

Design and Analysis of Electromagnetic Systems

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Design and Analysis of Electromagnetic Systems

Electromagnetic Radiation

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Section 1:

Waveguide and Dipole Antenna Design

Abstract

The transmission of electromagnetic (EM) waves from one point to another can be achieved through a number of methods. For high frequency applications

EM waveguides are typically employed for the efficient and low loss transmission of these EM waves. The rectangular hollow tube waveguide is a common choice for EM waveguides. In the hollow cavity of these waveguides a filling material can be inserted to change the characteristic of the waveguide. In this report the design of such a waveguide has been conducted with rectangular cross-section dimensions of 230mm by 3.5mm. To compare the effects of different fill materials the waveguide's cavity was filled with a vacuum and Teflon and through simulation the characteristic results were analysed.

Secondary to this, another key EM device are antennas - used to generate EM waves. Many types of antenna designs and geometries exist, but a widely used design is the dipole antenna. To explore the operation of a dipole antenna and its theory, one has been designed to operate at a frequency of 1.30GHz. This design has been simulated and characteristic results analysed.

1.1 Introduction

Electromagnetic (EM) waves are essential for applications like radio broadcasting, wireless communications, and radar. Generating EM waves rely on antennas, which, when excited by alternating current, produce oscillating electric and magnetic field that propagate as EM waves. Their transmission requires specialised structured for efficient point-to-point transfer. This report explores the design and practical use of a dipole antenna and a rectangular waveguide.

1.1.1 Rectangular Waveguides

Waveguides are structures designed to transmit waves between two points with minimal power loss. For EM waves, waveguides come in various geometries and configurations, including parallel plate, circular, and rectangular designs. They are primarily used in high-power, microwave-frequency applications due to their wavelength-dependent size and efficient transmission with minimal losses [1]. One of the most commonly used types is the rectangular waveguide; *Figure 1* illustrates the geometry of a waveguide.

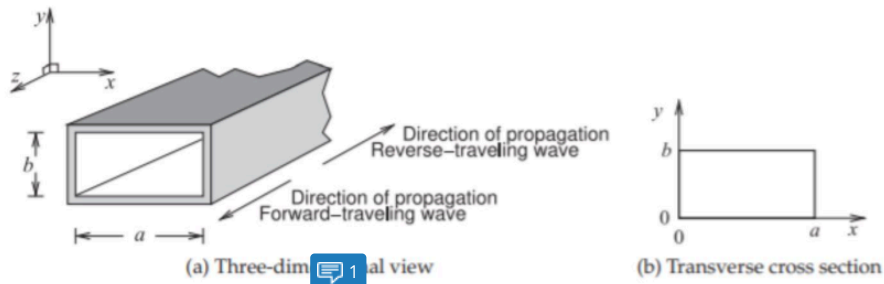


Figure 1. Boundary construction of a rectangular waveguide. Left is a 3-dimensional construction the rectangular waveguide. Right shows the waveguide cross-section. [2]

Transmitting EM waves through a rectangular waveguide, the conductive structure bounds the propagating wave. For the waveguide structure in FIGURE, these conditions require the tangential components of the electric field (E-field) and the normal components of the magnetic field (H-field) to be zero at the boundaries where $x=0,a$ and $y=0,b$. As demonstrated in [3, pp. 110-120], these conditions allow waves to propagate in different modes: transverse electric (TE), where the electric field is entirely perpendicular to the direction of propagation, and transverse magnetic (TM), where the magnetic field is purely perpendicular to the propagation direction. Another mode, transverse electromagnetic (TEM), can exist but requires the waveguide to have more than one conducting element.

For TE mode, the field components within a rectangular waveguide are determined as follows:

$$E_x = \frac{j\omega\mu n\pi}{k_c^2 b} A \cos \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-\gamma z} \quad (1)$$

$$E_y = \frac{-j\omega\mu m\pi}{k_c^2 a} A \sin \frac{m\pi x}{a} \cos \frac{n\pi y}{b} e^{-\gamma z} \quad (2)$$

$$E_z = 0 \quad (3)$$

$$H_x = \frac{\gamma m\pi}{k_c^2 a} A \sin \frac{m\pi x}{a} \cos \frac{n\pi y}{b} e^{-\gamma z} \quad (4)$$

$$H_y = \frac{\gamma n\pi}{k_c^2 b} A \cos \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-\gamma z} \quad (5)$$

$$H_z = A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} e^{-\gamma z} \quad (6)$$

And for TM mode:

$$E_x = \frac{-\gamma m\pi}{k_c^2 a} A \cos \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-\gamma z} \quad (7)$$

$$E_y = \frac{-\gamma n\pi}{k_c^2 b} A \sin \frac{m\pi x}{a} \cos \frac{n\pi y}{b} e^{-\gamma z} \quad (8)$$

$$E_z = A \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-\gamma z} \quad (9)$$

$$H_x = \frac{j\omega\epsilon n\pi}{k_c^2 b} A \sin \frac{m\pi x}{a} \cos \frac{n\pi y}{b} e^{-\gamma z} \quad (10)$$

$$H_y = \frac{-j\omega\epsilon m\pi}{k_c^2 a} A \cos \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-\gamma z} \quad (11)$$

$$H_z = 0 \quad (12)$$

Where a and b are the width and height of the waveguide cross-section respectively, m and n are the mode numbers' indices corresponding to the number of half-wavelengths that fit into the dimensions a and b respectively, ω is the angular frequency, μ is the permeability and ϵ the permittivity of the medium filling the waveguide, A is an arbitrary amplitude constant, k_c the cut-off wavenumber and γ is the propagation constant.

The propagation of both TE and TM modes depends on the propagation constant $\gamma = \alpha + j\beta$, particularly its phase constant components β , where:

$$\beta = \sqrt{k^2 - k_c^2} \quad (13)$$

For a wave to propagate, β must be real-valued, meaning the wavenumber and corresponding frequency must exceed the cut-off values determined by k_c , given by:

$$k_c = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (14)$$

$$f_c = \frac{k_c}{2\pi\sqrt{\epsilon\mu}} = \frac{1}{2\pi\sqrt{\epsilon\mu}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (15)$$

These equations show that a rectangular waveguide functions as a high-pass filter, preventing wave propagation below the cut-off frequency. The cut-off frequency is dependent on the waveguide's cross-sectional geometry and propagation mode indices. Additionally, since TM_{10} or TM_{01} modes cannot exist, the TE_{10} mode is dominant when $a > b$.

1.1.2 Half-Wave Dipole Antennas

A simple and widely used antenna is the dipole, which is employed in many applications. Dipoles are typically made of two equal-length conductive elements, excited across a gap between them, as shown in *Figure 2*. While dipole lengths vary, the most common design is the half-wavelength dipole, where the total antenna length equals half the operating wavelength. This design is preferred due to its efficiency, as it has a resonant input impedance of 73Ω , closely matching common system impedances [1].

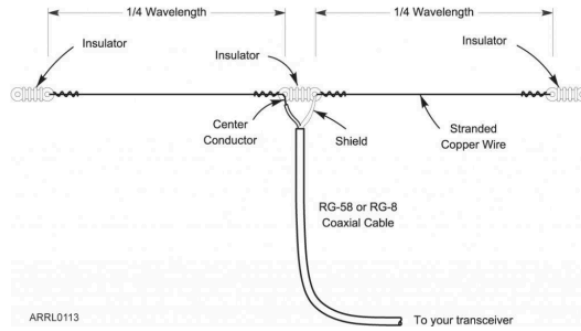


Figure 2. Construction of a dipole antenna with the typical element lengths for a half-wavelength dipole antenna [4].

In practical dipole designs, the abrupt truncation of the current path at the element ends creates fringing fields, effectively increasing the antenna's electrical length beyond its physical length. This results in added inductance and a longer resonant wavelength [5]. To achieve resonance at a desired wavelength, the antenna can either be impedance-matched to cancel out the reactive component or have its element length reduced so that the effective length equals half a wavelength. For a thin dipole (where $d \ll \lambda$), a reduction to 0.48λ is typically sufficient, but thicker dipoles may require further length reduction [6, pp. 182-184].

Dipole thickness is a key factor influencing the bandwidth, determined by the length-to-thickness ratio. Another critical dimension is the feed gap size, which should be minimised for optimal performance [7] and is often calculated as $g = \frac{l}{200}$ [8].

1.2 Methodology

Designing both the waveguide and antenna was achieved using the High Frequency Structure Simulator in the Ansys Electronics Desktop software.

1.2.1 Waveguide Design and Simulation

Creating the rectangular waveguide in Ansys requires only defining its internal structure, as the software assumes the external faces as the waveguide boundaries. Figure 3 shows the constructed waveguide cavity with its corresponding dimensions. Initially, the cavity was modelled as a vacuum and then Teflon, whose key properties are listed in Table 1. The boundary faces of the waveguide were defined as being perfect electric conductor (PEC).

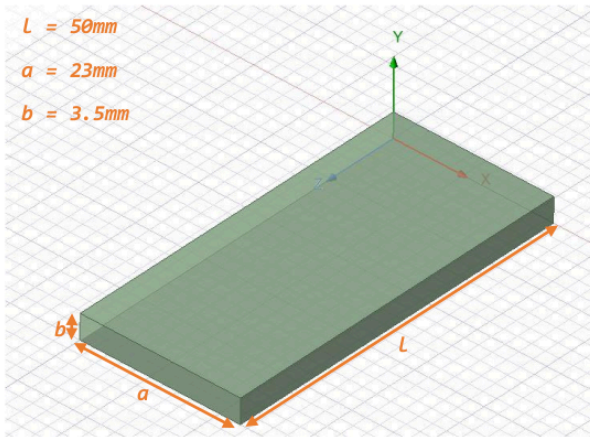


Figure 3. Rectangular waveguide cavity of the waveguide being designed and simulated. Labelled are the dimensions of the waveguide with L being the length, a being the cross-section width and b the cross-section height.

Material	Relative Permittivity, ϵ_r	Relative Permeability, μ_r	Loss Tangent, $\tan \delta$
Vacuum	1	1	0
Teflon	2.1	1	0.001

Table 1. Key material properties of the different waveguide fills simulated



For the simulation setup, both ends of the waveguide were assigned as wave port to simulate 3 modes, as shown in FIGURE. The waveguide response across these modes was analysed over a frequency range of 2GHz to 30GHz using an interpolating sweep with 401 defined points. Figure 5 detail the applied analysis settings.

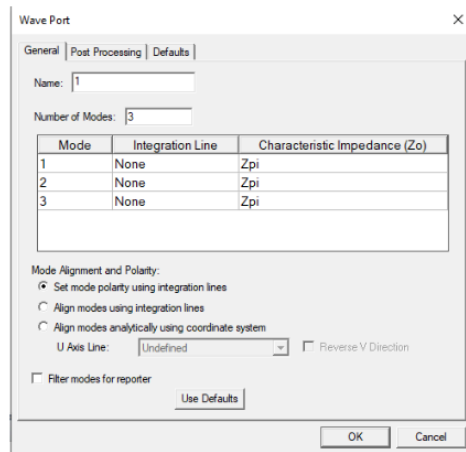


Figure 4. Wave port setup applied to both ends of the waveguide.

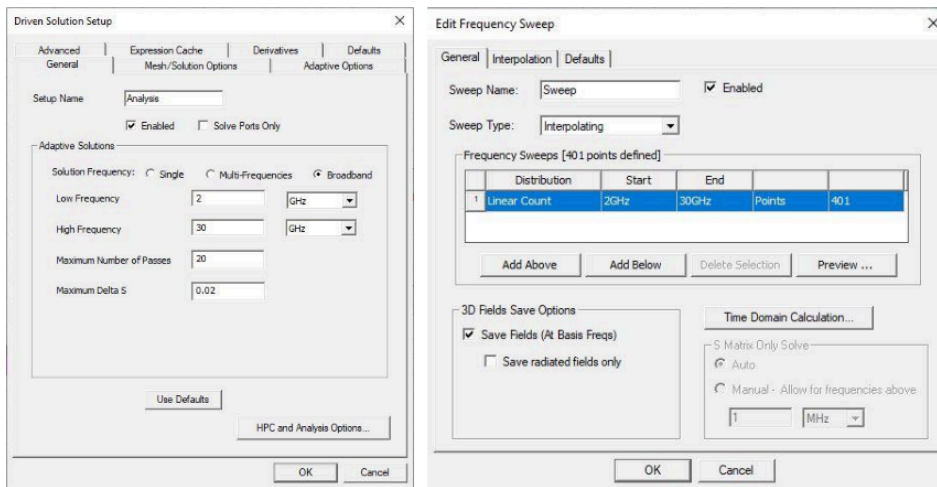


Figure 5. Analysis setup settings applied for simulating the waveguide across a 2GHz to 30GHz frequency sweep.

1.2.2 Antenna Design and Simulation

Designing a half-wavelength dipole to resonate at a wavelength of 230mm, using the element material of PEC the geometric parameters of the antenna were determined from the theory discussed in section 1.1.2 **Half-Wave Dipole Antennas.**

With $\lambda = 230\text{mm}$ the total element is calculated with:

$$\text{Total element length, } L = 0.48\lambda$$

$$= 0.48 \times 230 = 110.4 \text{ mm}$$

Calculating the feed gap size:

$$\text{Feed Gap, } G = \frac{L}{200}$$

$$G = \frac{110.4}{200} = 0.552 \text{ mm}$$

Through design constraints, the element diameter is limited to 1mm.

From these calculated dimensions the antenna in *Figure 6* was create with all of its dimensions outlined int *Table 2*.

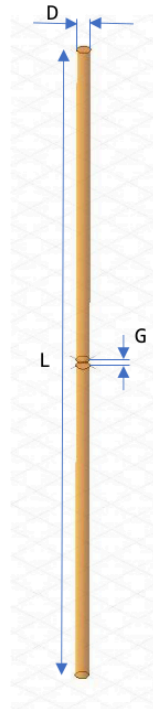


Figure 6. Designed dipole antenna.

Parameter	Value
Wavelength, λ	230 mm
Operating Frequency, f	1.303 GHz
Total Element Length, L	110.4 mm
Element Diameter, D	1 mm
Feed Gap Size, G	0.552 mm
Element Material	PEC

Table 2. Dimensions and parameters values used for the design and simulation of the dipole antenna.

Simulating the antenna in Ansys, first required defining a lumped port across the feed gap, set to operate at 1 mode with a 50Ω port impedance, as shown in *Figure 7*. For far-field simulations, a perfectly matched layer (PML) boundary was applied around the antenna. The simulation was run from 500MHz to 2.5GHz to capture the full frequency response beyond the desired operating frequency of 1.303GHz. *Figure 8* illustrates the applied analysis setup.

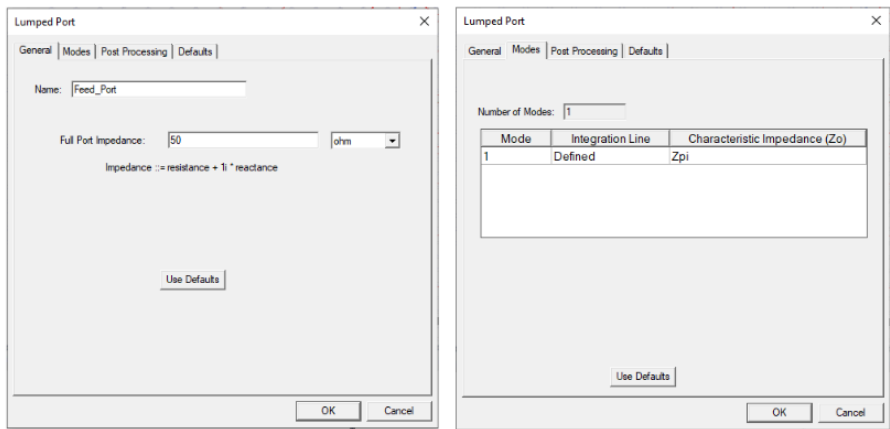


Figure 7. Feed port setup applied across the feed gap of the antenna.

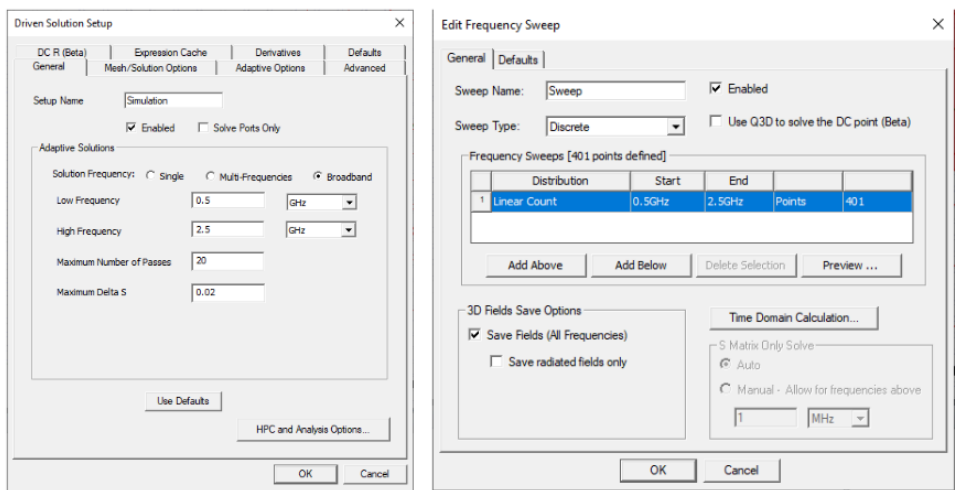


Figure 8. Analysis setup applied for simulating the antenna from 500MHz to 2.5GHz.

1.3 Results

1.3.1 Waveguide

The simulations of the rectangular waveguides for the 3 modes, showed the vacuum and Teflon fills produced different responses from the waveguide. Figure 9 shows the phase constant of each mode in the vacuum and Teflon filled waveguides and from this the cut-off frequencies of each mode has been determined by taking frequency at which the phase constant becomes sufficiently close to zero. Table 3 outline these cut-off frequencies. The port fields for the excitation ports of the waveguide are shown in Figure 10 for the different modes and within the figure the corresponding mode

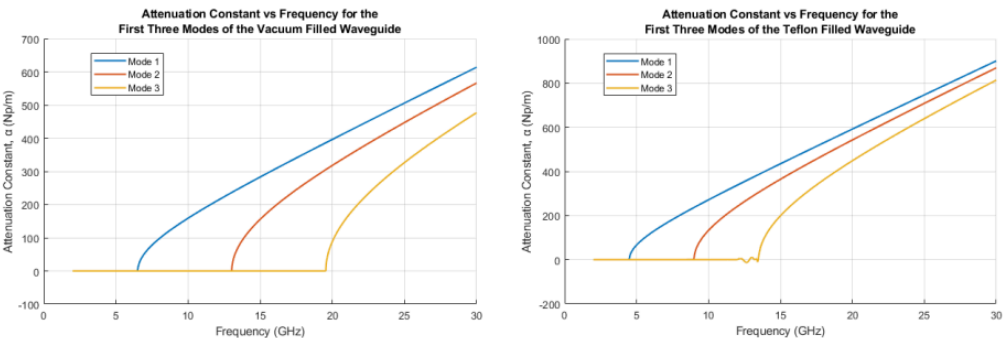


Figure 9. Graphs showing the phase constant vs frequency for the first 3 modes of the rectangular waveguide. Left is the graph for the vacuum filled waveguide and right is the graph for the Teflon filled waveguide.

Mode	Cut-off Frequency (GHz)			
	Theory		Simulation	
	Vacuum Filled	Teflon Filled	Vacuum Filled	Teflon Filled
1	6.52	4.45	6.5	4.45
2	13.03	8.99	13.03	8.95
3	19.55	13.49	19.55	13.45

Table 3. Cut-off frequency of the waveguides filled with a vacuum and Teflon. These results contain the cut-off frequencies calculated from the theory and those determined by the simulations.

4

propagation type is also indicated. Magnitude and vector plots of the E and H fields propagation throughout the waveguide at each mode can be found in APPENDIX.

1.3.2 Antenna

From the simulation result of the dipole antenna, the operating frequency was determined to be at 1.23GHz. This was measured from the minimum values of the S_{11} characteristics of the antenna, shown in *Figure 11*. Also, from *Figure 11* the antennas bandwidth was calculated using the -10dB points, which was determined to be 125MHz. The radiation pattern of the antenna, at the desired operating frequency of 1.3GHz, is displayed in the *Figure 12* and is seen to have a peak gain of 2.28dBi.

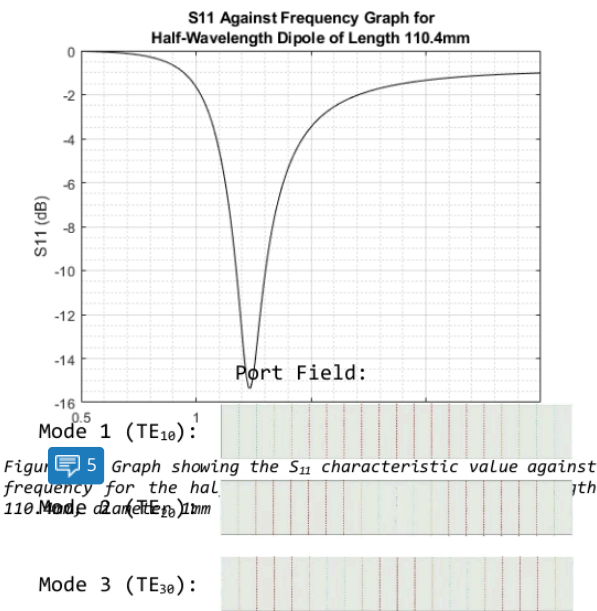


Figure 10. Port field pattern for each mode excited in the waveguide, with the corresponding determined mode type.

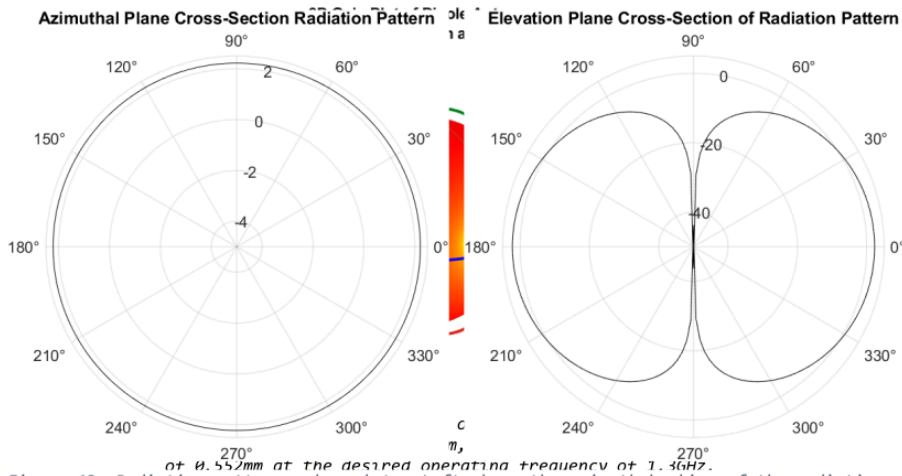


Figure 13. Radiation pattern polar plots. Left shows the azimuthal slice of the radiation pattern at an elevation of 0° . Right shows the elevation slice of the radiation pattern when the azimuth angle is 0° .

1.4 Discussion

1.4.1 Waveguide

The waveguide simulations showed that the Teflon-filled waveguide had lower cut-off frequencies for the first three modes compared to the vacuum-filled waveguide. This aligns with the theoretical cut-off frequency equation (...), where the relative permittivity and permeability of the fill material influence the cut-off frequency of each mode. With Teflon's higher permittivity ($\epsilon_r = 2.1$) than a vacuum ($\epsilon_r = 1$), the decrease in cut-off frequency observed was expected. This suggests that smaller waveguides can support lower operating frequencies when the cavity is filled with a dielectric like Teflon. However, it was also seen Teflon increased the attenuation of the transmitted wave, due to its dielectric loss. It should be noted this was minimal, but it still introduces noise to the propagating wave (determined as a function of the dielectric's loss tangent [9]) which may be problematic in low noise applications [10]. Additionally, the Teflon fill raises the reflection coefficient, requiring aperture matching to maximise feeding efficiency [11], as seen in the TE_{10} mode S_{11} characteristics in Figure 14.

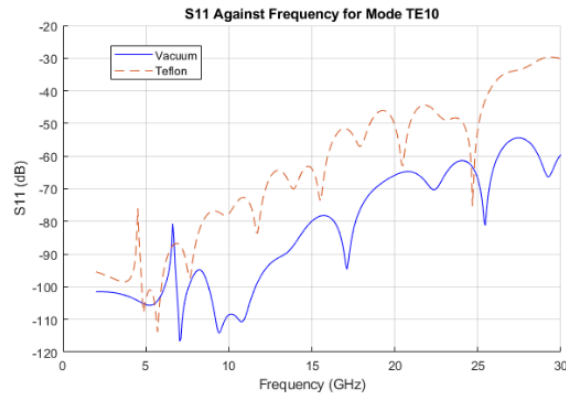


Figure 14. S_{11} characteristic of the rectangular waveguide for the vacuum fill and Teflon fill against frequency for mode TE_{10} .

1.4.2 Antenna

From the simulation of the half-wave dipole, the operating frequency was observed to be less than the expected 1.303GHz. This suggests the impedance characteristics of the designed antenna is not as expected by the theory. The cause of this is likely the antenna's thickness, invalidating the assumptions made for the simple length reduction to 0.48λ to have 0 reactance at the desired wavelength [6]. Additional adjustments were made to the antennas length, and it was found an element length of 0.45λ ($l = 104.1\text{mm}$) resulted in a resonant frequency closer to the desired 1.303GHz. Figure 15 shows the S_{11} characteristics of the adjusted antenna. From this there is also seen to be a change in the antenna's bandwidth to 137MHz (a percentage bandwidth increase from 10.16% to 10.54%), which would originate from the length-to-diameter ratio increasing and the relationship between dipole bandwidth by having the diameter remain at 1mm. Slight changes to the radiation pattern were also seen with a new peak gain of 2.16dBi, seen in Figure 16. This would be linked to the relationship between directivity,

element length, and operating wavelength [12]. With the directivity of the adjusted antenna being reduced at the operating frequency.

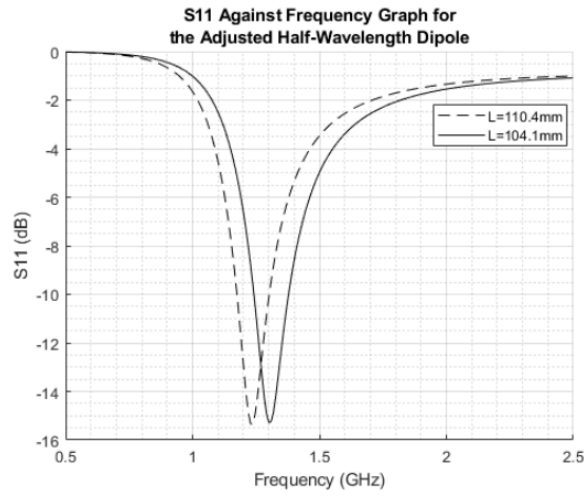


Figure 15. *S11 against frequency showing the changing in results for the further adjusted antenna.*

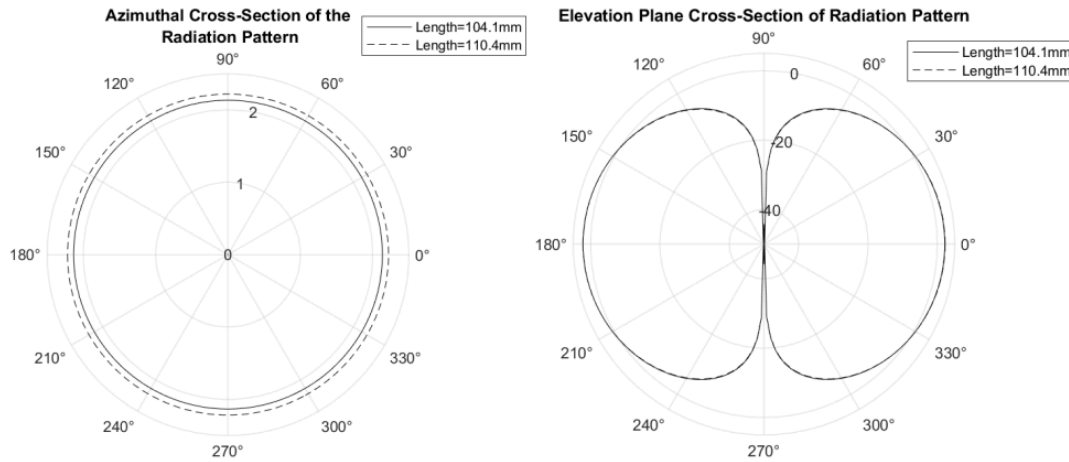


Figure 16. *Radiation pattern polar plots of adjust Length antenna and original Length antenna. Left shows the azimuthal slice at an elevation of 0° . Right shows the elevation slice at an azimuth of 0° .*

1.4.3 Simulation Limitations

The simulations are limited by the use of PEC materials, which present them as being lossless and having infinite conductivity. In the waveguide simulation, the PEC walls ignore conductor losses which are important to understand as this can disturb the propagating fields [13]. Similarly, for the antenna, element conductivity is seen to impact key characteristics [14], but using PEC prevent these effects from appearing in the results.

Another limitation is the exclusion of external interactions. As noted in [14], real-world factors like feed port structures can significantly affect antenna performance. Including these components in simulations may be necessary for a more accurate representation.

1.5 Conclusion

A rectangular waveguide was designed and simulated using both vacuum and Teflon as fill materials to assess their impact on waveguide performance. The results confirmed theoretical cut-off frequencies for different modes and demonstrated that dielectric filling enables smaller waveguides for lower operating frequencies. However, it also introduced additional noise and the requirement for matching.

Following this, a half-wavelength dipole was designed to operate for a 230mm wavelength and simulated. The results revealed limitations in simplified theory, particularly when the element length-to-diameter ratio is low. To achieve the target wavelength, the element length had to be reduced to 0.45λ .

Simulation limitations were also examined, including the effects of using PEC as a material and the accuracy of results for real-world applications.

Section 2:

A Review of Radar technology and its Applications for the Detection of Small Drones

Abstract

Drones have rapidly increased in popularity and with their vast range of capabilities make them suitable for many applications. However, drones are beginning to be used for illegal and illicit activities and pose a very real threat to the safety and security of the UK. A key part of handling the threat of drones is in the ability to detect them. Thus, this section reviews current radar technology and future research taking place, identifies challenges faced detecting drones, particularly small systems, and explores applications of the radar technology to the problem.

2.1 Introduction

Drones are an escalating security threat, with rising incidents involving their use for illegal or malicious activities. The 2018 Gatwick airport incident [15], where a drone grounded aircraft for 36 hours, highlighted the threat they pose, and challenges faced detecting and countering them. Following this, incidents have only increased with over 6000 incidents being reported in 2023, including unauthorised flying near airports and sensitive sites, and facilitating illicit deliveries to prisons. Additionally, the ease of weaponizing commercially-off-the-shelf (COTS) drones, as seen in the Ukraine war, raises concerns about inspiring new attack methodology for terrorists and other hostile actors [16] [17]. Mitigating these threats requires advanced countermeasures, with radar technology emerging as a critical defence tool.

Radar has long been essential for identifying, tracking and targeting distant objects, with applications in both military and civilian sectors, including air defence systems, air traffic control, weather monitoring and navigation. Traditionally designed for detecting large airborne targets, radar systems must now be adapted to detect and track smaller drone systems to provide a key tool in countering their rising threat. This report analyses current radar technological capabilities and its application to detecting small drone systems.

2.2 Literature Review

Radar operates by transmitting electromagnetic waves, typically at frequencies between 5MHz and 300GHz [18, p. 2], and detecting the reflections off objects. By comparing the transmitted and received signals and using the delay and property changes, the distance, direction and speed of an object can be measured. Various techniques-each with specific benefits and drawbacks-can be implemented to optimise radar for different applications, with key types being the two main transmission types: continuous wave (CW) and pulsed.

2.2.1 Continuous Wave Radar

CW radar uses separate transmit and receive antenna, with the transmitter constantly sending signals and the receiver detecting reflections. *Figure*

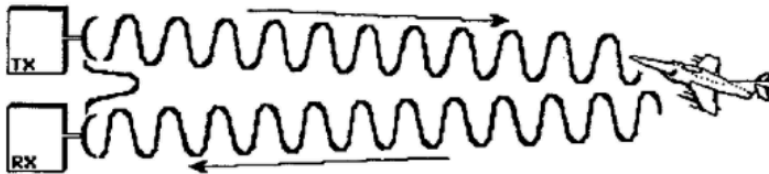


Figure 17. Illustration of the operation of continuous wave radar. The transmitter continually transmits a signal at the same time the receiver listens for reflection from targets. [19]

17 illustrates this operation. With a simple unmodulated signal, the Doppler effect can be utilised to enable measurement of object velocities based on frequency changes of the received signal. However, not modulating the signal limits range measurement and static object detection due to the lack of a

time reference. This can be overcome by modulating the signal's phase or frequency, enabling time delay measurements [20]. Frequency-modulated CW (FMCW) radar is the most common variant, offering high accuracy, reliability, and low hardware requirements. Research into Phase-modulated CW (PMCW) radar, however, shows advantages with resilience to interference, no Doppler-coupling and ability to discriminate weak radar cross-section (RCS) targets near stronger targets, though more complex hardware is required. [21]

CW radar systems have benefits and limitations that suit specific applications. One limitation is transmitted power, to prevent leakage into the receiver, which restricts CW radar to short-range sensing. Despite this, the continuous transmission removes a minimum detection range. In addition, FMCW's success, depends on optimising its modulation bandwidth, period and beat frequency. Figure 18 shows impacts of these parameters. These factors make CW radar ideal for missile seekers, police radar guns, and automotive ADAS applications. [22]

Waveform Parameter	Reasons to Decrease	Reasons to Increase
Modulation bandwidth	• Narrower bandwidth RF components • Higher power sources available • Lower amplitude and phase noise	• Finer ideal range resolution • Lower radiated power spectral density • Increased slope • Increased beat frequency
Modulation period	• Increased slope • Increased beat frequency • Avoids interference with conical scan and other modulations • Reduced beat frequency chirp or smear due to target motion • Increased unambiguous velocity	• Increased transmit and receive overlap • Increased coherent processing interval • Increased effective processed transmit bandwidth and power • Better range and Doppler resolution • Narrower bandwidth linearizer
Beat frequency	• Lowered ADC sample frequency • Narrower bandwidth range bin filters • Less beat frequency bandwidth required to cover given range swath • Greater source phase noise correlation	• Lower amplitude and phase noise at greater separation from carrier

Figure 18. Trade-offs of changing the parameters of a FMCW waveform with practical impacts of making the changes as outlined in [22].

2.2.2 Pulse Radar

Unlike CW radar, pulsed radar alternated between transmitting EM pulses and listening for reflection, as shown *Figure 19*. During transmission, the

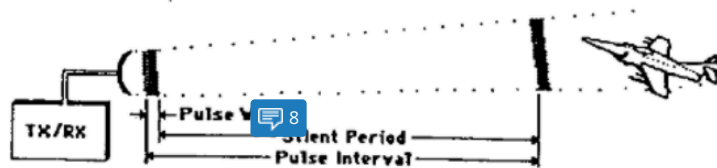


Figure 19. Depiction of the operation of pulsed RADAR. Pulses are transmitted with silent periods in between where reflected waves can be received [19].

receiver is isolated from the antenna, and vice versa, preventing simultaneous operation. Key parameters defining its operation are pulse repetition frequency, pulse width, and peak power. The pulse width affects the detection range and resolution: wider pulses increase the detection range by increasing average transmitted power, but reduces range resolution and increases minimum detection range, while narrower pulses improve resolution but decreases range. Pulse repetition frequency controls the maximum ambiguous range by governing the receiver's listening time, affecting the distance at which a target can be detected within the same pulse period. Peak transmit power determines the maximum radar range, though it may be constrained by the other parameters, so the power should be selected to balance effectiveness and efficiency. 9

Overcoming some of the limitations of pulsed radar, techniques like linear frequency modulation of the pulses are used. This modulation helps better distinguish reflections from closely spaced targets and enhances the signal-to-noise ratio after processing with a matched filter. [24]

2.3 Discussion 10

Modern radar systems should be capable for detecting smaller targets, but drone detection presents unique challenges. Unlike conventional radar applications, which focus on high-altitude targets, drone detection requires operation closer to the ground, introducing a more complex environment [25]. Challenges identified in [25] and [26] include the small size and material composition for drones, their similarity to other objects, low operating altitude, short detection ranges, diverse flight patterns and terrain masking.

The small size and low-reflectivity material typical of drones (e.g., plastics, as seen in the DJI Phantom 2 Vision [27]) result in low RCS, making them difficult to detect. Additionally, their RCS can resemble other objects within the low altitude environment such as birds, complicating classification. Techniques exploiting changes in the reflected wave properties such as RCS modulation, micro-Doppler analysis, and polarisation data have been explored to distinguish drones from birds. Using polarimetric data is a newer concept but shows promise for classification even when micro-Doppler and RCS modulation effects are minimal [28].

Low-altitude radar operation also introduces significant ground clutter, further impairing detection ability. Moving Target Indication (MTI) can help by exploiting the higher Doppler frequencies caused by moving targets compared to little or no Doppler frequencies seen by clutter [29]. However, unconventional drone flight patterns and varying speeds can limit MTI due to blind speeds where targets become undetectable to the radar. An alternate technology which could be used is PMCW, with it offering high contrast resolution [30], potentially improving discrimination between targets and clutter.

2.4 Conclusion

Modern radar technology has been shown to have the necessary capability to be adapted from the detection of large aircraft to small drones. Harnessing this technology to mitigate the challenges discussed it has been identified an ideal radar system should consist of the capabilities outlined in *Table 4*. Determined ideal capabilities of a radar system for the detection of

Capability	Implementation
Short detection range	CW radar is preferred due to the blind spots and ambiguities of using pulsed waveforms.
High resolution	Millimetre-wave frequencies and high signal bandwidth improves a radars sensitivity to small structures, enhancing measurement and classification of targets [31] and also enabling narrow detection beam width, resulting in greater target location accuracy.
Clutter mitigation	MTI should be used to distinguish targets from clutter and with further research into PMCW this may become suitable to provide high contrast resolution capability for a radar system.
Effective target classification	Micro-Doppler should be used to aid in separating drones from similar RCS objects and as suggested in [28] further research into analysing polarimetric data shows promising results in improving target classification.

Table 4. Determined ideal capabilities of a radar system for the detection of small drones and suggested technological implementations to achieve this.

small drones and suggested technological implementations to achieve this..

This is supported by an existing drone detection radar system by Fraunhofer [32], implementing a FMCW waveform at 94GHz, with a 1GHz bandwidth which achieve a range resolution of 15cm. This has been shown to successfully detect drones of RCS above 0.01m^2 at ranges between 50-150m, with potential for significant range extension by increasing transmit power.

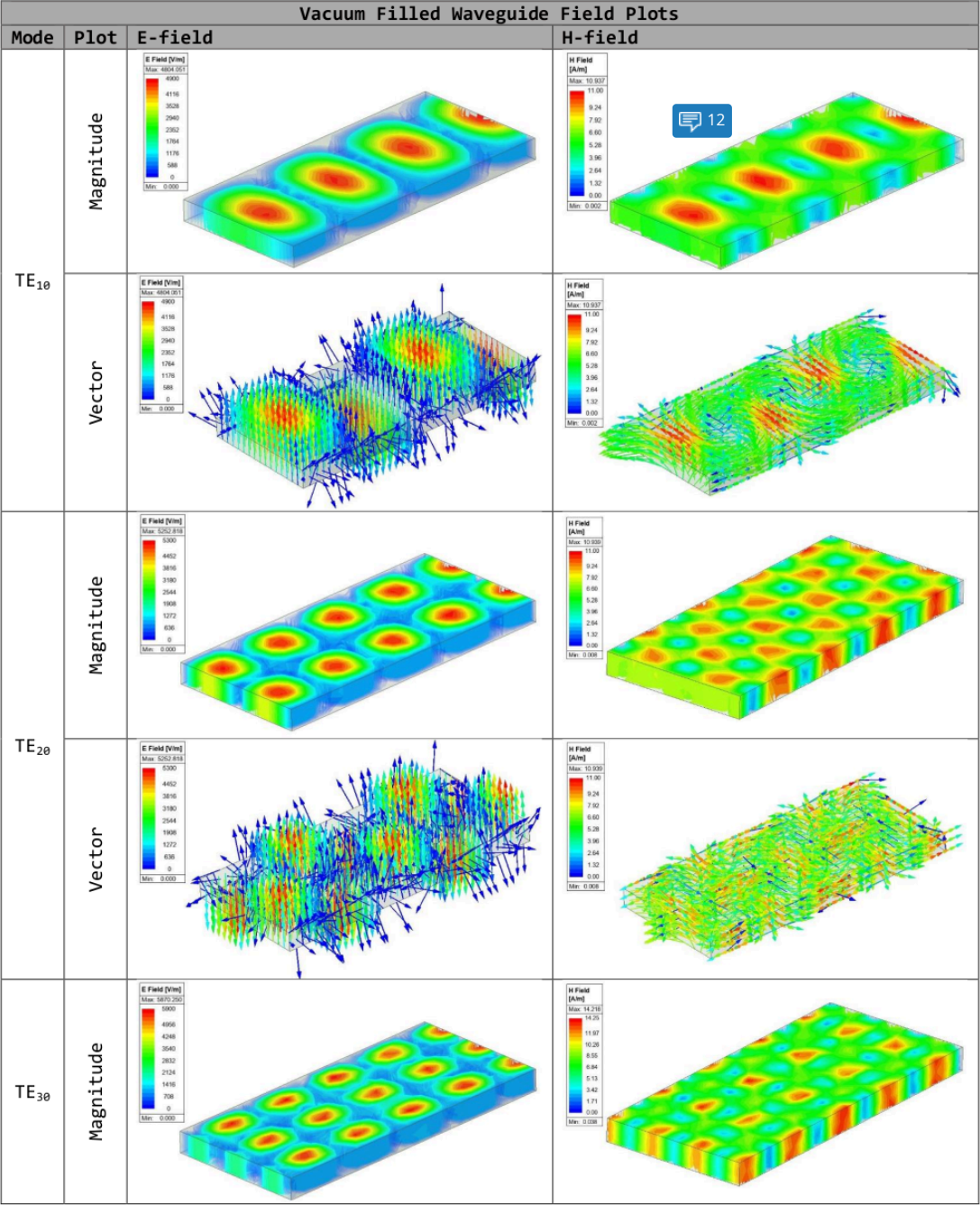
References

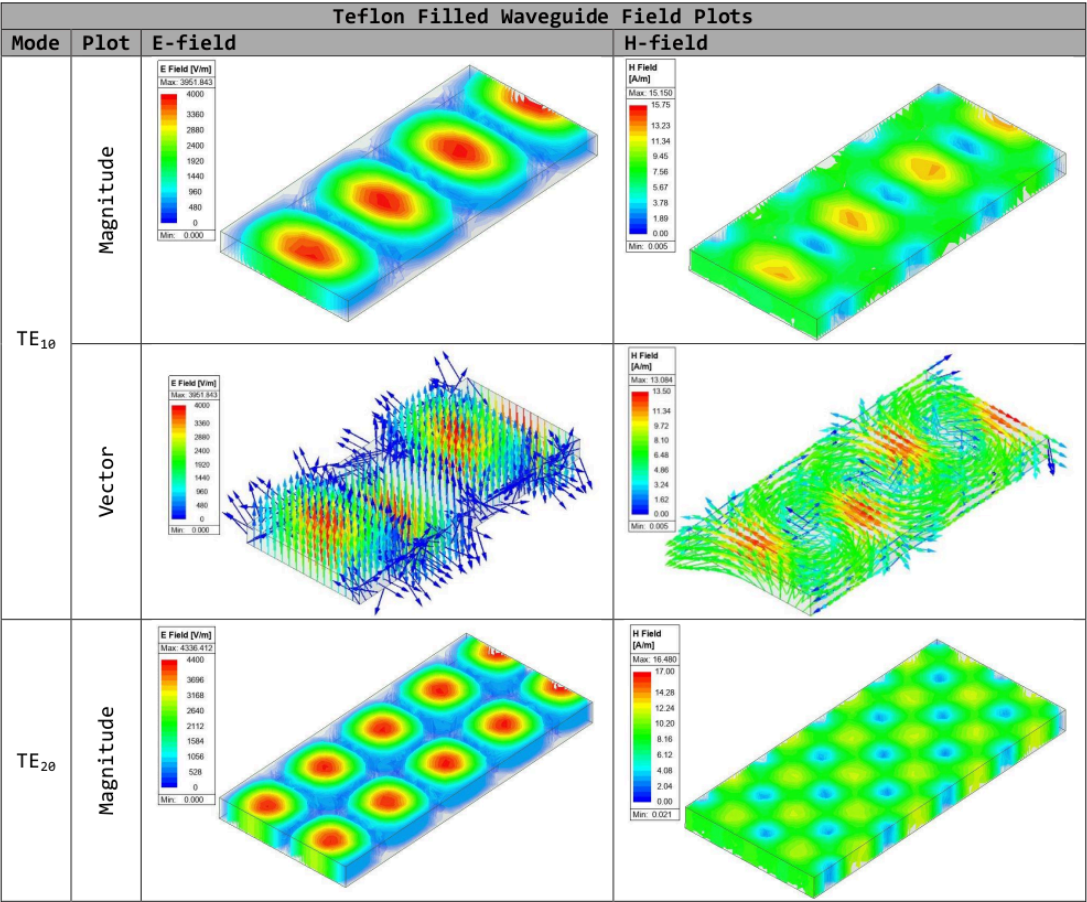
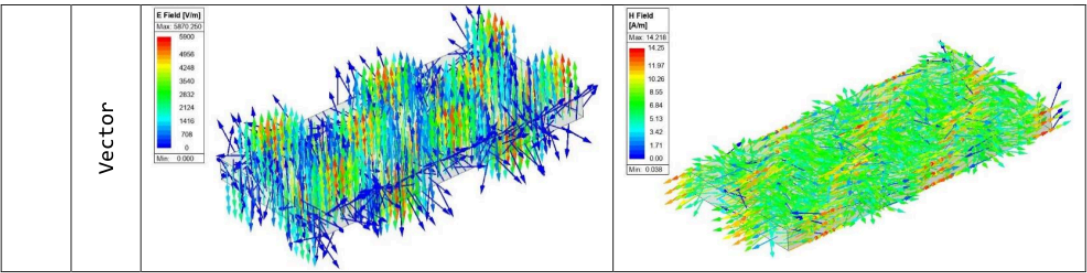
- [1] Y. Huang and K. Boyle, *Antennas: From Theory to Practice*, Chichester, UK: John Wiley & Sons Ltd, 2008.
- [2] M. Steer, "Rectangular Waveguide," LibreTexts Engineering, [Online]. Available: [https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_\(Steer\)/06%3A_Waveguides/6.04%3A_Rectangular_Waveguide#:~:text=A%20rectangular%20waveguide%20is%20shown,using%20coaxial%20lines%20for](https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Microwave_and_RF_Design_II_-_Transmission_Lines_(Steer)/06%3A_Waveguides/6.04%3A_Rectangular_Waveguide#:~:text=A%20rectangular%20waveguide%20is%20shown,using%20coaxial%20lines%20for). [Accessed 29 March 2025].
- [3] D. M. Pozar, "Transmission Lines and Waveguides," in *Microwave Engineering*, 4th ed., John Wiley & Sons. Inc., 2012, pp. 95-164.
- [4] ARRL, "Single band Dipoles," [Online]. Available: <http://www.arrl.org/single-band-dipoles>. [Accessed 29 March 2025].
- [5] K. L. Smith, "The Half-Wave Dipole: Design," 2020. [Online]. Available: <https://innovationspace.ansys.com/courses/wp-content/uploads/sites/5/2022/07/TheHalfWaveDipole-Design.pdf>. [Accessed 24 March 2025].
- [6] C. A. Balanis, *Antenna Theory: Analysis and Design* 3rd Ed., Hoboken, New jersey: John Wiley & Sons Inc., 2005.
- [7] F. T. Celik, S. Joof and K. Karacuha, "A Filtering Dipole Antenna Design with Bandwidth Enhancemnet for 5G," in *2023 17th European Conference on Antennas and Propagation (EuCAP)*, Florence, Italy, 2023, pp. 1-5.
- [8] M. Tareq, D. A. Alam, M. Islam and R. Ahmed, "Simple Half-Wave Dipole Antenna Analysis for Wireless Applicatoin by CST Microwave Studio," *International Journal of Computer Applications*, vol. 94, no. 7, pp. 21-23, 2014.
- [9] S. Kelz, M. Grozing and M. Berroth, "Experimental Investigation of Dielectric Loss Induced Noise in Charge Detection Systems for Cosmic Dust," in *International Conference on SMACD and 16th Conference on PRIME*, Online, 2021, pp. 1-4.
- [10] M. N. Kehn, P.-S. Kildal and S. P. Skobelev, "Minitaurized Dielectric-Loaded Rectangular Waveguides for use in Multi-Frequency Arrays," *IEEE Antennas and Propagation Society Symposium*, vol. 1, pp. 803-806, 2004.

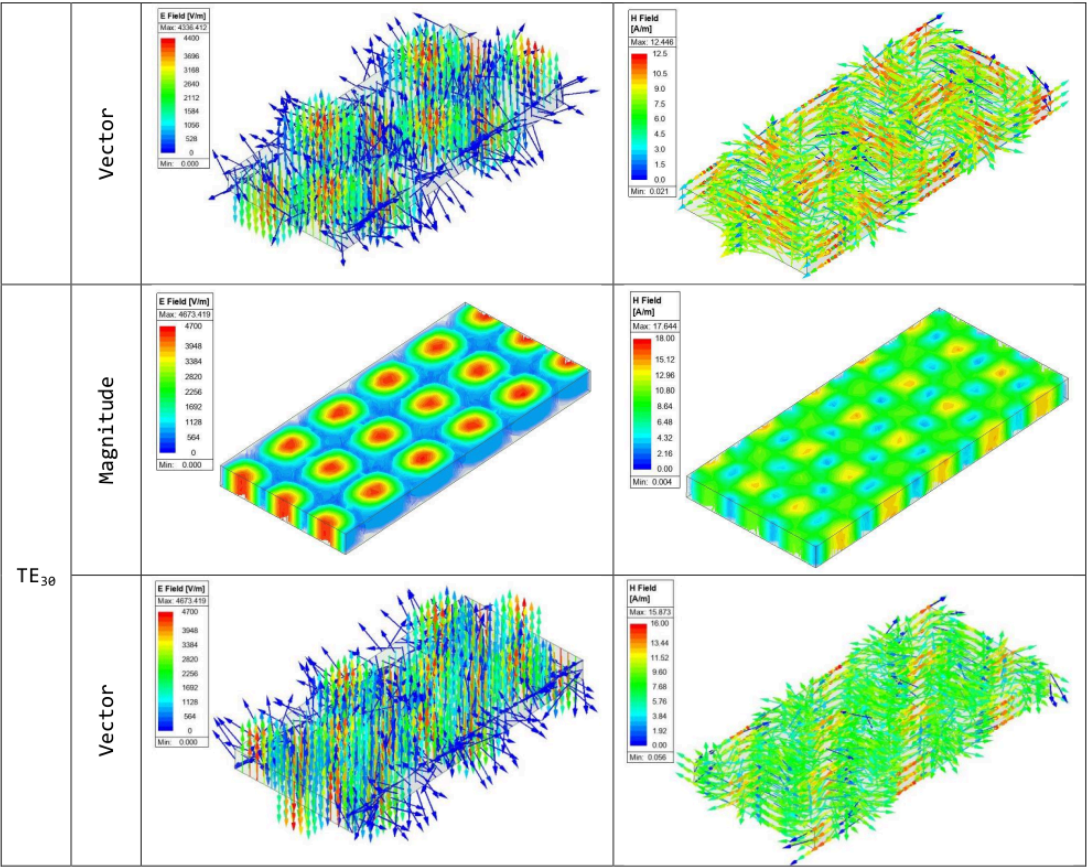
- [11] S. Xu, J. Heo, B.-K. Ahn, C.-S. Lee and B.-C. Ahn, "Simulation-Based Approach to the Matchin of a Dielectric-Filled Circular Waveguide Aperature," *Sensors*, vol. 24, no. 3, p. 841, 2024.
- [12] antenna-theory.com, "The Dipole Antenna," [Online]. Available: <https://www.antenna-theory.com/antennas/dipole.php>. [Accessed 26 March 2025].
- [13] D. R. Jackson, "Waveguiding Structures Part 2: Attenuation," 2019. [Online]. Available: [https://courses.egr.uh.edu/ECE/ECE5317/Class%20Notes/Notes%207%205317-6351%20Waveguiding%20Structures%20Part%202%20\(Attenuation\).pdf](https://courses.egr.uh.edu/ECE/ECE5317/Class%20Notes/Notes%207%205317-6351%20Waveguiding%20Structures%20Part%202%20(Attenuation).pdf). [Accessed 29 March 2025].
- [14] M. Shahpari and D. V. Thiel, "The Impact of Reduced Conductivity on the performance of wire antennas," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 11, pp. 4686-4692, 2015.
- [15] S. Shackle, "The mystery of the Gatwick drone," *The Guardian*, 01 Decmeber 2020. [Online]. Available: <https://www.theguardian.com/uk-news/2020/dec/01/the-mystery-of-the-gatwick-drone>. [Accessed 22 Feburary 2025].
- [16] National Counter Terrorism Security Office, "Threat from Drones in the UK," 08 August 2024. [Online]. Available: <https://www.protectuk.police.uk/threat-risk/threat-analysis/threat-drones-uk>. [Accessed 22 Feburary 2025].
- [17] Home Office, "Domestic Threat of Drones Inquiry, Written Evidence (DTD0012)," Defence Committee, London, 2019.
- [18] M. C. Bodge and S. R. German, "Chapter 1: Radar Basics," in *Basic Radar Analysis, Second Edition*, Artech, 2020, pp. 1 - 17.
- [19] National Weather Service Training Center, "Radar Basics," [Online]. Available: <https://training.weather.gov/nwstc/NEXRAD/RADAR/Section1-2.html>. [Accessed 29 March 2025].
- [20] A. Manikas, *Principles of Classical and Modern Radar: Continuous Wave (CW) Radar*, London: Department of Electrical & Electronic Engineering, Imperial College London, 2020.
- [21] M. Caffa, F. Biletta and R. Maggiora, "Binary-Phase vs Frequency Modulated Radar Measured Performances for Automotive Applications," *Sensors*, vol. 23, no. 11, p. 5271, 2023.
- [22] W. L. Melvin and J. A. Scheer, *Principles of Modern Radar Vol. III: Radar Applications*, Edison: SciTech Publishing, 2014.

- [23] Tektronix, "Radar Basics," 2017. [Online]. Available: <https://download.tek.com/document/Radar%20Basics1.pdf>. [Accessed 08 March 2025].
- [24] MATLAB, "Pulse waveform basics: Visualizing radar performance with the ambiguity function," 18 April 2023. [Online]. Available: <https://www.youtube.com/watch?v=UCir6mOW20U>. [Accessed 08 March 2025].
- [25] P. Wellig, P. Speirs, C. Schuepbach, R. Oechslin, M. Renker and U. Boeniger, "Radar System and Challenges for C-UAV," in *2018 19th International Radar Symposium (IRS)*, Bonn, Germany, 2018, pp. 1-8.
- [26] U. Seidaliyeva, L. Iipbayeva, K. Taissariyeva, N. Smailov and E. T. Matson, "Advances and Challenges in Drone Detection and Classification Techniques: A State-of-the-Art Review," *Sensors*, vol. 24, no. 1, p. 125, 2024.
- [27] J. Farlik, M. Kratky, J. Casar and V. Stary, "Radar cross section and detection of small unmanned aerial vehicles".
- [28] B. Torvik, K. E. Olsen and H. Griffiths, "Classification of Birds and UAVs Based on Radar Polarimetry," *IEEE Geoscience and Remote Sensing Letters*, vol. 13, no. 9, pp. 1305-1309, 2016.
- [29] MathWorks, "Ground Clutter Mitigation with Moving Target Indication (MTI) Radar," [Online]. Available: <https://uk.mathworks.com/help/radar/ug/ground-clutter-mitigation-with-moving-target-indication-mti-radar.html>. [Accessed 23 March 2025].
- [30] M. Caffa, F. Biletta and R. Maggiora, "Binary-Phase vs. Frequency Modulated Radar measured performances for Automotive Applications," *Sensors*, vol. 23, no. 11, p. 5271, 2023.
- [31] S. Stanko, "UAV Detection in Millimetre Wave Radar Bands," Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR, Wachtberg, Germany.
- [32] Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR, "Detection of Small Drones with Millimeter Wave Radar," [Online]. Available: <https://www.fhr.fraunhofer.de/en/sections/Industrial-High-Frequency-Systems-IHS/Detection-of-small-drones-with-millimeter-wave-radar.html#:~:text=The%20detection%20of%20unwanted%20drones,particularly%20when%20visibility%20is%20poor..> [Accessed 23 March 2025].

APPENDIX A







Design and Analysis of Electromagnetic Systems

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

83 / 100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7



Comment 1

It would have been better if captions (a) and (b) were removed and their descriptions included in the caption of Figure 1, as they appear to have been copy-pasted.

PAGE 8

PAGE 9

PAGE 10



Comment 2

Caption for the table should be positioned at the top of the table.

PAGE 11

PAGE 12



Comment 3

Caption for the table should be positioned at the top of the table.



Comment 4

Caption for the table should be positioned at the top of the table.



Comment 5

alignment missing



Comment 6

It would have been better if a clearer image had been included.



Comment 7

It would have been better if this table is redrawn with the same font as the text in the document



Comment 8

It would have been better if a clearer image had been included.



Comment 9

It is better to include the citation before the full stop



Comment 10

It is better to include the citation before the full stop



Comment 11

Caption for the table should be positioned at the top of the table.



Comment 12

Caption for the table should be positioned at the top of the table.

GRADING FORM: EMR MAY

BRYAN SKEEN

82.65

ENGAGEMENT WITH LITERATURE

The report should demonstrate the use of relevant, high-quality academic and professional sources. Comprehensive research incorporating recent journal articles, textbooks, and reliable sources should be evident. The credibility of each source should be evaluated, favouring peer-reviewed materials. All references must follow IEEE format, with consistent in-text citations.



Engagement with an extensive range of relevant and credible literature. Consistently accurate application of referencing. References include

8

textbooks, journal articles, conference papers. In-text referencing is consistently applied and relevant to the context, The inclusion of more peer-reviewed journal sources would have strengthened the work. .

KNOWLEDGE AND UNDERSTANDING

The report must exhibit sound knowledge of RF principles, waveguides, and antenna theories. Theoretical concepts such as wave modes and propagation should be clearly explained. Concepts should be related meaningfully to practical contexts. The report should demonstrate how this knowledge informed the design decisions.



Exceptionally detailed knowledge and outstanding critical understanding of the waveguide behaviour, TE modes, cut-off frequency, antenna radiation, wave propagation, mode identification, and material impacts on cut-off frequency. Formulas are accurate and clearly explained. The dominance of TE_{10} is justified. The dipole antenna section is described correctly. The theoretical explanation for the simulation deviations should be strengthened.

21.25

COGNITIVE AND INTELLECTUAL

The report should present a critical analysis of simulation results and theoretical data. Findings must be discussed with evidence, leading to logical and valid conclusions. Comparisons between theoretical and simulation results should be presented. Discussions should include implications, limitations, and alternative solutions.



Excellent critical analysis of antenna and waveguide concepts. Good comparison of theoretical vs. simulated results with quantified differences. Dipole antenna design shows excellent reasoning. Task 3 reflects advanced

21

thinking and correctly identifies the factors causing small discrepancies. In Task 1, include a table comparing theoretical and simulated cutoff frequency (f_c) values with percentage error to strengthen your argument and highlight the accuracy of your results.

Designed effective solutions using industry-standard tools with a clear focus on performance and usability. Waveguide and antenna designs demonstrate good understanding of material choices and commercial considerations. The radar section aligns well with societal, environmental, and user needs, and incorporates innovative technologies such as machine learning.

PRACTICAL SKILLS

Appropriate engineering software and methodologies should be applied to design waveguides and antennas. The simulation process and parameters should be documented clearly, with justifications for methods used. Results should be presented with neat plots and visuals. Problem-solving skills should be demonstrated through analysis and design refinements.



Exceptional levels of application and deployment skills using established methods, materials, tools and techniques. Excellent use of HFSS simulations, including all required plots: field magnitudes, vector plots, S-parameters, and radiation patterns. Screenshots are clear and well-labelled. The application context is well considered and insightful. To improve further, specify the boundary conditions used (e.g., PEC, radiation boundary) and the solver settings.

17.2

TRANSFERABLE SKILLS FOR LIFE

The report should be clear and well-structured for technical and non-technical readers. Complex ideas must be communicated effectively, with appropriate terminology and visual aids. A logical flow from introduction to conclusion should be maintained. Professional presentation elements such as clear headings, subheadings, and a well-organised reference list should be included.



Communicates professionally and consistently using a medium appropriate for the intended audience. The work is coherent, highly fluent, and presented proficiently. The report has a clear structure with effective use of figures, tables, and headings. Report is well structured with logical flow. Clear and professional tone throughout. Writing is technically good, and explanations are mostly professional and focused. Alignment should be improved, and table captions should be positioned above the tables. A thorough proofread is also recommended to enhance the overall quality of the report.

15.2