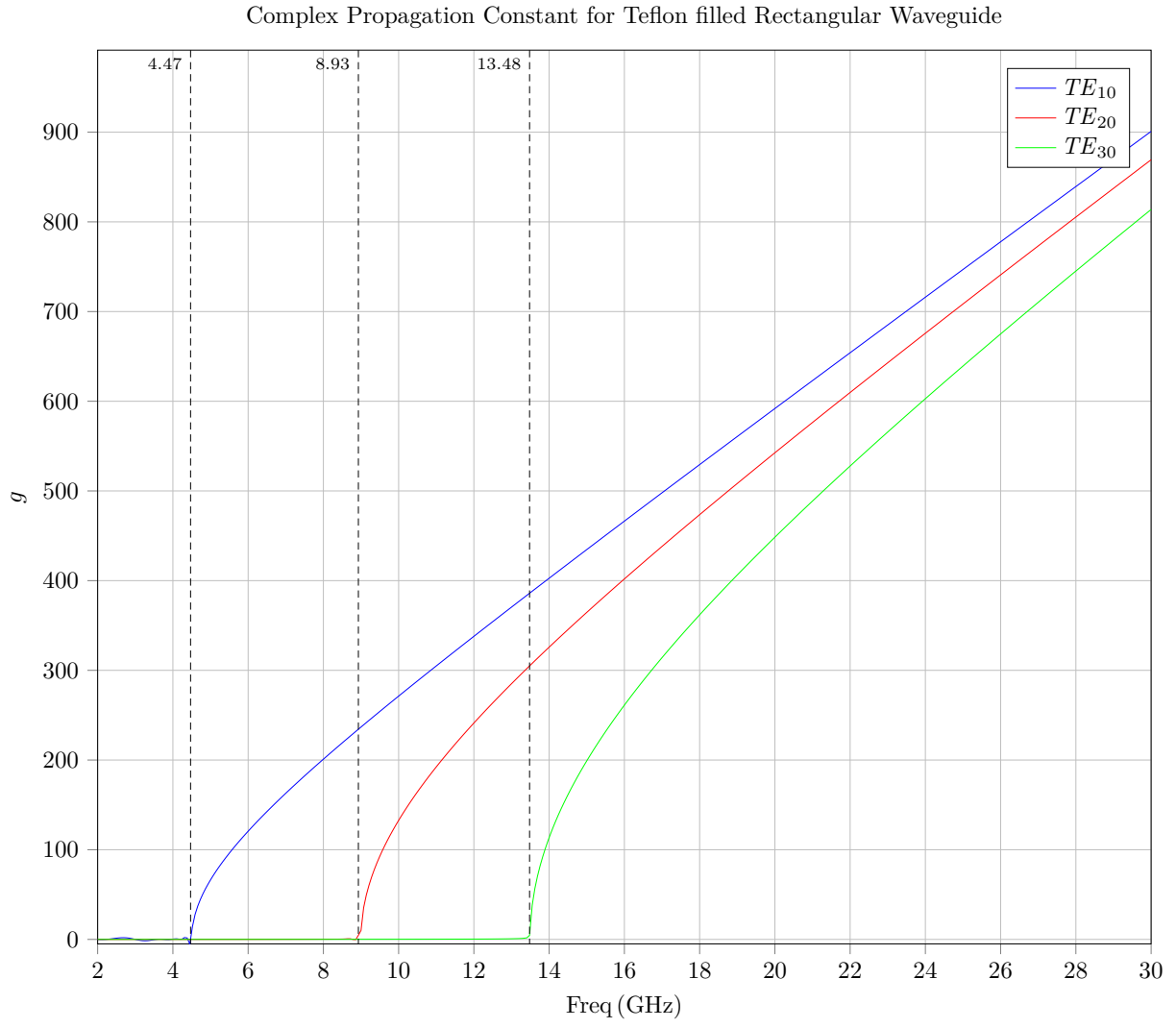


Figure 16: Complex Propagation Constant for the Rectangular Wave-guide filled with Teflon

2.6 Comparison

The difference between the two materials filling the wave-guide is the permittivity. The higher the permittivity, the lower the speed of light travelling through that material and hence a lower cutoff frequency [3].

This can be shown by calculating the speed of light in Teflon

$$c = \frac{c_0}{\sqrt{\mu_r \epsilon_r}} \quad (2)$$

where c_0 is the speed of light in a vacuum. The scalar is $\frac{1}{\sqrt{\mu_r \epsilon_r}}$ and is 0.69 for Teflon. Applying this scale factor to the to the cutoff frequencies for the vacuum filled wave-guide produces Figure 17.

Vacuum f_c	Teflon f_c	Scaled Teflon f_c
6.517 GHz	4.497 GHz	4.497 GHz
13.034 GHz	8.995 GHz	8.995 GHz
19.550 GHz	13.491 GHz	13.491 GHz

Figure 17: Scaled Cutoff Frequency for Rectangular Wave-guide

3 Half-wave Dipole Antenna

Dipole antennas are one of simplest designs for an antenna, consisting of two pole conductors and a port in between. The length of the poles characterises the antenna for optimally transmitting or receiving particular frequencies. The most common is the half-wave dipole antenna that has the accumulative length of the poles as $\lambda/2$.

3.1 Specification

The specification dictates that the wavelength is the first three digits of our student number, which gives 231 mm, the radius of each pole is 1 mm, each pole is constructed of Perfect Electric Conductor (PEC), and port has an impedance of 50Ω .

3.2 Theoretical Characteristics

The length of each pole can be derived from the wavelength. They each have a length of $\lambda/2$ to give the overall length of $\lambda/4$. This makes each pole 57.75 mm in length [4].

The operating frequency for this antenna can also be derived from the wavelength. The equation $f = c/\lambda$ calculates the frequency, f , where c is the speed of light $299\,792\,458\text{ m s}^{-1}$. For this antenna, the frequency is 1.298 GHz.

3.3 Simulation

The half-wave dipole antenna was simulated using ANSYS.

Throughout designing the antenna in ANSYS, every step of the process was checked multiple times to verify each step was performed correctly. Before any analysis was performed on the antenna, the model was validated using tools in ANSYS. This identified mistakes and missing components needed to perform the analysis.

Alongside the verification, the model was designed to be as modular as possible. This would allow the model to be easily adjusted when modifications were made. To accomplish this, multiple properties were used to describe the dipole length (dL), dipole radius (dR), and gap length (gL). The gap length represents the port size. The final values for each property is show in Figure 18.

Property	Value
dL	115.5 mm
dR	1 mm
gL	1 mm

Figure 18: Properties used to characterise the dipole.

3.4 Input Return Loss

The Scattering Parameter, or S-parameter, characterises the input-output relationship between ports in a network. The format S_{nm} is typically used when discussing S-parameters, and represents the power transferred from port n to port m for a given signal frequency [5]. For this network, there is only one port, the dipole, hereafter referred to as port 1.

Input return loss shows how much of the signal is reflected back by the port for various input frequencies. This, expressed in decibels, can be calculated from the S-parameter

$$RL_{in} = -20 \log_{10} |S_{11}| \quad (3)$$

The input return loss plot is shown in Figure 19.

Frequencies whose input return loss is close to 0 have most of the power reflected and a small amount is radiated. The lower the value, the more power is radiated by the dipole.

For the designed dipole, the operating frequency can be found at the minimum of the curve; 1.178 GHz with an input return loss of -15.457 dB . This results in a power loss of 16.87% at the operating frequency.

The input return loss plot can also shows the bandwidth of the antenna. The bandwidth of an antenna is the range of frequencies whose input return loss is less than -6 dB . For this dipole the bandwidth is 0.239 MHz.

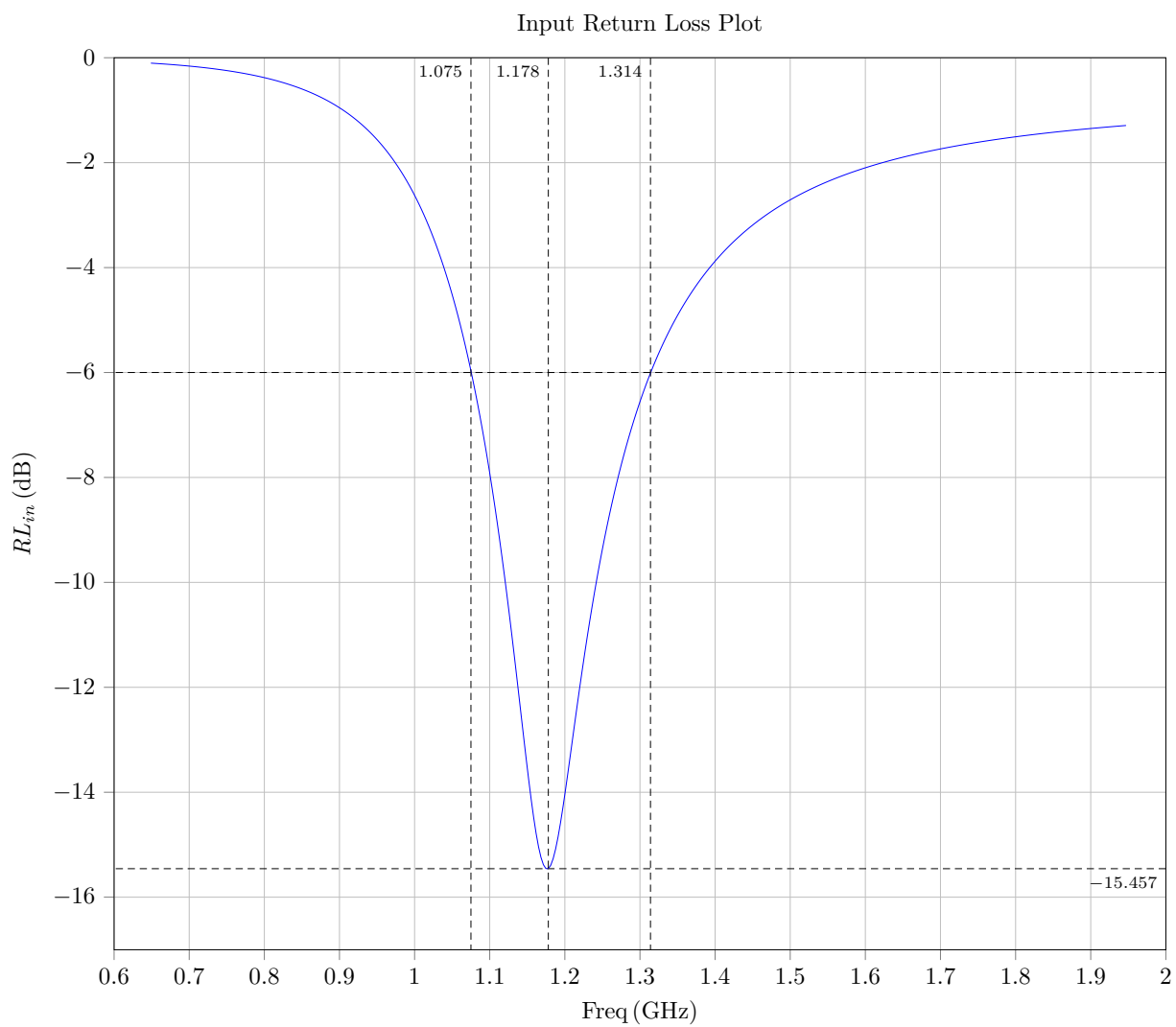


Figure 19: Input Return Loss results from ANSYS analysis

3.5 Radiation Pattern

The gain, measured in dB_i , shows how much power is radiated in a particular direction compared to an isotropic source. An isotropic source has a uniform distribution of power radiating in all directions. An antenna with 10 dB_i of gain in a particular direction radiates 10 times more power in that direction compared to an isotropic source [6].

By measuring the gain in all directions around an antenna, the radiation pattern can be plotted. This shows the directivity of the radiation that can be emitted or received by the antenna.

The radiation pattern plot is shown in Figure 20.

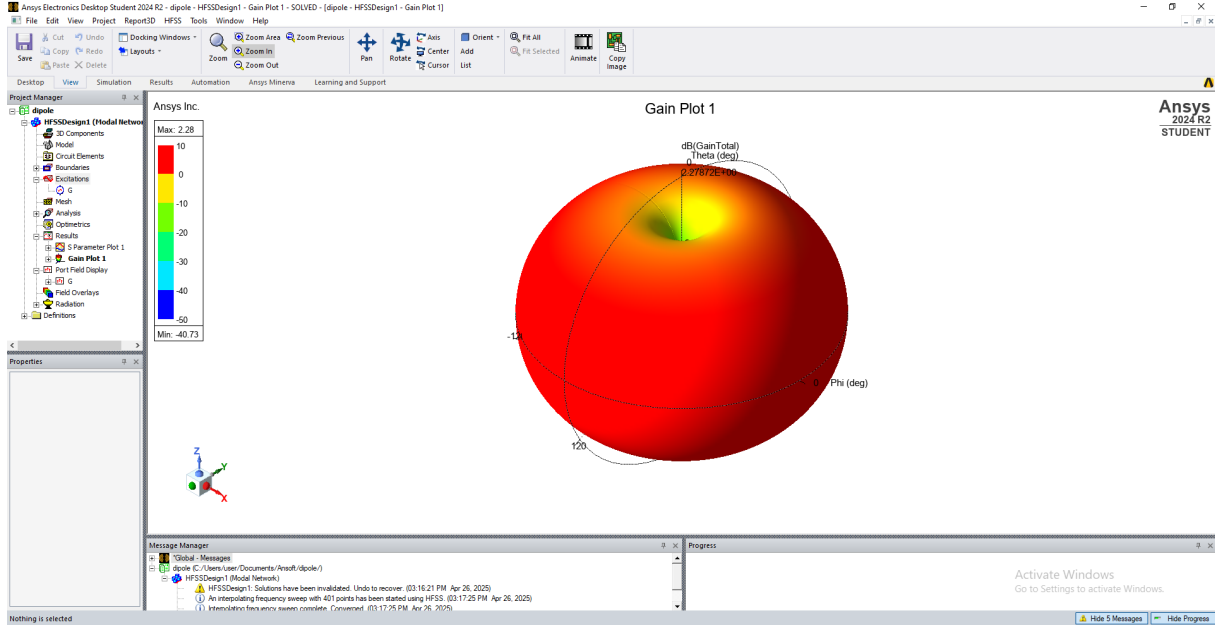


Figure 20: Radiation Pattern results from ANSYS analysis

The radiation pattern for this dipole shows loss at the top and bottom of the antenna, but uniform gain - with a maximum of 2.28 dB_i - in all directions along the length of the antenna.

3.6 Comparison

The simulated operating frequency, 1.178 GHz is greatly reduced when compared to the theorised operating frequency 1.298 GHz . This is most likely due to the port in the simulation being configured to the wrong impedance. Typical input impedance for a half-wave dipole is approximately $(70 + 42.5i) \Omega$, whereas the simulation port input impedance is 50Ω .

Adjusting the port impedance to $(70 + 42.5i) \Omega$ results in an operating frequency of 1.258 GHz . However, for practical applications, this impedance is not possible, with the closest being 70Ω .

Therefore, impedance matching is required. For a dipole of small width, the overall length is multiplied by 0.96 to 110.88 mm , and the port impedance adjusted to 70Ω [4]. This results in an operating frequency of 1.240 GHz . These adjustments are shown in Figure 21.

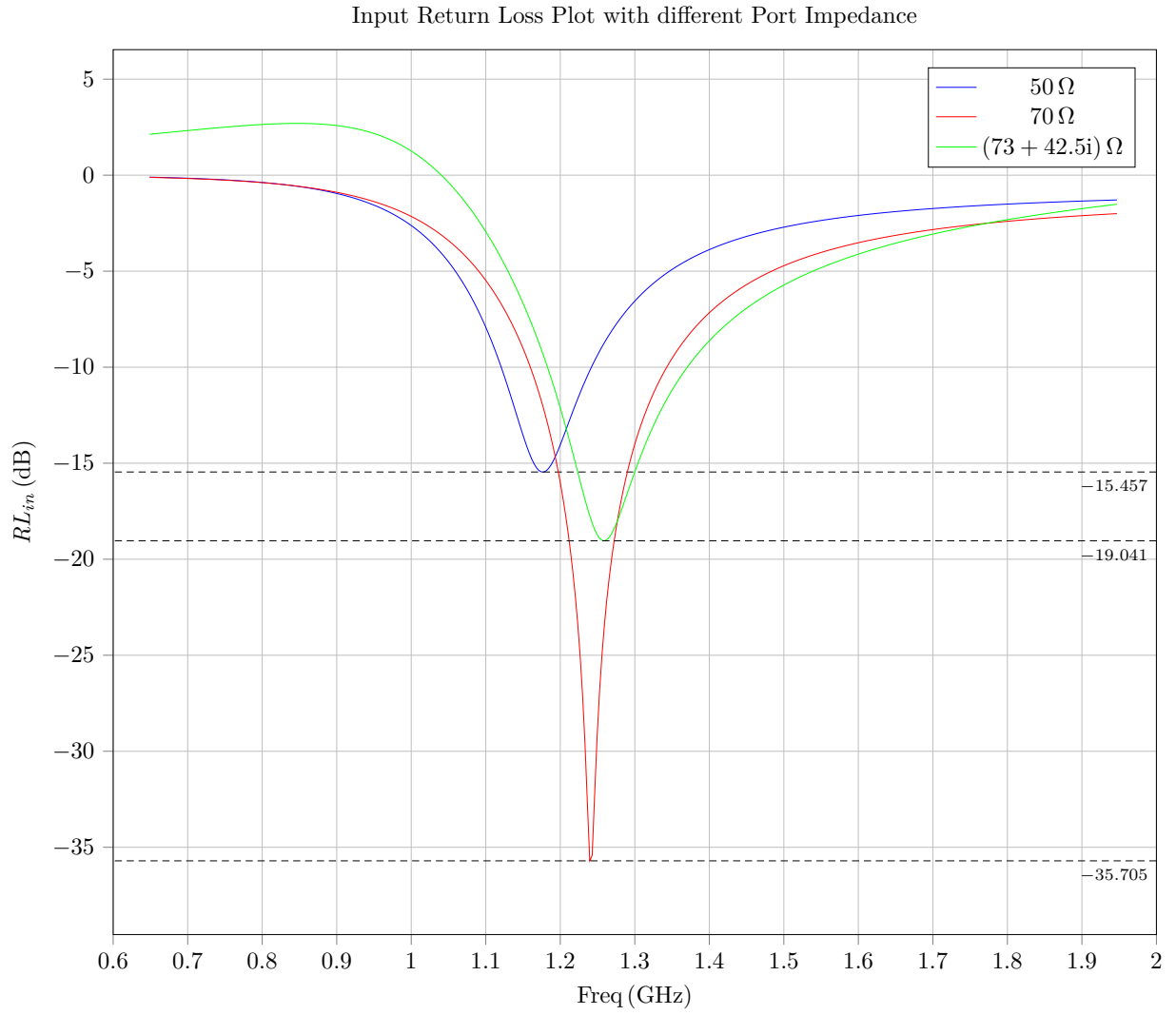


Figure 21: Input Return Loss results from ANSYS analysis with different Port Impedance

4 Conclusion

The simulations were beneficial to solidify knowledge regarding wave-guides and dipoles. Plots and interactive diagrams allow for experimentation and understanding to be gained in ways unachievable by a textbook.

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Detection of Drones using Radar

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1 Introduction

Radar is a common technology for detecting and tracking aerial vehicles. However with the rise in use of smaller unmanned aerial vehicles (UAVs), such as drones, the existing infrastructure is not designed for detecting and tracking such targets. This report discusses recent developments for detecting and tracking such vehicles.

2 Drone Usage

Improper use of drones can cause serious harm to society. This includes smuggling, airport/restricted areas disruptions, and the invasion of privacy for individuals and neighbourhoods [1]. The tracking and detection of drones in these scenarios can help identify the people involved to prosecute.

Drones are also taking on a much larger role in warfare, taking on the traditional role of spotters and surveillance for effective command and control, and are also used as guided munitions to effectively target ground targets such as vehicles and infantry. The most recent conflict that has a large use of drones on both sides is the Russia Ukraine conflict [2]. Accurately detecting and tracking enemy drones can be decisive in keeping equipment and manpower safe.

3 Detection Issues

The problems that traditional radar face when detecting drone can be classified into three areas: radar cross-section, velocity, altitude. The cross-section of drones is small, resulting in it often being filtered out as noise by traditional signal-to-noise ratio detectors.

Compared to most aerial vehicles, the velocity of the drone is relatively low, making pulse-Doppler radar ineffective. Since their altitude is also low, it is difficult to detect them from the clutter received from the environment around the drone.

4 Micro-Doppler

Whilst the overall velocity of the drone is relatively low, the velocity of the propeller blades is high. The blade rotations result in small Doppler shifts at recurring intervals, which results in sharp spikes when plotted against time, and can be easily detected by radar [3] when using a Continuous Wave.

This technique also enables small drones to be distinguished from birds and other small objects in the skies. This reduces the complexity of having to track more objects than is necessary, and would help to reduce false alarms which would be very beneficial for installations at airports or other no fly zones.

To effectively detect these micro-Doppler's, high frequencies are required. This not only increases power requirements, but will also reduce the range at which drones can be successfully detected.

5 Doppler Signal-to-Clutter Ratio Detector

Unlike traditional signal-to-noise ratio detectors, which struggle to detect small drones, deploying the Doppler signal-to-clutter ratio detector greatly decreases missed targets and false positives [4].

Signal-to-noise ratio detectors can lower the noise threshold in order attempt to detect drones, but this increases missed targets and false positives considerably.

However, since the natural environment has a low Doppler shift, the threshold can be much lower. This, when combined with micro-Doppler can effectively identify small drone targets.

Existing radar technology can also continue to be used. Only the algorithms would need to be adapted to detect drones, making upgrades to existing installations cheap.

6 Passive Radar

Passive radar is the use of radar equipment to listen to signals emitted by other devices nearby. Passive radar can triangulate the location of not only the drone, but the drone flyer by using the control and video signals sent between the drone and the controller [5].

Changes by the FAA in the United States of America have introduced a new technology called Remote ID [6]. This requires all drones to broadcast information about their flight to comply with local regulations. These transmissions provide unique identifiers for each drone, making it simple to both detect and track.

This is beneficial when finding threats, but also means that the location of law abiding flyers are also identified. This could lead to the harassment of such people by members of the community that are unhappy with this technologies use.

7 Application Impact

A large number of radars that would be needed to effectively detect and track a drone through a urban area. Resulting from this would be a large increase in congestion on the frequencies used, a large addition to the areas electrical usage, and lots of visual clutter on the sides of buildings. There has already been a large amount of push-back concerning the erection of 5G masts in populated areas [7] [8] [9] and this would likely continue with the addition of this technology.

8 Conclusion

Developing effective tracking and detection methods for drones is critical for keeping the public, governments, and militaries safe. Combinations of the techniques discussed in this report would provide the best coverage, whilst reducing false-positives.

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