DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

MM-WAVE HIGH GAIN ANTENNA ARRAY FOR 5G/6G WIRELESS COMMUNICATION

AUTHOR	OKIERETE EDU
SUPERVISOR	DR SHAKER ALKARAKI
MODERATOR	DR STEVE GREEDY
DATE	SEPTEMBER 2023

Project thesis submitted in part fulfilment of the requirements for the degree of Master of Science [ELECTRONIC COMMUNICATIONS AND COMPUTER ENGINEERING], The University of Nottingham.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

- mm-Wave: millimetre-wave
- SIW: Substrate Integrated Waveguide
- CST: Computer Simulation Technology
- IoT: Internet of Things
- PC: Personal Computer
- CP SIW: Circularly polarized siw slot antennas
- LP SIW: Linearly polarized siw slot antennas
- VSWR: Voltage Standing Wave Ratio
- TE: Transverse Electric
- PCB: Printed Circuit Board
- RWG: Rectangular waveguide
- dB: Decibels
- Q: Quality Factor
- EM: Electromagnetic
- SNR: signal-to noise ratio
- VHF: Very High Frequency
- UHF: Ultra-High Frequency

ABSTRACT

Wireless communication technologies have been around, for quite some time. We have witnessed their evolution first-hand. Currently there is a growing need for high gain antennas that operate in the millimetre wave (mm Wave) range (30 300 GHz) to support the existing 5G and upcoming 6G networks. This thesis delves into the design and simulation of a high gain antenna array specifically tailored for the 24 30 GHz frequency band, which's crucial for both 5G and 6G applications. Working in these frequencies poses challenges to antenna designs and transmission lines like microstrip and coplanar waveguides due to increased propagation losses and atmospheric attenuation factors. To overcome these limitations this paper explores the utilization of Substrate Integrated Waveguide (SIW) technology known for its ability to minimize radiation losses, at mm Wave frequencies. [1]

ACKNOWLEDGEMENTS

I would like to express gratitude to my supervisor Dr Shaker Alkaraki for the constant feedback, guidance, and support throughout undertaking this work. I would also like to thank my moderator Dr Steeve Greedy for the encouragement provided in taking this project. I am also thankful to my family for their love and vote of confidence.

1.0 OVERVIEW

Over the past years there has been an expansion of wireless communication and because of that there is a demand for more reliable communication networks. The limitations of 4G LTE technologies have forced researchers to explore beyond microwave frequencies. This paper focuses on the mm wave spectrum for the advancement of 5G and 6G technologies. Mm waves provides higher data rates and larger bandwidths. There are challenges in every new development and this one has its own such as increased free space path loss and atmospheric absorption. To address these challenges high gain antenna arrays are used. [2]

1.1 REASON FOR CHOICE OF PROJECT

I chose this project so as to pick up simulation skills as it is essential for an engineer and my background is mostly coding skills. This decision was also fuelled by the want to be at the forefront of this technological evolution as we have come a long way from the 1920's.

1.2 DESCRIPTION OF THE PROJECT

This project shows the start to finish process of designing an SIW transmission line with slot antennas etched into it. Based on calculations of various parameters, this was designed to be a high gain antenna array for mm-wave frequencies.

In this paper, we will see how parameters like substrate material, array geometry, and spacing will be changed to maximise gain and minimise sidelobe levels.

1.3 GOALS [3]:

Design a high-gain antenna array for 5G/6G wireless communication with its operating frequency in the 24-30 GHz band using on SIW technology. [3]

1.4 OBJECTIVES [3]:

1. Do a literature review on mm-Wave high gain antenna arrays and SIW to completely understand the scope of the project.
2. Determine the design parameters for the antenna array i.e frequency, impedance matching, and gain.
3. Choose the right substrate, feed, and top materials.
4. Calculate the values of the parameters using the formulas from the literature review done.
5. Design 1x4 antenna arrays.

[3]

1.5 SUMMARY OF CHAPTERS.

Chapter 1 Introduction presents the goals and objectives, the reason for choosing the topic, and gives a brief overview of the project.

Chapter 2 Background and Literature Review provides some history, tools used, and existing research for similar applications.

Chapter 3 Design and Implementation goes into the details of the design phase and methodology, the project requirements, and the different developmental stages.

Chapter 4 Results and Discussion shows the results obtained from the running the simulations on CST.

Chapter 5 Challenges Encountered gives a summary of issues faced in designing this project and how it was overcome. It also shows the things I would add if there was more time.

Chapter 6 Project Management is a discussion and reflection of what management technique was used and how well suited it was for the project.

Chapter 7 Conclusion and Future Directions presents the close, final, and general overview of the whole project. Future directions are also included to show how this project can be taken further.

2.0 BACKGROUND OF WIRELESS COMMUNICATION

Wireless communication refers to the transfer of information between two or more points without using wires or physical electrical conductors. The history of wireless communication spans over a century and has revolutionised our world—from radio broadcasts to today's smartphone connectivity.

The origins of communication can be traced back to James Clerk Maxwell in the 19th century (1860s). Maxwell played a role, in developing theories related to electromagnetism.

His calculations predicted the existence of waves which serve as the foundation, for all communication.[4][5] Heinrich Hertz was the pioneer who experimentally demonstrated the presence of waves thus validating Maxwells theories. Guglielmo Marconi played a role in enabling distance wireless communication. His initial experiments eventually led to the achievement of radio communication in 1901.[6]

2.1 THE ERA OF RADIO AND TELEVISION:

People from the 1920s witnessed the come up of radios as a medium for communication. This era is known as "the rise of the radio" where stations started broadcasting news, music, and programs. Many could not afford it in this time. The late 1920s was the beginning of experimental broadcasts. During the 1930s, television started gaining popularity and capturing the public's eye.

2.3 CELLULAR COMMUNICATION: A PARADIGM SHIFT [4]

Cellular network breaks up whole service area into small cells also known as regions. These cells are hexagonal in shape and all fit together. This allows for frequency reuse and increases network capacity.

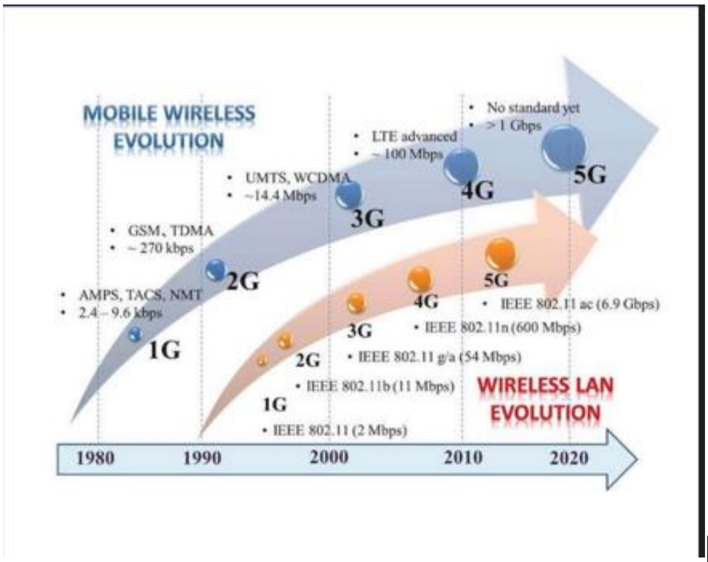
1. The first generation (1G) were analogue signals meaning in this period one could on make calls. Japan introduced this and the rest of the world followed. primarily focused on voice communication.

2. The second generation (2G) had a transition from analogue to digital. Finland developed 2G and text messaging (SMS) and internet access came alive. The text messages were encrypted ensuring a form of security for users.

3. The third generation(3G) was introduced by Japan in 2001. Multimedia services, faster internet speeds and video calls is what 3G brought about.

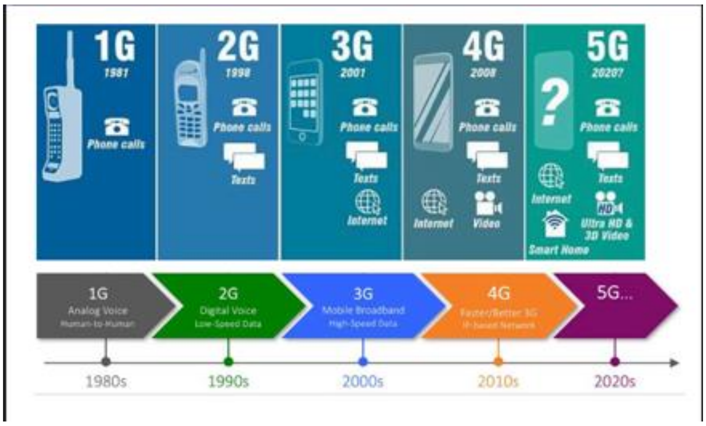
4. Fourth Generation (4G/LTE) which will soon be phased out provided users with high-definition streaming, faster speeds, advanced mobile applications, improved latency and more. This came about in the late 2000s and early 2010s.

[4][7]



[7]

Figure 1 showing the evolve in wireless evolution from 1G-5G



[7]

Figure 2 showing the evolve in wireless evolution from 1G-5G

2.4 WI-FI

Coming from the need for wireless LANs (WLAN), Wi-Fi is short for wireless fidelity, and it is a standard for wireless internet access. Wi-Fi technologies have gone through evolutions, from the initial 802.11 standard to the a/b/g/n/ac/ax iterations, each improving speed, range, and reliability.[8]

2.5 CURRENT LANDSCAPE: 5G AND BEYOND

With promises from researchers and engineers of speeds up to 100 times faster than 4G, lower latencies, and a large device connectivity, 5G is here to revolutionise industries from entertainment to autonomous vehicles. 6G is still in theoretical stages and aims for even higher speeds, lower latency, and integration of AI in networking.

Associated Challenges:

1. Wireless networks are accessible without a physical connection therefore making users susceptible to hacking, eavesdropping, and other malicious activities.
2. There are health effects caused by prolonged exposure to EM fields from wireless devices.
3. The present frequency spectrum is limited and is becoming congested as more devices connect.

2.6 TOOLS

Personal Computers (PC)

This design uses CST Studio Suite, the student version and the PC used to generate this simulation is a ThinkPad.

2.7 LITERATURE REVIEW

ANTENNA ELEMENTS

These elements are components within an antenna array that emit or receive waves. They act as the building blocks for complex antenna systems such as arrays or phased arrays. Essentially, they are the units within the antenna structure of effectively radiating or capturing electromagnetic fields. [9]

2.8 MICROSTRIP PATCH ANTENNAS

Microstrip patch antennas have a radiating patch placed on a dielectric substrate with a ground plane backing it. These antennas are designed to operate on resonant frequencies, and they use the TE10 mode for radiation.

The research and application of microstrip patch antennas have seen development since the 1970s when PCB technology advanced significantly. These antennas offer both advantages and limitations. On one hand their compact size makes them suitable for applications and allows for easy integration with other components, on the same substrate.

Microstrip patch antennas have gained popularity due to their cost effectiveness, structure, and ease of fabrication. Unlike horn antennas, they offer versatility because of their shape, size and feed methods which can be easily adjusted for applications. Additionally, these antennas can be used in an array configuration to achieve gain. They also have the advantage of multiband operations meaning they can operate at multiple frequencies simultaneously for various applications. Being planar in nature allows them to be easily integrated into phased array systems, multiple-input-multiple-output MIMO systems and beam forming applications. [10]

The disadvantages too should be considered when choosing an antenna for an application. One drawback is their bandwidth, which makes them less suitable for wideband operation requirements. However, techniques such as stacking or using substrates can help increase the bandwidth if needed. Another limitation is that compared to antennas microstrip patch antennas generally have gain. This may restrict their use in long range communication systems where higher gain's necessary. Also, the dielectric substrate used in these antennas can lead to surface wave propagation issues that could result in reduced antenna efficiency and increased coupling between elements, in an array. [10]

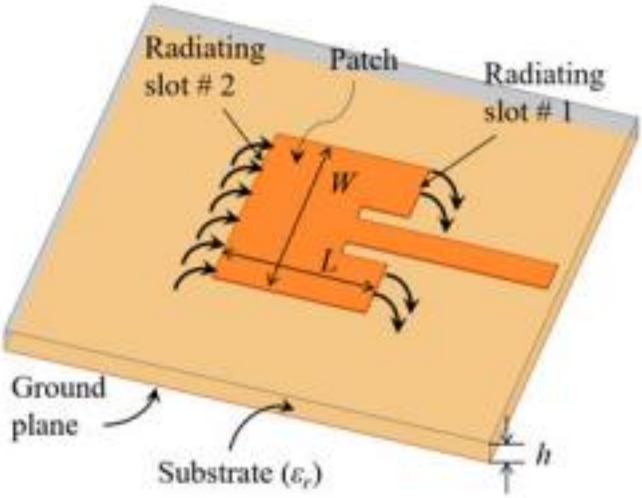


Figure 3 showing overview of the Microstrip Patch Antenna [10]

Figure 4 showing the cross-sectional view of the microstrip patch. [10]

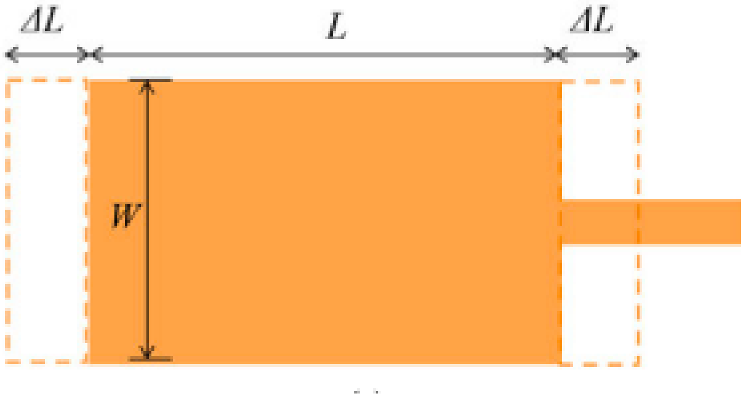


Figure 5 showing the length of the patch antenna along radiating edges. [10]

A way to mitigate these limitations is by adopting a thicker substrate, the impedance bandwidth can be expanded, however this results in greater radiation inside the substrate causing more losses. [10]

Substrates with low permittivity (ε_r) can also be used because this will lead to the shrinking of the L value and an increase in Q value (Quality factor). These changes will make it more narrow-band. [10]

Carver and Mink are researchers in this field, and they have expanded the potential of microstrip antennas.

They have sought out different feeding techniques like coaxial, aperture-coupled, proximity-coupled feeds and array configurations as they lead to better impedance matching and give rise to better radiation characteristics.

They are used in a number of systems i.e radar systems, medical imaging, aerospace and defence, satellite communications, and IoT devices. [11]

CORE CONCEPTS IN MICROSTRIP PATCH ANTENNA

These antennas have two edges that radiate as seen in Figure 3 above. The antenna's operational frequency is based on the length (L). [12]

The centre frequency is:

$$fc = \frac{c}{2L\sqrt{\varepsilon r}} = \frac{1}{2L\sqrt{\varepsilon 0 \varepsilon r \mu 0}}$$

[12]

εr is the relative permittivity of the substrate material used. It is a dimensionless measure that quantifies how easily a material can become polarised by an electric field, relative to the permittivity of vacuum.

c is the speed of light in vacuum.

The fringing fields shown in Figure 4 is a function of h/L and ε_r as they affect its length and resonant properties. These fields extend away from the margins/dimensions of the patch. In addition, certain lines of the fields also exist in the air, therefore they are not entirely contained within the substrate. An effective dielectric constant ($\varepsilon reff$) is added for the combined effects of the fringing fields and make the medium appear homogeneous because waves are present in both the substrate and the air. The value of $\varepsilon reff$ can range from 1 to εr. [10] [12]

The formula:

$$\varepsilon reff = \frac{\varepsilon r + 1}{2} + \frac{\varepsilon r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} [10]$$

W is the width and it controls input impedance. [12]

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon r + 1}}$$

Then L= Leff -2ΔL is the natural length of the patch [10]

2.9 DIPOLE ANTENNA

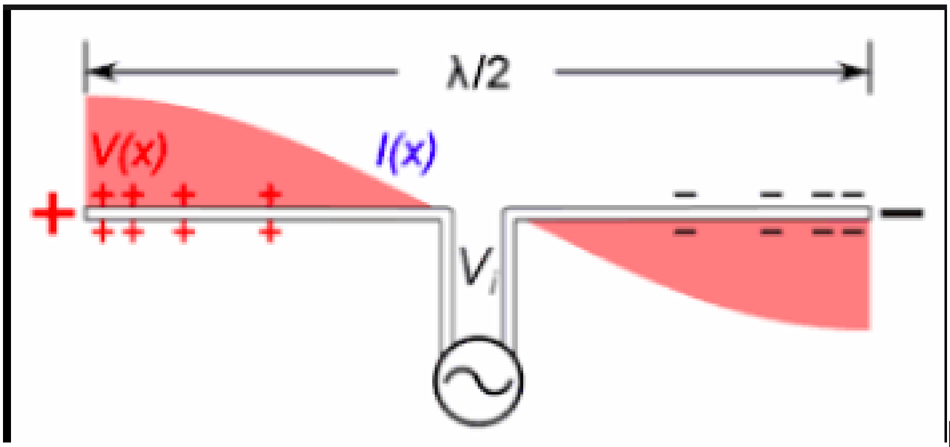
Dipole antennas are one of the simplest types of antennas. They have been widely used in electromagnetics and wireless communications due to their versatility. [13]

Dipole antennas are made up of two components like wires or rods, each one-fourth the length of a wavelength. These components are fed out of sync by 180° as shown in Figure 6, eliminating the need for a ground plane. This is different from antennas such as microstrip patch antennas that do require a ground plane to function. The radiation pattern of a dipole antenna is omnidirectional in the H plane and bi-directional in the E plane resembling a doughnut when represented in three dimensions. [10]

Because of its simplicity and ability to radiate signals in all directions the dipole antenna finds applications in fields including AM/FM radio broadcasting, WiFi technology and other wireless communication systems. It is also used for RF measurements and serves as a reference antenna for testing antenna performance. The fact that dipole antennas can be easily constructed using materials like wires or rods makes them suitable for emergency situations and portable communication systems. In industrial settings dipoles serve as solutions for wireless sensor networks, telemetry systems and RFID technology. [14]

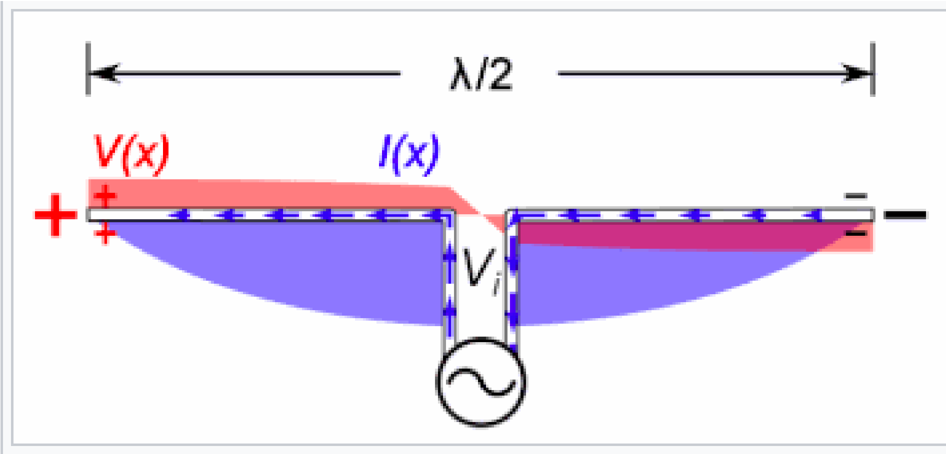
Recent research has been focused on improving the performance characteristics of dipole antennas. Advancements, in miniaturization techniques now allow these antennas to be incorporated into devices.

Furthermore advancements, in the fields of materials science and medicine have introduced the utilization of novel substrates and superconductors thereby enhancing both efficiency and bandwidth. Ongoing research is also focused on phased array systems that incorporate elements with the goal of precisely controlling the radiation pattern for various applications such as radar and satellite communications. [15]



[13]

Figure 6 showing the transmitting half-wave dipole (Voltage red)



[13]

Figure 7 showing the transmitting half-wave dipole (Voltage blue)

In Figure 6 we observe a representation of a transmitting half wave dipole antenna where the voltage is depicted in red. Similarly Figure 7 illustrates another transmitting half wave dipole antenna with the voltage shown in blue. In these antennas during transmission, we witness a phenomenon known as a standing wave which exhibits profiles along the length of the antenna. Unlike traveling waves where voltage and current are in phase, standing waves exhibit them as being 90° out of phase. This behaviour indicates that energy is primarily stored within the wave than being transferred. [13]

To achieve this an oscillation state in an antenna, an oscillating voltage Vicos(wt) is applied across its two elements by the transmitter. At its resonant frequency there is synchronization, between input voltage and current phases. As a result, the antenna presents itself as purely resistive to optimize power transfer efficiency—a desired outcome.

The efficient emission of energy into space in the form of radio waves is ensured by this phase alignment. [13]

When the antenna is set to reception mode, the voltage phase in the transmission line changes indicating that it is absorbing energy from radio waves. In this state the antenna absorbs energy and converts it into voltage and current that can be utilised by the receiver. [13]

Both the folded dipole and half wave dipole antennas have expanded their usage to phased arrays which allows for better impedance match and higher gain. Dipole antennas are commonly used in Very High Frequency (VHF) applications, which have a frequency range of 30MHz 300MHz [16] and in Ultra High Frequency (UHF) applications such as broadcasting and RF modules for wireless communication.

2.10 SLOT ANTENNA

Babinets principle used in EM theory compares the radiation characteristics of a structure with its complementary counterpart. The way a slot in a metal sheet emits EM waves will mirror the radiation pattern of a metal piece that would fit into that slot but with a 180-degree phase shift and different impedance. This principle serves as a shortcut, for antenna designers allowing them to predict the behaviour of forms based on existing knowledge of one structure. [17]

A slot antenna consists of a metal surface, with an opening. When this opening is stimulated by a microwave source it emits waves. Early studies on slot antennas focused on understanding their radiation patterns and impedance characteristics. Babinets principle, which states that the voltage, current distribution, and polarization of the slot antenna are opposite to those of a dipole antenna aids in comprehending how slot antennas operate. For instance, while a vertically oriented dipole antenna exhibits vertical polarization, a vertically oriented slot antenna exhibits horizontal polarization. [10] Although both dipole and slot antennas have similar radiation behaviours, their polarizations are opposite to each other.

The formula for Babinet’s Principle is:

$$Z_{slot} Z_{dipole} = \frac{\eta^2}{4} \text{ [9]}$$

When:

Z_{slot} = impedance of the slot antenna

Z_{dipole} = impedance of the dipole antenna

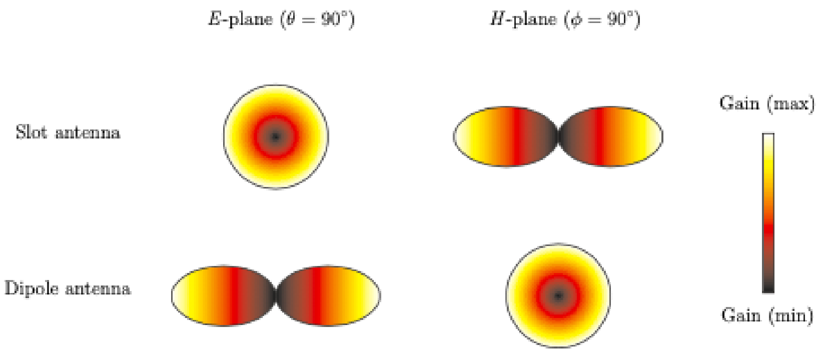


Figure 8 illustrates the E and H plane of the complementary nature of the slot and dipole antennas [9]

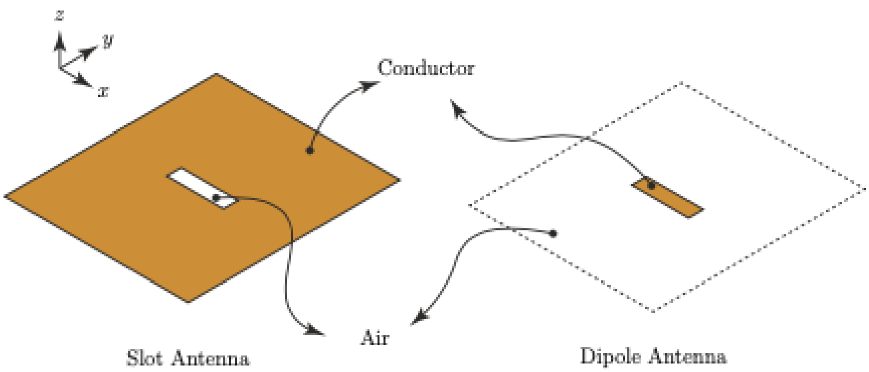


Figure 9 showing A slot antenna and a dipole antenna. [9]

Air has been changed with a conductor, and the conductor was changed with air to get complementary antenna. The Figure 9 above is showing the complementary property.

Figure 9 showcases a slot antenna alongside a dipole antenna [9]. By interchanging air, with a conductor and vice versa we can achieve Babinet's properties in these antennas.

Advantages of Slot Antennas

1. Slot antennas offer the benefit of being integrated making them valuable, in applications that require efficiency and stealth capabilities like in the aerodynamics field.
2. They are well suited for high frequency uses such as mm-Wave communications and the design of phased arrays for beam steering.
3. Slot antennas tend to outperform microstrip and dipole antennas in terms of gain although they usually have a reduced bandwidth. [18][19]

2.11 SIW BASED SLOT ANTENNAS

2.11.1 CIRCULARLY POLARIZED SIW SLOT ANTENNAS (CP SIW)

These types of antennas employ configurations like crossed or spiral slots to generate electric field components that are orthogonal with a phase difference of 90 degrees. These antennas prove useful in scenarios where orientation flexibility is required. CP SIW slot antennas are recognised for their moderate to high gain ranging from 6 dB to as high as 14 dB depending on design factors. The directivity ranges from 7dBi to 15 dBi for CP SIW slot antennas. The radiation patterns of CP SIW tend to be more intricate because of polarisation. Circularly Polarised antennas address challenges related to polarisation mismatch and interference caused by polarisation mismatch and multi-path interference.

For the SIW cavity function like the metallic cavity, certain criteria must be met. The ratios d/dp and d/λ0; d/dp should be at least 0.5 and d/λ0 should not exceed 0.1 (where λ0 is the wavelength in free space) [20].

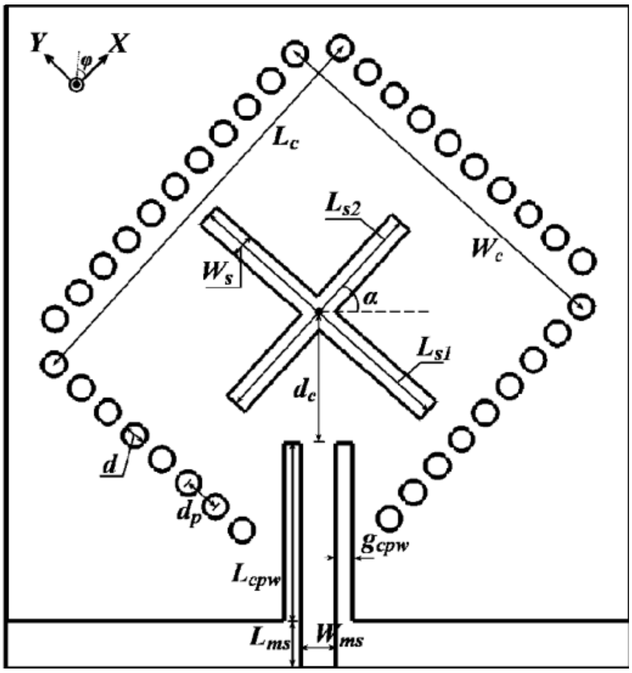


Figure 10 showing low profile cavity backed crossed slot antennas.

Recent developments in CP SIW slot antennas are focusing on improving gain and directivity through techniques like stacked layers and parasitic elements. One of the studies achieved a gain of 12.8 dB with a directivity of 13 dBi using a stacked configuration.

2.11.2 LINEARLY POLARIZED SIW SLOT ANTENNAS (LP SIW)

This type of polarised SIW uses square slots cut into the waveguide surface to achieve linear polarisation. These antennas offer moderate gain, and it is a simple structure, but it needs external components for polarisation manipulation.

Compared to CP SIW, LP SIW slot antennas gain ranges from 4 dB to 10 dB, therefore, not as high but moderate which makes them useful in applications where moderate gain is sufficient, like local area networks (LAN) or short-range communications.

The directivity of LP SIW slot antennas ranges from 5 to 11 dBi.

The radiation patterns of these antennas are simpler and perfect for situations where the signal path is straightforward and not affected by polarisation mismatches. [9]

2.12 YAGI-UDA ANTENNA:

Characteristics:

The Yagi-Uda antenna has several director elements, a reflector and a driven element. This antenna design has a directive radiation pattern and it works by maximising interference in the desired direction whilst minimising it in the unwanted directions resulting in high gain. These antennas are used for television reception due to their directional properties. We see see them outside sometimes. They are also popular in ham radio operations. [21]

Recent Developments:

Researchers have pushed for the construction of Yagi-Uda antennas using materials like graphene to enhance conductivity and overall efficiency for the past decade now. Going back to chemistry, graphene is a material with an energy gap which why it is of interest for this nanotechnology. Efforts have been made to reduce the size of Yagi-Uda antennas so that they can be easily integrated into devices without compromising performance. Furthermore, modern iterations aim to expand the bandwidth of Yagi-Uda antennas to make them suitable for a wider range of applications.[22]

2.13 PARABOLIC REFLECTOR ANTENNA:

Characteristics:

This antenna uses a parabolic reflector, a curved surface with a feed antenna at its focus. The most common one seen has a dish-like shape and in countries like Nigeria, this was seen outside of people's homes. As the name states, this antenna reflects the energy from the feed antenna in a coherent, parallel beam; it directs EM waves to a single point. This feature provides high gain and narrow bandwidth which is a necessity for point-to-point communications. [23]

Recent Developments:

This antenna is being used in satellite communications, radio astronomy and radar systems. Dynamic control systems are the most recent development for this antenna and its purpose is to adjust the shape of the parabolic surface for better advantages like beam steering and optimization. Transmitters and receivers are used directly into the antenna system and this reduces losses. Parabolic antennas are quite bulky, so researchers are trying to make them more compact without affecting the gain. [24]

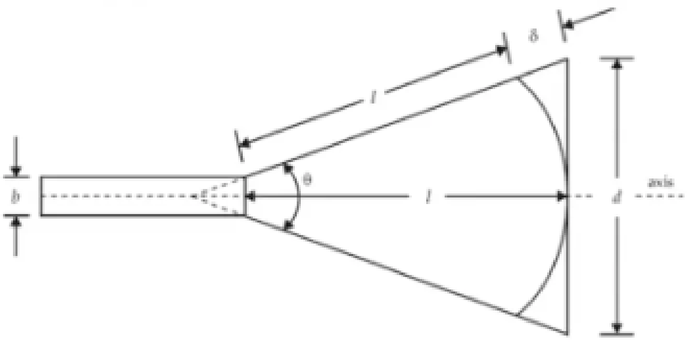
2.14 HORN ANTENNA:

Characteristics:

Horn antennas are recognised by their flared shape at the end of a waveguide. They tend to match the impedance between the waveguide and free space ensuring efficient radiation. Horn antennas are commonly used as feeders for antenna structures like parabolic reflectors especially in microwave and mm wave ranges [25].

Recent Developments:

Recent developments in horn antenna technology focuses on expanding their bandwidth through designs. Similar to parabolic reflectors there is a trend, towards integrating transmitting or receiving systems directly within the horn antenna structure. Furthermore, researchers are exploring materials and fabrication techniques to enhance performance, durability and size efficiency of horn antennas.



[25]

Figure 11 showing Horn Antenna Parameters

Factors	MM-Wave High Gain Antenna Array	Microstrip Patch Antenna	Yagi-Uda Antenna	Horn Antenna	Parabolic Antenna	Dipole Antenna	Slot Antenna
Frequency Range	30-300 GHz	1-100 GHz	3 MHz-3 GHz	1 GHz-20 GHz	300 MHz-100 GHz	100 MHz-3 GHz	1-100 GHz
Gain	High	Moderate	Moderate	Moderate to High	High	Moderate	Moderate
Beamwidth	Narrow	Moderate	Moderate to High	Wide to Moderate	Narrow	Moderate to Wide	Moderate to Narrow
Array Configuration	Planar, Circular	Single, Array	Linear Array	Single	Single	Array or Single	Array or Single
Number of Elements	Varies (e.g., 64, 128, 256, 512)	1 or more	Varies (3, 5, 7 etc.)	1	1	1 or more	1 or more
Polarization	Linear/ Circular	Linear/ Circular	Linear	Linear/ Circular	Linear/ Circular	Linear	Linear/ Circular

Factors	MM-Wave High Gain Antenna Array	Microstrip Patch Antenna	Yagi-Uda Antenna	Horn Antenna	Parabolic Antenna	Dipole Antenna	Slot Antenna
Efficiency	High	Moderate	Moderate	High	High	Moderate	Moderate to High
Applications	5G/6G communications, Radar Systems	Cellular Communications, WiFi, GPS	TV Broadcast, Amateur Radio	Radar, Satellite Communication	TV Broadcast, Satellite Communication	FM Radio, TV, Wireless Communication	Radar, Satellite Communications
Materials	Metamaterials, Silicon, Gallium Arsenide	Copper, FR4, Ceramic	Aluminium, Copper	Aluminium, Copper	Steel, Aluminium, Copper	Copper, Aluminium	Copper, FR4
Fabrication Technology	Photolithography, Etching, Sputtering	PCB Etching, Additive Manufacturing	Metal Fabrication, Welding	Metal Fabrication, Welding	Metal Fabrication, Welding	Metal Fabrication	PCB Etching, Additive Manufacturing

Factors	MM-Wave High Gain Antenna Array	Microstrip Patch Antenna	Yagi-Uda Antenna	Horn Antenna	Parabolic Antenna	Dipole Antenna	Slot Antenna
Impedance (GHz)	Varied	50	50	50	50	50-75	50
Bandwidth (%)	2-5	2-5	10-20	15-25	1-5	10-20	5-10
Peak Gain (dB)	15-25	8-12	10-15	10-20	25-35	2-5	5-10

Table 2.1: Proposed MM-wave high gain antenna arrays characteristic comparison with other antennas. [26][27][28][29][30][31][32][33].

3.0 DESIGN AND IMPLEMENTATION

Planar antennas i.e slot and patch antennas are widely used due to their construction and easy integration into compact systems. Patch antennas have been applied in the radar and satellite communication fields. However, it is the slot antenna that is more popular in 5G/6G wireless systems [9].

3.1 SLOT ANTENNA

Slot antennas offer advantages including wider bandwidth, better radiation patterns and simpler feeding mechanisms making them suitable for high frequency mm-Wave applications. As mentioned earlier these antennas consist of a metal surface with a slot cut out. The shape, size and orientation of the slot determines the radiative properties of the antenna. Typically backed by a ground plane, the slot antenna works by emitting energy confined within the slot and transforming it to an EM wave that can be guided or directed as needed [9].

Slot antennas have the capability to form high gain antenna arrays. High gain antennas concentrate energy in specific directions increasing SNR signal-to noise ratio and enabling robust and efficient communication. When multiple slot antennas are arranged in an array configuration, they generate a far-reaching directional beam. [10]

The slot antennas adaptability allows for radiation pattern optimization and minimizes interference [34] in situations such as directional radiation patterns where the interference is reduced drastically by the antenna sending or receiving signals in specific directions not equally in all directions. By focusing the transmitted or received signals in desired directions and reducing them in others, interference from systems in other directions can be minimised. [35]

Another scenario where the slot antenna proves useful is frequency selectivity. Its dimensions and design make it capable of being selective to frequencies or a narrow range of frequencies. Signals outside this range will have next to nothing impact, thereby reducing interference from signals at those frequencies.

In an array configuration operating at mm-Wave frequencies, slot antennas can get gains of up to 15 to 20 dBi. They also often exceed a fractional bandwidth of 20%. This advantage proves valuable in 5G and 6G applications where large bandwidths are necessary for high-speed data transmission. By continuously changing and micro-observing the geometric parameters of the slot; its length, width, distance from the centre of the SIW and distance from the vias, a specific impedance bandwidth will be gotten while maintaining a Voltage Standing Wave Ratio (VSWR) value less than 2:1. [36][37]

Transmission line principles are used to solve and understand the behaviour of the slot antenna. [38]

They are:

1. The voltage is highest in the centre of the slot and drops to its lowest at the slot's ends.
2. The current is the weakest at the centre and is the strongest at the slot's ends.
3. The currents at the two ends of the slot (on the x-axis) are out of phase, meaning they don't peak at the same time.
4. When the impedance of the source matches the slot antenna's impedance (this is a condition for optimal performance, known as resonance), the slot antenna emits electromagnetic fields.

5. These fields radiate in opposite directions along the z-axis (both +z and −z directions). This radiation is due to the in-phase distribution of voltage along the x-axis.

   [38]

3.2 ARRAY FACTOR

The antennas are spaced apart at a distance. This forms an antenna array and each of them are powered to aim the arrays to a particular direction. By adjusting the amplitude and phase of each element, one can boost the signal in a desired direction while mitigating unwanted signals from other directions. [10]

3.3 SUBSTRATE INTEGRATED WAVEGUIDE

A waveguide is designed to channel electromagnetic waves from one location to another. Consisting either of an air-filled or dielectric-material-filled cavity enclosed by a metallic conductor, the waveguide directs electromagnetic waves along its axis through a series of internal reflections. These reflections happen at the interface between the air and the conductor, minimising radiation loss especially when the metal enclosure is thicker than the wave's skin depth. [9]

The air-filled design produces lower attenuation and higher quality factors, but at the cost of mechanical stability and ease of integration with other components. An air-filled SIW is less robust and more susceptible to external physical distortions but for some specialised applications where these drawbacks are not a concern, air-filled SIWs can give a better performance. In this paper, we will be going forward with the dielectric-material-filled cavity as it offers advantages such as broader bandwidth, supresses unwanted propagation modes, better ease of integration, better thermal stability and some dielectric materials handle higher power levels than air allowing for more powerful signal transmission. [39]

SIW is a combination of waveguide technology and modern planar circuitry. It acts as an intermediary between the non-planar metallic waveguides and fully planar transmission lines like microstrip or strip line. [40] [9] SIW is popular amongst researchers and engineers working on high-frequency applications, such as Ka-band systems.

The dielectric substrate is sandwiched between two conductive layers, usually made of copper. Metal vias are introduced along the edges to act as sidewalls of the waveguide. These vias connect the top and bottom conductive layers, "trapping" the electromagnetic wave within the substrate. [41] This allows the SIW to support Transverse Electric (TE) modes like TE10, TE20, etc. This planar structure allows for cost-effective fabrication techniques like Printed Circuit Boards (PCB), making SIW an economical alternative to traditional waveguides.

The primary application of SIW is in planar antennas. SIW-based slot antennas, provides better front-to-back ratios [42] and gains than the other applications using other types of feeding structures. Their disadvantage is having a narrow bandwidth, but this has been mitigated in several designs by introducing complex slot shapes or multiple resonant frequencies.

3.4 INTRODUCTION TO DESIGN AND IMPLEMENTATION

Conventional waveguides, particularly Rectangular Waveguides are well suited for transmitting high frequency signals due to their excellent electromagnetic disturbance protection and minimal signal leakage. However, integrating them into used PCBs poses challenges due to their big size. The geometric mismatch, between these waveguides and planar circuits often requires transitional structures and transitional structures are expensive to produce [43].

SIW offers a compromise by combining the advantages of Rectangular Waveguides and planar lines; high quality factor, good power handling capabilities and economic feasibility thanks to their smaller dimensions and reduced cost. A flaw, in the design of this system can cause unwanted wave modes to spread within the SIW resulting in a degradation of signal quality and bandwidth. [43]

In this research paper we continuously simulate the design to assess its performance. Based on these results we create a customised SIW model for EM optimisation. The dimensions of this SIW needs to meet criteria; achieving the target cutoff frequency and minimising back reflections and maximising the bandwidth of the primary wave mode. [43]

Flowchart Diagram showing the steps to design the High-Gain Array Antenna

Design of SIW substrate; Calculation of design parameters

↓

Design of SIW substrate, feed, top and taper; Material of substrate chosen based on thickness of a dielectric substrate, relative permittivity, and dielectric constant.

↓

Define port, and boundary conditions.

↓

Antenna modelling using CST STUDIO SUITE software.

↓

Design Array of Antennas

The initial step involves calculating the parameters for the SIW. I first determined the operating frequency and waveguide width. For this case I am using 28GHz with a RWG [44] in the Ka band. The standard waveguide is WR-28 with dimensions of 7.112x3.556mm.

To calculate these parameters, we use the following formula for waveguides:

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

In our case 'b' is not relevant for TE10 mode as it does not affect the cutoff frequency.

However, adjusting thickness can have an impact on losses; a thicker substrate is associated with reduced losses [45]. Hence when operating in TE10 mode it may be more beneficial to focus on substrate thickness than 'b' dimension as it could lead to better performance metrics such, as lower attenuation. When designing waveguides for certain applications, these variables are taken into consideration to optimise the design for minimal loss and maximum efficiency.

Other factors are to be considered when designing a rectangular waveguide, such as the choice of material for the walls. Typically, metals are used for the waveguide walls. This choice impacts the attenuation and propagation characteristics of the waveguide. Higher electrical conductivity in metals leads to lower ohmic losses.

Although in the project the wave guide has only been designed on CST, it is important to consider factors that could affect a fabricated waveguide, such as temperature and humidity. These factors can have an impact on performance by influencing the material properties of the substrate. They may cause changes in propagation constants and even alter the dielectric constant of the substrate.

3.5 SIW PROCEDURE AND CHOICES

Selection of a Suitable Dielectric Substrate for SIW structure:

The selection of a dielectric substrate plays a role in how electromagnetic waves propagate through the system. It affects parameters like speed, attenuation, and energy confinement. Choosing a dielectric substrate is a first step, in our design methodology.

The antenna is positioned in the xy plane within a coordinate system. Is constructed on a Rogers RT5880 substrate, which has a dielectric constant of 2.2. This substrate was chosen for its mechanical advantages, among other factors [9]. The small loss tangent ($\tan \delta =$

0.0009) indicates small signal loss making it an appropriate choice for this design [46]. Loss tangent refers to the amount of energy lost by a wave as it passes through a material. It is a parameter provided in datasheets for dielectric materials like substrates [47].

Electrical Advantages:

Rogers 5880 is renowned for its loss tangent making it well suited for high frequency applications where minimising signal loss is crucial. This aspect becomes especially important in mm wave systems such as 5G/6G, where any loss can negatively impact system performance.

With a constant of 2.2 this substrate exhibits reduced dispersion and ensures a more linear phase response. This is essential where phase integrity is important. [48]

Moreover, when considering requirements such, as bandwidth, gain and efficiency this substrate outperforms alternatives.

Mechanical Advantages:

A mechanical advantage when using Rogers 5880 (lossy) is thermal stability because when it is exposed to environmental factors such as temperature and humidity, it will fare well.

RT5880 is not the cheapest material, but there is a balance between performance and cost. The properties of RT5880 are well-documented, and this is a product that is widely available, making it easier to source and integrate into various designs. [49]

It is compatible with PCB fabrication techniques, which is important for manufacturability i.e scaling up from prototypes to mass production.

Substrate thickness and relative permittivity:

The substrate's thickness and relative permittivity (εr) determines the size of the waveguide and the overall antenna structure.

Define Port and Boundary conditions:

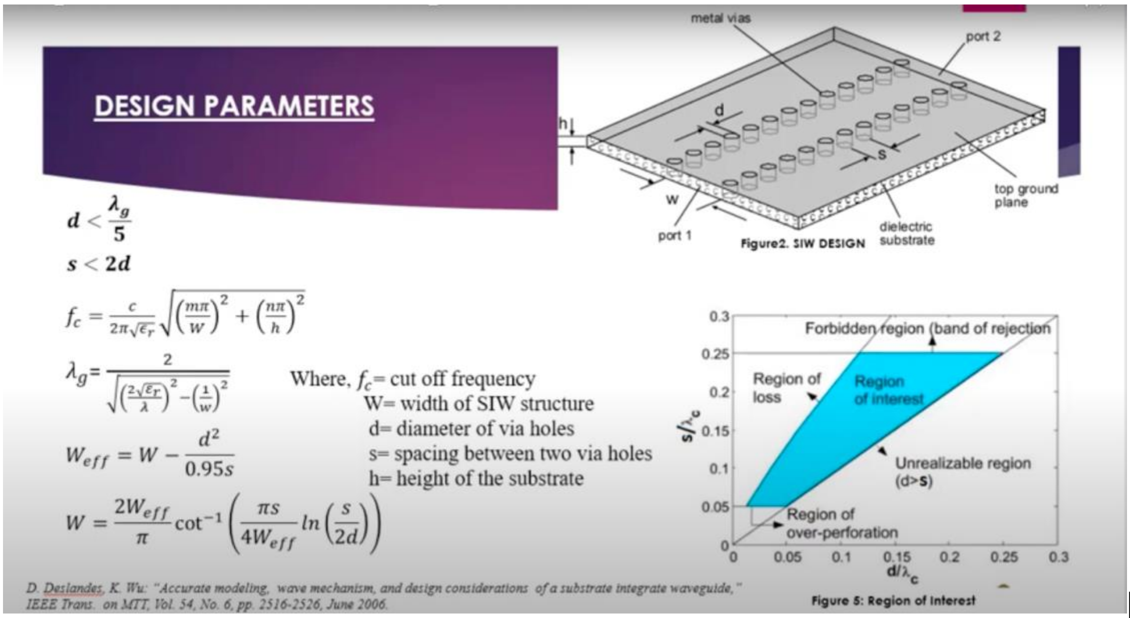
The port is a signal source for antennas. It is the interface where EM waves are fed into or extracted from the antenna. Proper definition of the port and boundary conditions is ideal for accurate simulation and proper functionality. Incorrect settings can lead to signal reflection, increased VSWR, or a breakdown of the simulation.

Model Parameters:

Results of a simulation are reflection coefficient(S11), radiation patterns, gain estimation and efficiency. The model parameters used to design the SIW and slot antenna array are optimised to achieve the best results.

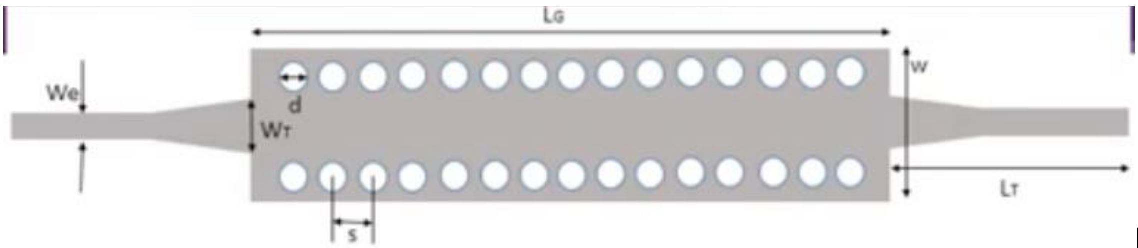
This is important because the reflection coefficient, radiation patterns, gain, efficiency are performance indicators for an antenna. They provide quantitative data that can be used to assess whether the design meets its criteria and purpose which is to provide high-gain results. If the initial results do not meet up to par, optimization algorithms can be used to tweak model parameters for improved performance.

3.6 DESIGN METHODOLOGY



[50]

Figure 12 showing the design parameters.



[50]

Figure 13 showing the Dimensions of antenna band.

The bandwidth of the SIW transmission line is determined by the first two modes of propagation, specifically the TE10 and TE20 modes.

This calculation below is for TE10 mode [26]:

$$fcTE10 = \frac{c}{2a}$$

$$a = \frac{c}{2fcTE10}$$

$$a = \frac{c}{2x}$$

Using 15 Ghz as cutoff frequency:

$$a = \frac{3x10^8}{2x15x10^9} = 0.01m = 10mm$$

$$fcTE_{20} = \frac{2c}{2a}$$

$$fcTE_{20} = \frac{2x3x10^8}{2x0.01} = 30\ GHz$$

[26]

The frequency bandwidth of 15-30 GHz intersects with the Ka frequency band (26.5-40 GHz) and also extends into the Ku-band (12.4-18 GHz). [44] The Ka band is commonly used in satellite communications and radar systems. [51] The Ku band is known for its applications in satellite television, broadcast services and Very Small Aperture Terminals systems. [52] This dual overlap presents an advantage as it allows for dual/multi-band operation therefore increasing the versatility and application potential of the antenna systems. It opens up possibilities for using the design, in high frequency applications.

The choice of the 15-30 GHz frequency range is important for high frequency systems because it provides a range of compatibility and future proofing. This is relevant in today's era where multi-band and multi-mode operations are becoming more common. Having such a broad spectrum gives engineers flexibility in their design considerations making sure that the technology can meet the requirements of both future and high-frequency applications.

The effective width of the waveguide, known as Weff takes into account the impact of the dielectric filling of the waveguide or structural complexities like slots within the waveguide. Weff gives a simplified dimension used in models to describe wave propagation characteristics such as phase velocity, cutoff frequency, and impedance. [53] In this design I chose to use 8.8 as the value for Weff.

The substrate width directly affects how different propagation modes are supported or suppressed within the waveguide. This is crucial for signal transmission and minimising losses.

The substrate width also impacts the mechanical stability of the waveguide or antenna. A substrate that is too narrow will not provide sufficient mechanical strength, while a substrate that is overly wide will make the component unnecessarily bulky, affecting the overall size and weight of the device it is part of.

Lastly, the width of the substrate can influence the bandwidth of the antenna or waveguide. A carefully chosen width can facilitate a broader bandwidth, which is valuable in multi-band or wideband applications.

Centre frequency of 15 and 30 GHz is 22.5 GHz

$$\lambda = \frac{c}{f} = \frac{3x10^8}{22.5x10^9} = 0.0133 \text{ x}1000 \text{ [26]}$$

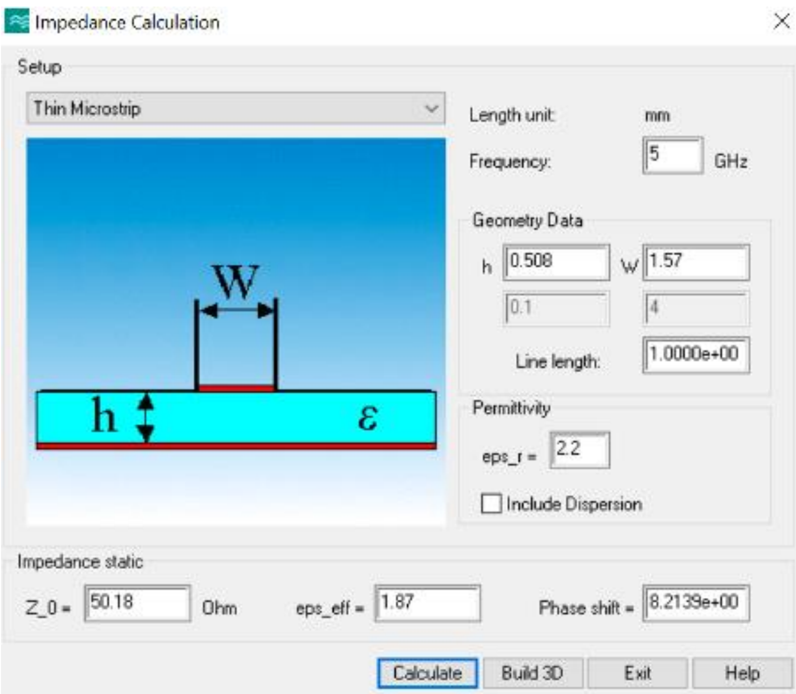
LG (refer to Figure 13) = 13.33 x 2.386 = 31.8mm. LG is the length of the top layer of the SIW and this is where the slots are located. The length of the SIW directly affects the resonant frequency of the system. A longer SIW resonates at a lower frequency, whilst a shorter one resonates towards higher frequencies. Choosing 31.8mm as the top layer length was also based on testing and running simulations to get the best desired S1.1 (and s2.2) port result.

LT (refer to Figure 13) is 8.92mm, which was a back-and-forth process in choosing which value is best desirable. Initially, LT was 10mm, but this value was too big and produced S1.1 results were not acceptable.

h is the height/thickness of the dielectric substrate in mm. The value used is 0.508.

t is the copper thickness as copper is the metal of choice in this design. The value of t is 0.035 mm.

we is the microstrip feeding line and has a value of 1.57mm



[26]

Figure 14 showing the impedance calculation.

The diagram above (Figure 14), has a target impedance (Z0) value of 50Ω, which is needed to facilitate the transition from the microstrip's quasi-TEM mode to the SIW's TE10 mode [17]. The value is set as 1.57, after putting in the h as 0.508 and εr as 2.2 achieving an impedance of approximately 50.18Ω. [26]

Connectors aren't necessary for powering the antenna instead, the antenna is linked to the RF component's output like a power amplifier or a filter, through various waveguiding techniques. [9]

Wt was set as 2.693 after continuous simulation and picking out the most appropriate value.

d is the diameter of the vias, and the set value was 1.12mm

s is the distance between consecutive vias and s $\leq$ 2d, and the set value was 1.38mm

Parameters	Value (mm)
w	8.8
LG	31.8
LT	8.92
h	0.508
t	0.035
we	1.57
wt	2.693
d	1.12
s	1.38

Table 3.1 showing parameter values.

In an SIW, vias are conductive cylinders that connect the top and bottom metal plates of the waveguide structure. They confine electromagnetic fields within the substrate material making sure that the waveguide's operating mode is maintained. Vias are the sidewalls that create a closed environment for wave propagation. [40]

A larger diameter (d) provides better EM confinement, but this increases the waveguide's size and cost. A smaller "d" leads to a less effective field confinement, affecting the SIW's radiation parameters i.e bandwidth, loss, and efficiency.

The spacing between the centres of consecutive vias affects the SIW's performance by determining how effective the EM fields are confined within the waveguide. The spacing was carefully chosen to optimise the waveguide's performance across its operating bandwidth. It also kept changing based on the S1.1 results for guidance. The closer the vias are spaced, the better the field confinement, but this leads to higher fabrication costs and complexities. The via spacing is less than double the diameter to prevent higher-order modes from propagating and to maintain the desired TE10 mode. [50]

The reflection coefficient (S1.1), is found in the S-parameters option on CST, and it is a measure that quantifies how much of an EM wave is reflected by an antenna or a transmission line (SIW). It is complex in nature and is represented in the frequency domain.

S1.1 plot shows the frequency (GHz) on the x axis and decibels(dB) on the y axis. When S1.1 is plotted against frequency, the graph will show which frequencies the antenna or transmission line is well-matched to the characteristic impedance (Z0), which in this case is 50 ohms. A well-matched system has low reflection. The magnitude of the reflection coefficient is plotted in decibels. A value of 0 dB means that 100% of the power is reflected back (complete mismatch), while values approaching -∞ dB indicates that almost no power is reflected (ideal match). [36]

To have acceptable results:

1. The S1.1 magnitude should be lower than -10 dB as this means that less than 10% of the power is reflected back and more than 90% is transmitted. [36]
2. A VSWR value of 1:1 is a perfect match and not possible in the real world, so values up to 1.5:1 or 2:1 are acceptable.[36]

The best S1.1 magnitude for this SIW transmission line design {shown in Figures 15 and 16) is -20 dB or lower. This is the starting point, and it needs to be as accurate as possible for good final results. A -20 dB reflection coefficient means that only 0.01% of the power is reflected back, allowing 99.99% of the power to be transmitted. In radar applications, satellite communications, or medical devices where signal integrity and power efficiency are factors, this is required.

Signal Integrity is high when the value of S1.1 is quite low because it reduces the level of interference. In high-precision applications, minor reflections bring about data errors.

Lower reflected power leads to less heat generation which is good for the long-term reliability of a system. This design is not printed and is solely CST based so this does not directly affect this research.

4.0 RESULTS AND DISCUSSION

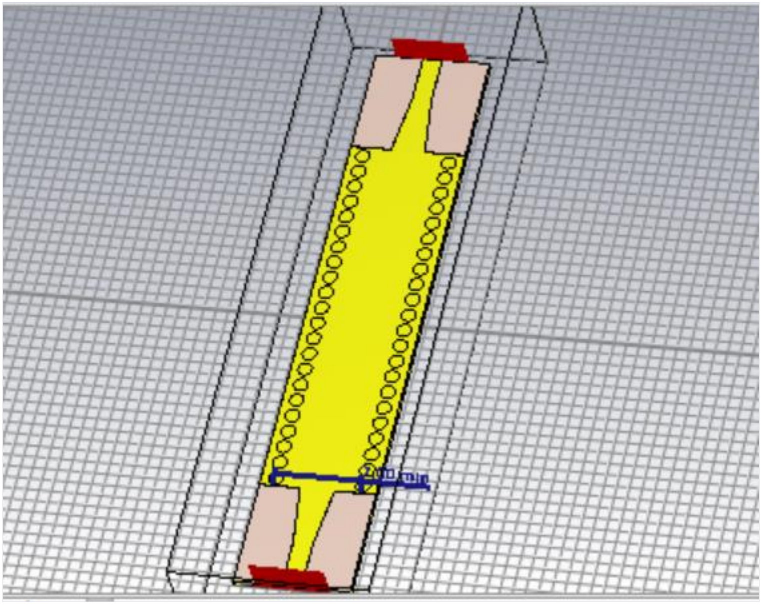


Figure 15 showing the designed SIW transmission line with the desired parameters.

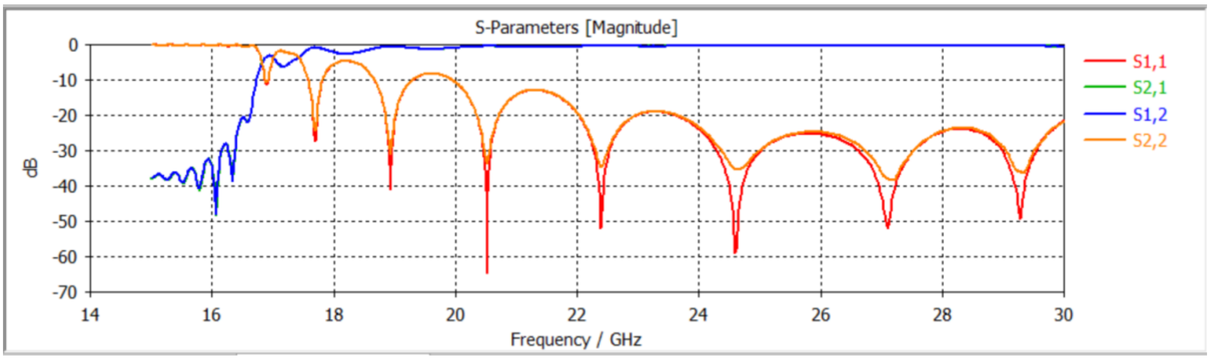


Figure 16 showing the S-Parameters of the SIW structure.

Figure 15 above was the first stage of the design. The structure contains two ports: Ports 1 and Ports 2. There is the taper part which is the transitional element that connects a microstrip line to the SIW. The taper portion gradually changes the width of the microstrip line so that it matches the dimensions of the SIW. This was done to ensure a smooth transition of electromagnetic waves from one guide structure (microstrip line) to another (SIW).

The taper helps convert the mode of the EM waves from the quasi-TEM mode supported by the microstrip to the TE10 mode supported by the SIW. This minimises reflections and losses that happen at the junction between the microstrip and SIW, maximising the efficiency of the system. [54]

In this optimised SIW design, the reflection coefficient S11(red) as seen in Figure 16 falls below -20 dB, and the transmission coefficient S21 approaches 0 dB in the operating frequency band. Insertion loss is minimised in this simulation which gives a good high frequency performance. [40]

In mentioning optimizing the antenna, optimization algorithms are put in place i.e the parametric study.

A parametric sweep was conducted to understand how each parameter impacts performance. This was done by varying one parameter at a time and keeping the others constant. In designing the slot antennas, I chose X1 – which is the distance between the centre of the waveguide and slot in the x-direction, SW – is the width of the slot, SL – is the length of the slot, Y1 – is the distance between the edge of the vias and the centre of the slot and k is the distance between each slot.

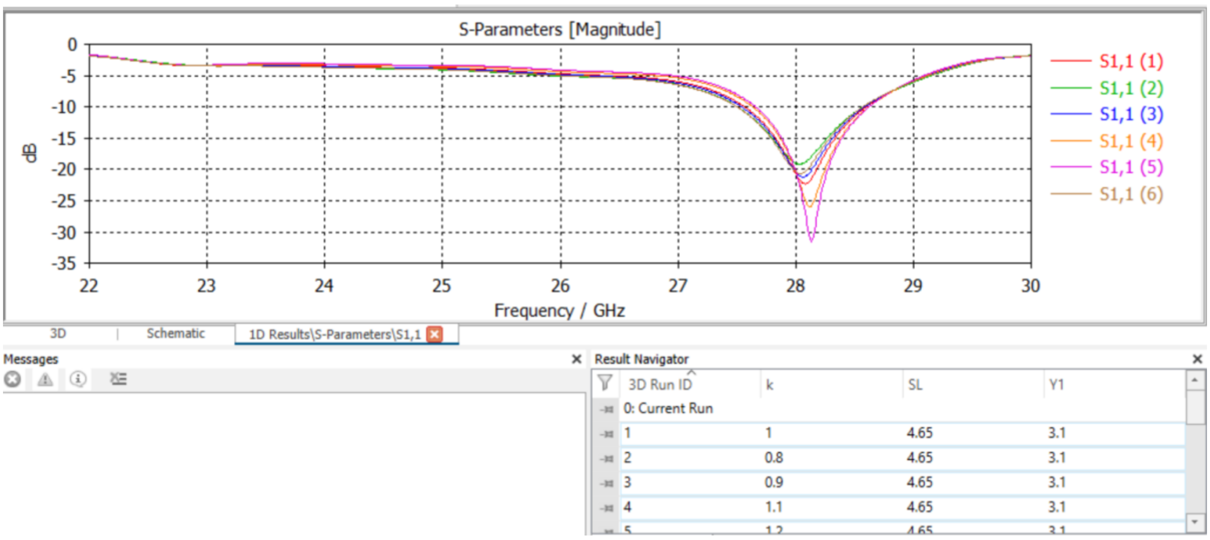


Figure 17 showing the effect of Parametric Sweep on parameter k

Figure 17 above shows the parametric study of the parameter k. As k increases, the dB result increases showing the amount of power reflected back. It goes lower as it increases which is a good sign but not enough reason to increase k as the desired frequency is at 28GHz and this is increasing it from that desired value.

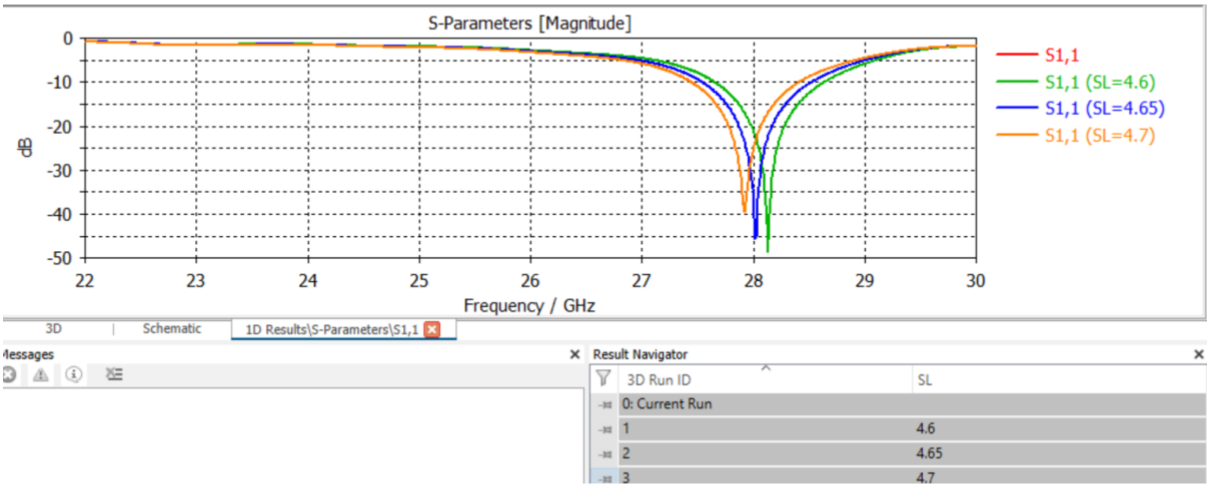


Figure 18 showing the effect of Parametric Sweep on parameter SL

Figure 18 shows how SL changes and as seen above, 4.65 is very ideal as it is right on 28Ghz the desired frequency. This is very easy to be missed but with making the step width change a width of 0.05 every detail and every possible value in the addition or subtraction within the chosen number range will be run.

Far-field results show the radiation pattern of an antenna. The far-field region is the area where the radiation from the antenna appears to be coming from a point source, where the EM wave becomes planar. In this region, the angular field distribution is independent of the distance from the antenna. The far-field results provide information on the performance indicators of the antenna design including:

1. Gain which Measured in dBi (decibels relative to isotropic radiator), it indicates how much power is radiated in a particular direction compared to an isotropic antenna, which radiates power uniformly in all directions.

2. Radiation efficiency which measures how efficiently the antenna converts input power into radiated power.

3. Directivity which quantifies how focused the energy is in a particular direction and is a measure of how 'directional' an antenna's radiation pattern is.

4. Polarization is the orientation of the electric field, which could be linear, circular, or elliptical, is also provided in the far-field results.

5. Beamwidth which describes the angular width of the main lobe of the radiation pattern, usually measured between the half-power (-3 dB) points.

6. Sidelobe Levels are the peaks in the radiation pattern that are not pointing in the main direction of radiation. Lower sidelobe levels are desirable to reduce interference and improve antenna performance. The side lobe label depends on the distance between the slots in the array. This distance differs the conductance that the slot is excited meaning each slot refers to how easily electromagnetic energy can flow or be radiated from that slot. Each slot in an SIW behaves like a radiating element that has a certain "admittance" or "conductance" to electromagnetic waves. [54]

7. Reflection Coefficient S1.1(dB) which is a parameter that measures how well the antenna is impedance-matched to the transmission line. It quantifies the fraction of power that is reflected back towards the source due to impedance mismatch as mentioned earlier.

4.1 SLOT 1

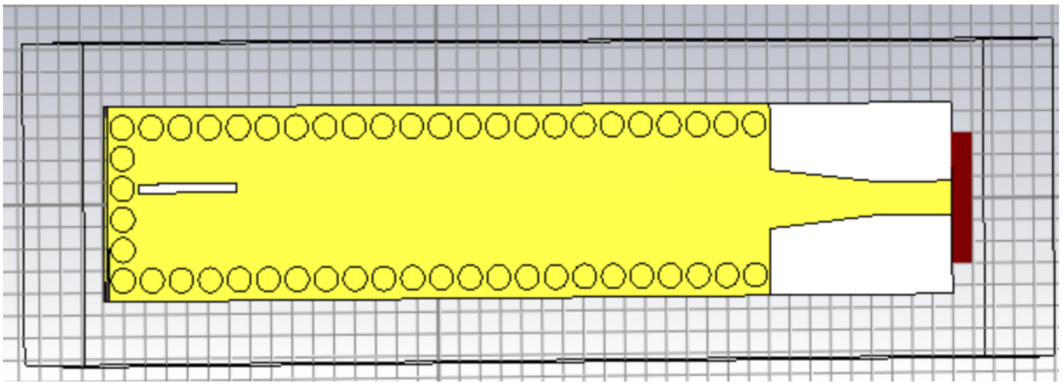


Figure 19 showing the inclusion of slot 1.

The SIW antenna with a single slot is shown above in Figure 19. One side of the microstrip to SIW transition was short-circuited meaning the electrical pathway at the side was closed. Additional vias were added and the taper and feed on the other side was removed. This kept only Port 1 and the only S parameter was S1.1. Four slots were etched on the SIW transmission line in the longitudinal direction. When the power is evenly distributed, each slot is positioned at an equal distance from the SIW's centre. All slots experience the same amplitude and phase excitation. This uniformity leads to symmetrical radiation patterns and is good for applications that require precise control over the transmitted or received signal. [54]

This equal distance is calculated using this formula:

$$Slot\ width = \frac{\lambda g}{20}$$

$$Slot\ length = \frac{\lambda 0}{2\sqrt{\varepsilon r + 1}}$$

$$Equal\ distance = \frac{aSIW}{\pi}\sqrt{sin^{-1}[\frac{1}{NxG}]}$$

[54]

Where

$$aSIW = \frac{a}{\sqrt{\varepsilon r}} + \frac{d^2}{0.95p}$$

Where

$$d < \frac{\lambda g}{5}$$

$$p < 2d$$

Where

$$\lambda g = \frac{1}{\sqrt{\left(\frac{1}{\lambda 0}^2\right) - (\frac{1}{\lambda c}^2)}}$$

[54]

λc is the cut off wavelength

λ0 is the free space wavelength.

In performing these calculations, I got these parameter values for the slots in the final design:

Parameter	Value(mm)
X1	0.74
SW	0.4

SL	4.9
Y1	2.88
k	1.05

Table 4.1 showing parameter values for the slot antennas.

The slots are placed at intervals of one-half wavelength guide (λg) and they are at the peaks of the standing wave pattern within the waveguide ensuring each slot extracts maximum energy from the waveguide for radiation into free space. A standing wave pattern is formed because of the interaction of forward and reflected waves. The peaks have the highest energy.[55]

The slots need to be in the same phase to achieve a coherent wavefront. When all radiators are in phase, the individual electromagnetic waves they produce will interfere with one another. This constructive interference enhances the radiated field and directs it in a specific direction. [55]

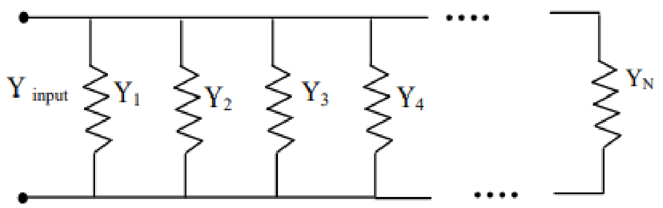


Figure 20 showing the schematic of the slot antenna [55]

As seen in the image above, Yinput = Y1+Y2+Y3+Y4+…+YN [55]. This is the schematic of the slot antenna and as seen, it is in parallel. This is because the input and output impedance are the same as the transmission line has repeating impedance. Each resistor stands for one slot and the admittance is purely resistive that is non-reactive impedance. [55]

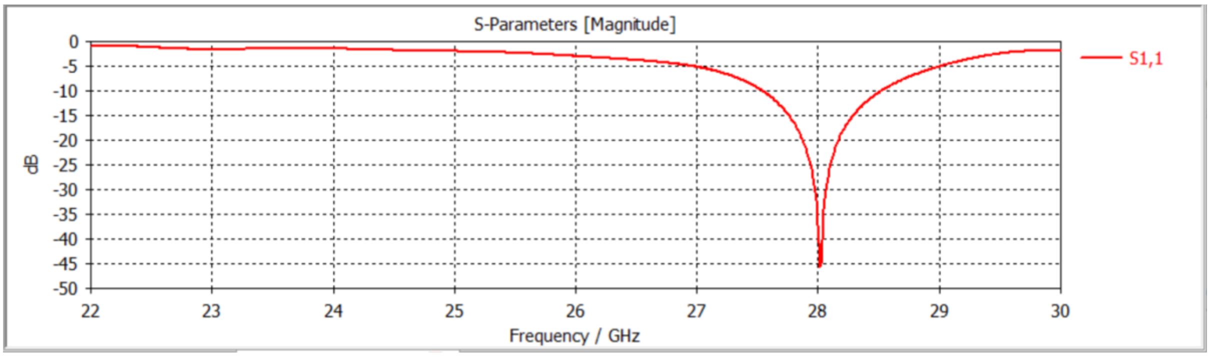


Figure 20 showing S11 results with only slot 1.

Figure 20 above shows the S1.1 results diagram with the inclusion of one slot. This is an excellent result as it indicates a very good impedance match between the slot antenna and transmission line at 28Ghz. This result being at -45dB indicates that an extremely small amount of power is being reflected back to the source which means almost all of the power is being transmitted into the antenna.

The bandwidth is narrow which is also an indicator of the excellent matching condition but only over a small range of frequencies around 28Ghz.

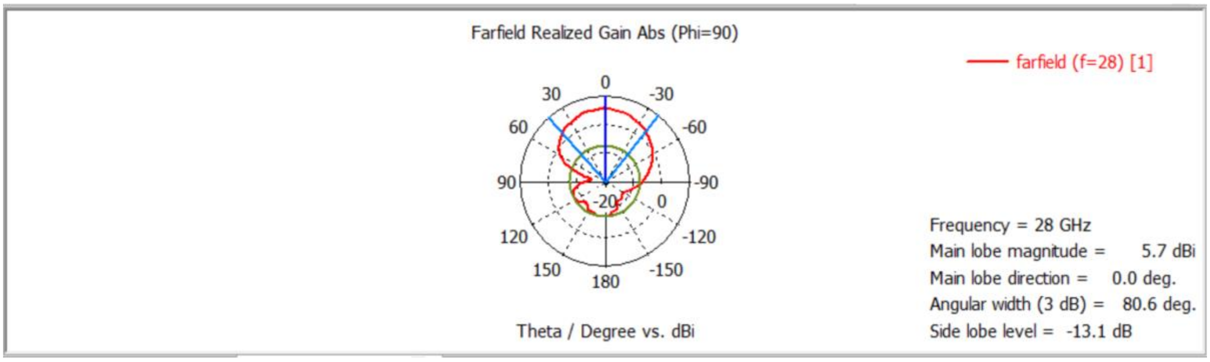


Figure 21 showing the 1D Farfield results of slot 1.

As seen in Figure 21, the main lobe level is 5.7dB, which means that the antenna amplifies the signal 5.7dB more than an isotropic antenna, which radiates equally in all directions.

The Side lobe level is -13.1dB. This value is the amplitude of the side lobes relative to the main lobe. The value being -13.1dB means the side lobes are weaker than the main lobe, which is a good thing for reducing interference from or to other directions.

The angular width at 3dB is the beamwidth of the main lobe. In this result the main lobe covers an angular range of 80.6 degrees (as seen in the blue lines in Figure 21) where the power drops to half (or -3 dB) of its peak value.

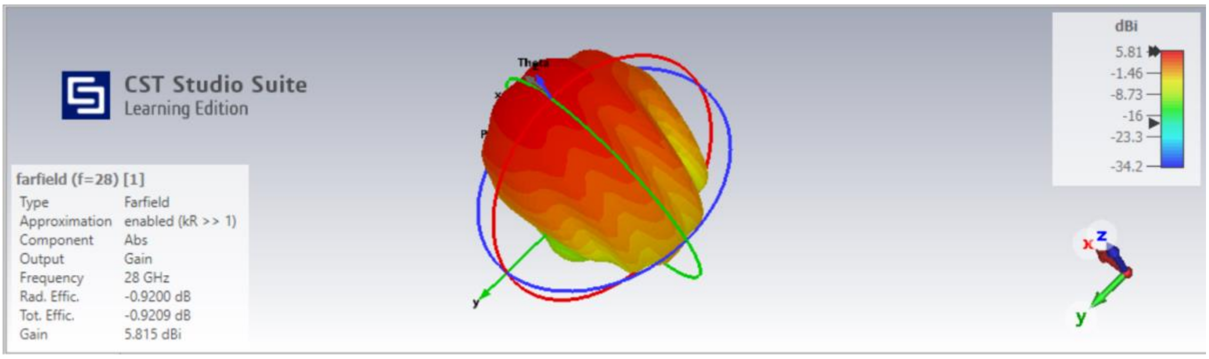


Figure 22 showing the 3D Farfield results of slot 1 (gain)

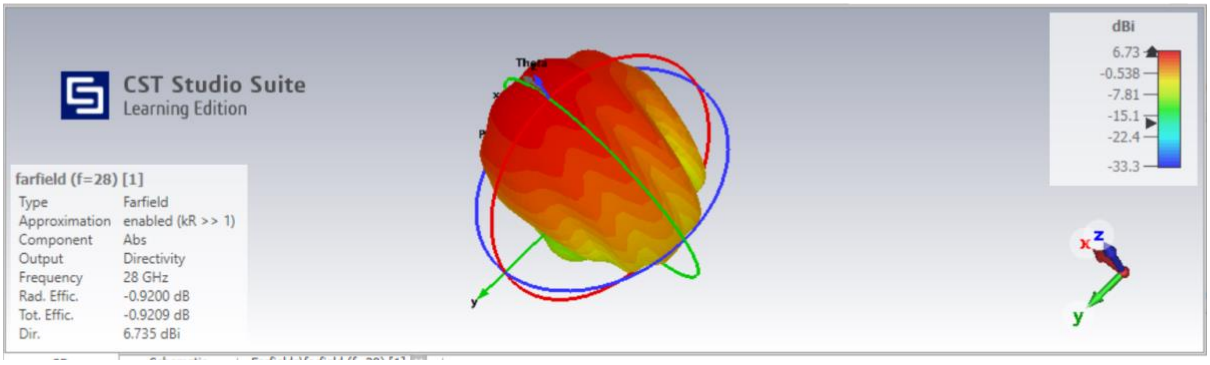


Figure 23 showing the 3D Farfield results of slot 1(Directivity)

In Figure 22 we can observe the 3D Farfield outcomes of slot 1 regarding gain. It indicates that the antenna performs better in directing signals compared to a radiator although, its gain is not exceptionally high(5.815dBi). A higher gain antenna focuses energy tightly in directions but becomes more sensitive to orientation. The moderate gain showcased here strikes a balance between focusing power and maintaining coverage.

The directivity; 6.735dBi indicates that the antenna has a focused radiation pattern, meaning it directs energy more in one direction than others.

The radiation efficiency (-0.9200dB) and total efficiency(-0.9209dB) are negative values which means that some power is being lost, but these losses are relatively small, which is good.

The far-field diagram shows a broad main lobe given the 3dB beamwidth of 80.6 degrees and a gain of 5.815 dBi. The minor lobes are small due to the side lobe level being -13.1dB.

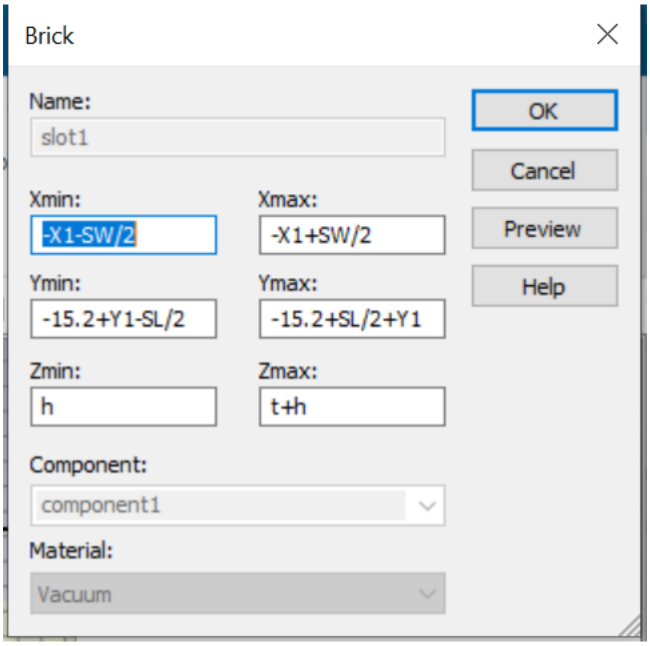


Figure 24 showing the parameters used to designing the first slot antenna.

4.2 SLOT2

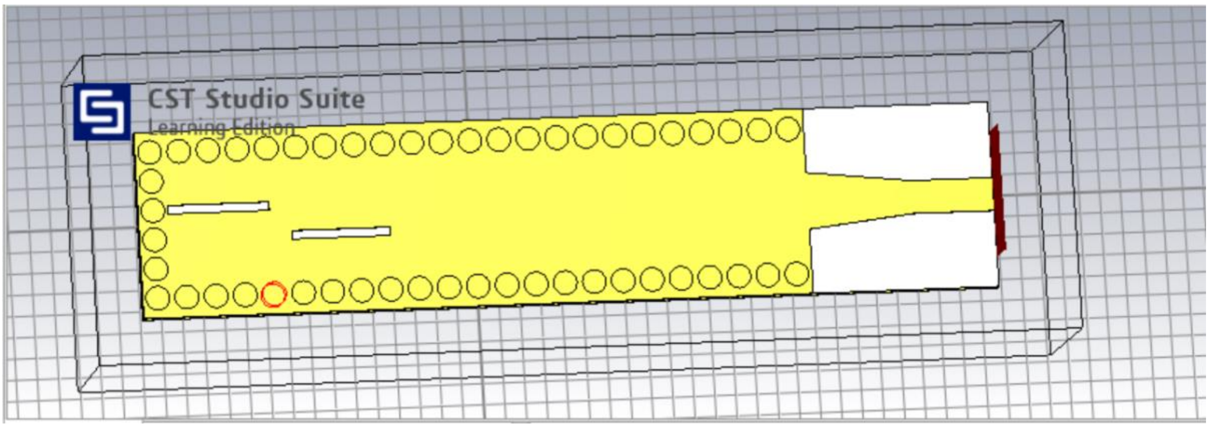


Figure 25 showing the inclusion of slot 2.

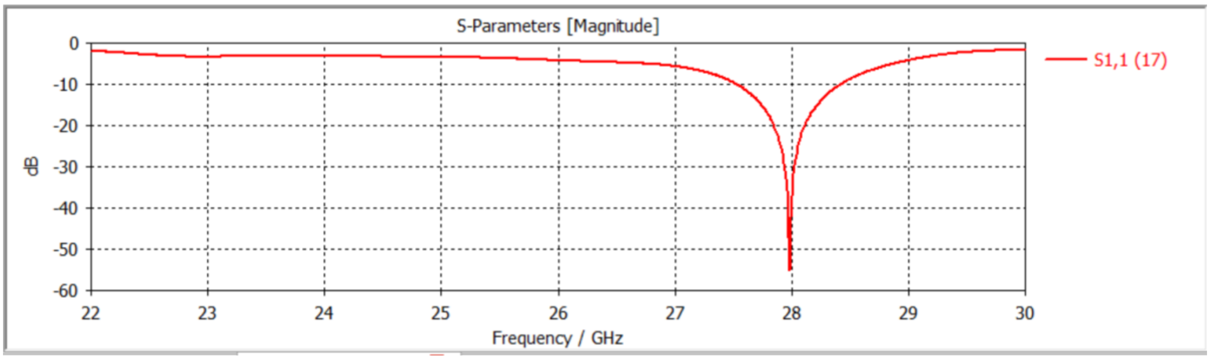


Figure 26 showing S11 results with slot 1 and 2.

Figure 26 above shows how good the inclusion of slot 2 is. The result being at -56dB which is even lower than slot 1 shows a smaller amount of power is being reflected back to the source and most of power is transmitted into the antenna.

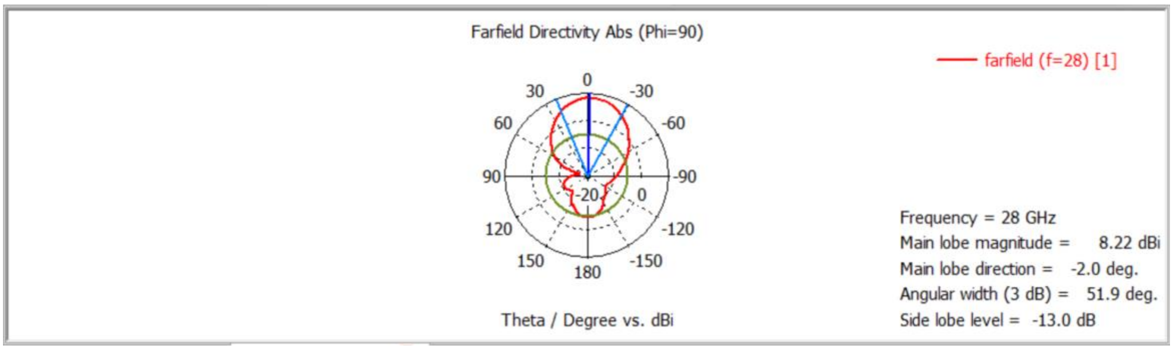


Figure 27 showing the 1D Farfield results of slot 2.

The main lobe magnitude of 8.22 dBi shows that the maximum power radiated from the antenna is concentrated within this lobe. The magnitude shows that the antenna focuses energy in its intended direction.

A 3dB beamwidth of 51.9 degrees is narrower compared to the previous 80.6 degrees, indicating a more focused radiation pattern. This means the antenna is more directional in its main lobe as mentioned above.

The side lobe level of -13.0 dB shows the strength of the secondary lobes in comparison to the main lobe. In this case, the side lobes radiate at a power level 13 dB below the main lobe, which is quite good in this application.

Far-Field Pattern Directivity Abs (Phi=90) Diagram Description:

The "bulb-like" shape in figure 27 shows the antenna's main lobe and it is where the antenna effectively radiates or receives energy.

The green circle is the origin of the radiation pattern. All metrics are relative to this point, so it is the point of reference for the radiation pattern.

4.3 SLOT 3

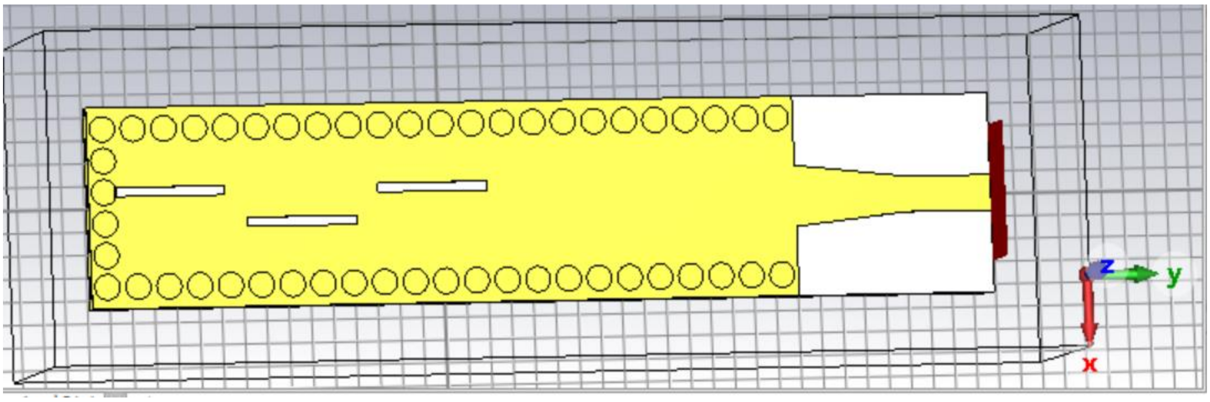


Figure 28 showing the inclusion of slot 3.

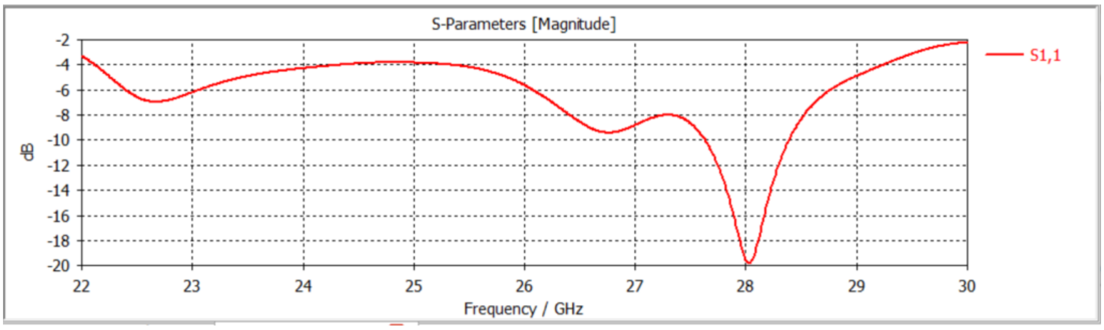


Figure 29 showing S11 results with slot 1,2 and 3.

Figure 29 is the result gotten after the inclusion of slot 3 and after performing the parametric sweep.

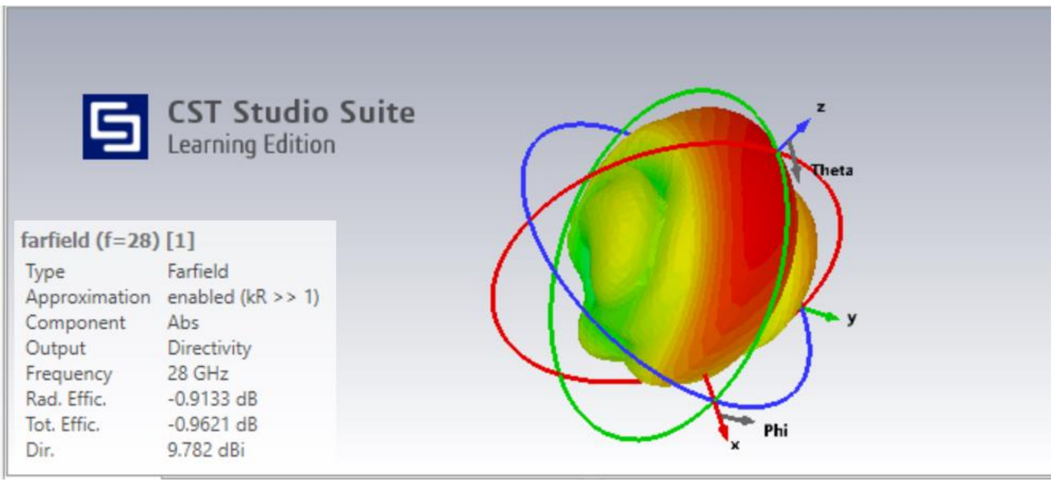


Figure 30 showing the 3D Farfield results of slot 3 (Directivity)

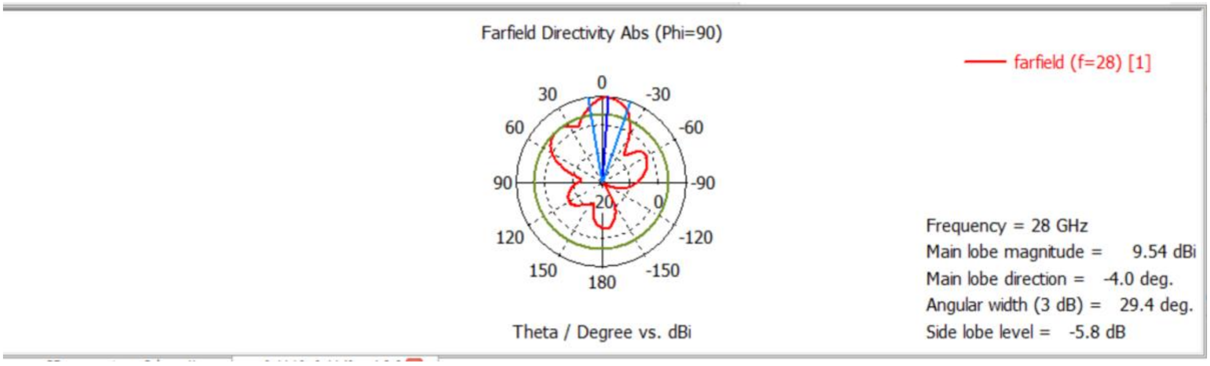


Figure 31 showing the 1D Farfield results of slot 3.

A side lobe level of -5.8 dB means that the side lobes are not really suppressed and are close in level to the main lobe. This leads to a higher interference and decreased antenna performance. Lower side lobe levels are preferable for minimising interference and enhancing this systems performance.

The antenna has a high gain in the main lobe (9.54dBi), which is good for long-range communication. The antenna gain of 8.869 is also high, which means it is efficient at converting input power to radiated power in the direction of the main lobe.

From these results it seems that only a small percentage of power is being lost as heat or in other forms of non-useful radiation.

4.4 SLOT4

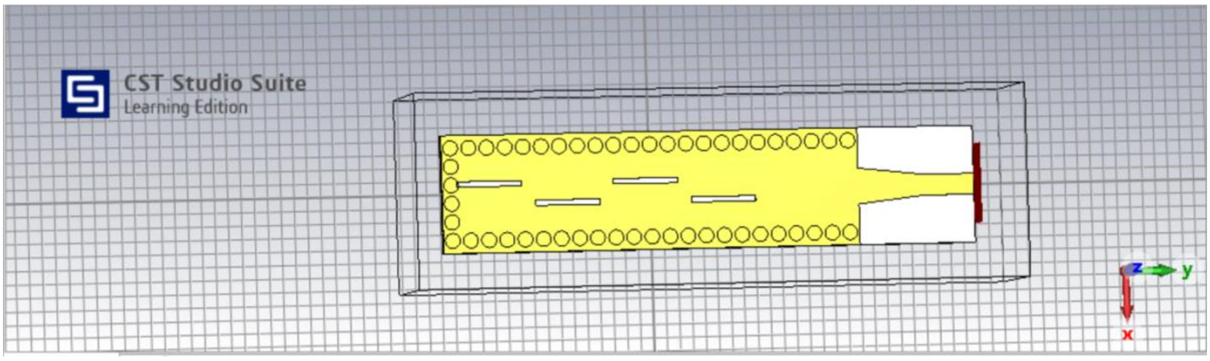


Figure 32 showing the inclusion of slot 4.

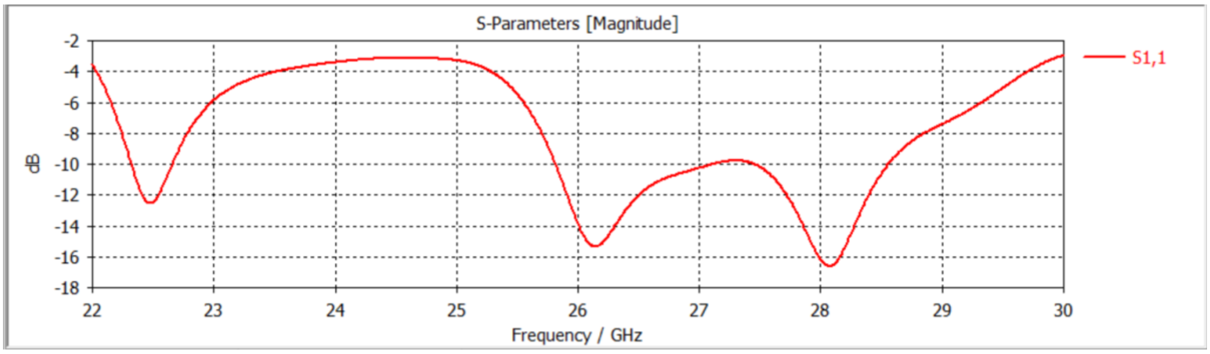


Figure 33 showing S11 results with slot 1,2,3 and 4.

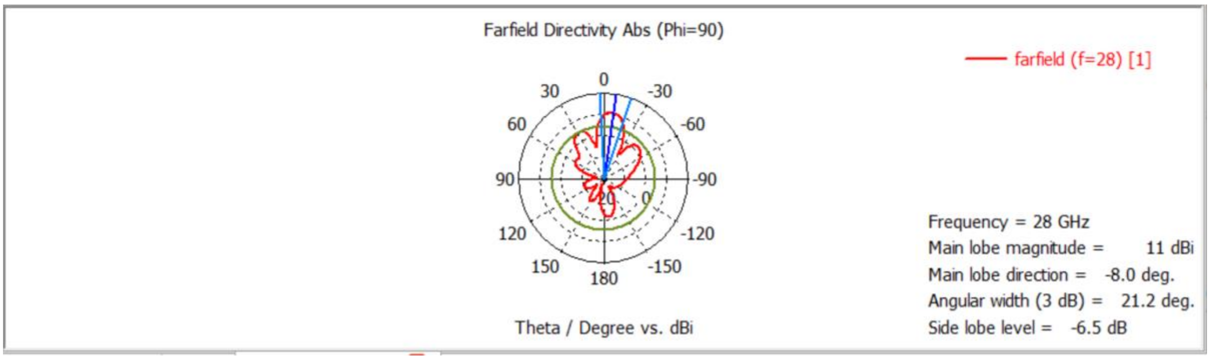


Figure 34 showing the 1D Farfield results of slot 4.

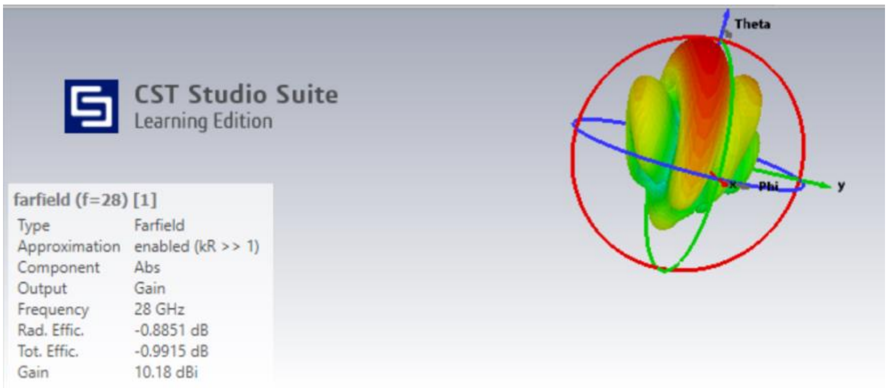


Figure 35 showing the 3D Farfield results of slot 3 (Gain)

The final design includes all four slots, in a 1x4 array which is shown in Figure 32 with an S1.1 value of -16.4dB. The figure indicates that the antenna reflects a small amount of power back to the source. While it may not be as good as achieving 20 dB or lower it still performs well since about 1.5% of the power is reflected back and the majority is transmitted into the antenna.

The directivity of 11.07 dBi demonstrates that this antenna concentrates radiated energy into a specific direction and does not uniformly radiate it in all directions.

The closeness between the gain and directivity values (10.18 dBi and 11.07 dBi) confirms that this design exhibits a high radiation efficiency. This is because Gain = Directivity × Efficiency. The antenna converts input power into radiated power also providing a well-matched system with low reflection and higher radiated power.

Having a sidelobe level of -6.5 dB means that this design has strong sidelobes, which makes it more susceptible to interference from all directions. It would have been preferable to have a lower sidelobe level.

With an angular width of 21.2 degrees at the 3 dB point, this design has a focused main beam. As the beamwidth is narrower it means that the antenna is more directional.

5.0 CHALLENGES/ERRORS ENCOUNTERED

Initially the parameters were:

Parameters	Value (mm)
w	7.65
LG	32
LT	10
h	0.508
t	0.035
we	1.57
wt	3.053
d	0.8
s	1.15

Table 5.1 showing initial parameter values.

These were the parameters for the initial SIW transmission line design.

I was presented with these S11 results:

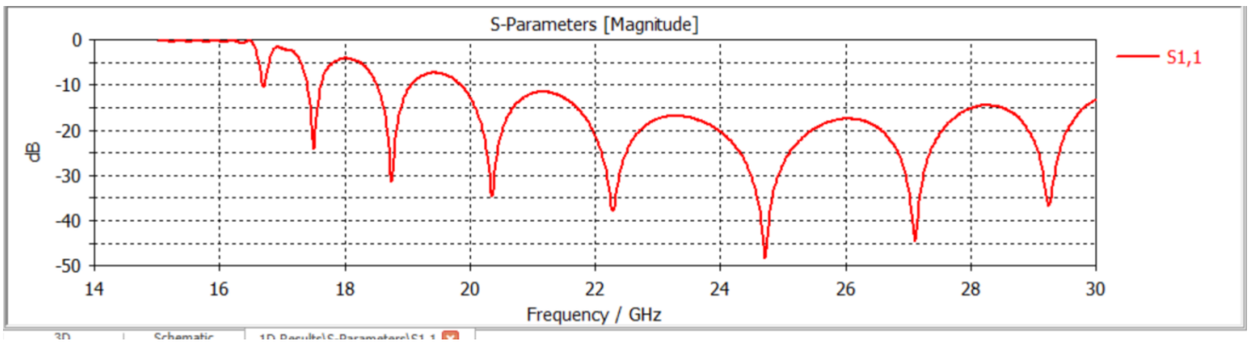


Figure 36 showing initial SIW wrong results.

As seen in Figure 36 above, this dB value is above -20dB. As a starting point this is not good enough as the desired S11 results should be below -20dB for good values in the inclusion of slots.

The mesh cells available to me as a student was only 100,000. Mesh cells discretize the geometry (break down a continuous geometric shape into a finite number of smaller pieces) for computer simulations and numerical analysis. Having a limit of 100,000 mesh cells was restricting therefore I did not include the 4x4 array as this limited that chance.

Regarding the 4x4 array time was also a problem, and if it wasn't along with more mesh cells granted, a 4x4 array would have been designed. I would have liked to have a more suppressed side lobe as I was not too satisfied with -6.5dB. With enough time, I believe it would have turned out better. It would also be beneficial to compare this design's performance with other existing antennas for the same applications to identify unique strengths and weaknesses better.

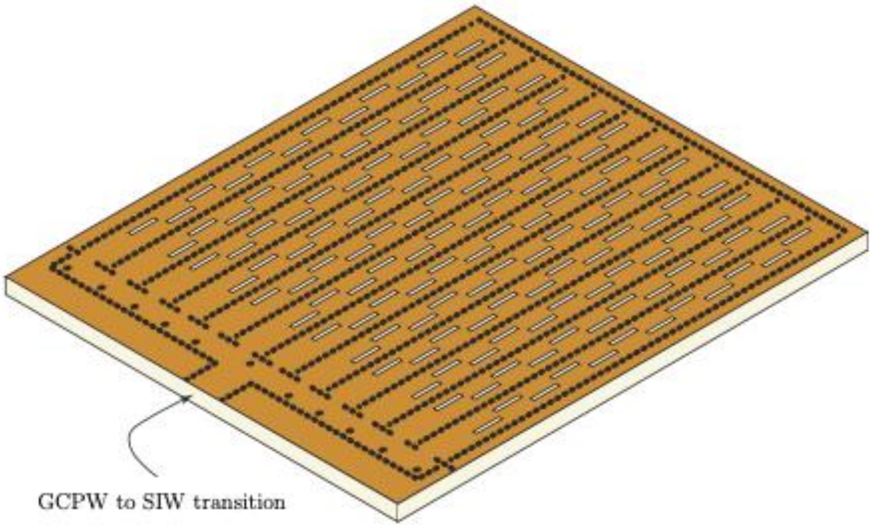


Figure 37 High gain planar array antenna [9]

Figure 37 above is a high gain planar antenna array. The operating frequency for this design is at 60 GHz with a maximum gain of 22 dB.

I would have liked to fabricate a prototype once the design was optimized on paper and through simulations. Then test the prototype in a controlled environment to measure parameters like VSWR, impedance, and radiation patterns.

6.0 PROJECT MANAGEMENT

Project management is the process of planning, executing, controlling, and closing a project to achieve set goals and objectives within a specified time frame. Waterfall methodology was the project planning method used for this project.

The project was divided into phases/objectives, and each phase length depended on the deliverables. Waterflow methodology has a linear flow, as I moved from one phase to the next only when the previous phase was complete.

In waterfall methodology, each phase must be completed before moving to the next and as seen, the SIW transmission line was completed and optimised before the completing slot 1 then slot 2, slot 3 and then slot 4 consecutively.

7.0 FUTURE DEVELOPMENTS

Future developments should see to it that machine learning and AI is used to optimise the antennas design parameters for more accuracy.

Researchers are trying to make the next generation of phased arrays very adaptive and flexible with reconfigurable antenna elements.

7.1 CONCLUSION

This project shows the process of designing and implementing mm-Wave high gain antenna array. An SIW design was optimised for operation at 28 GHz which is a good frequency is for modern 5G/6G communications. The SIW design consists of a microstrip line to SIW transition. It used a tapered geometry for the mode conversion. The dimensions of this transition, including the spacing between vias and their diameters, were calculated using researched calculations.

The final simulation results showed the system's efficiency, with an S11 value of -16.4 dB, which is a very low reflection coefficient and with good impedance matching. This value is approaching -20 dB therefore showing good transmission line to antenna coupling. Almost all the power is transmitted into the antenna, which means there are fewer losses. The side lobe level of -6.5 dB and a 3dB angular width of 21.2 degrees, shows a decently directional radiation pattern.

The capped mesh cells value was a limitation faced and forced certain constraints on the analysis. The mesh cell count was around 100,000 as it is student based.

With more time, the antenna array would have been extended to a 4x4 array and fine-tuning the SIW dimensions based on real-world testing.

In summary, the objectives were achieved, and a high-gain antenna array was designed and will hopefully be used in future applications.

CST filenames for easy identification:

SIW Transmission lineslot again1 -SIW Transmission line no slot

Siwcst41_, x1=0.7, fy1 =3.1, sl=4.65 redo -Inclusion of one slot

Siwcst41_, x1=0.7, fy1 =3.1, sl= 4.7, k=1 almost correct slot 2trial -Inclusion of 2 slots

Siwcst41_, x1=0.7, fy1 =3.3, sl=4.7, k=1 correct slot 3try -Inclusion of 3 slots

Final Design -All four slots included.

REFERENCES

[1] Malik, B.T., Robertson, I.D. and Raza, Z.S.A. (no date) Millimetre-waves antenna arrays for 5G and wireless power transfer, Millimetre-waves Antenna Arrays for 5G and Wireless Power Transfer. dissertation. Available at: https://etheses.whiterose.ac.uk/25635/.

[2] Tarafder, P. and Choi, W. (2022) MAC protocols for mmWave Communication: A Comparative Survey, Sensors (Basel, Switzerland). Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9144311/ (Accessed: 11 September 2023).

[3] Edu, O. and ALKARAKI, S. (2023) 'MM-WAVE HIGH GAIN ANTENNA ARRAY FOR 5G/6G WIRELESS COMMUNICATION'. Nottingham: University of Nottingham.

[4] James Clerk Maxwell (no date) Wikipedia. Available at: https://en.wikipedia.org/wiki/James_Clerk_Maxwell (Accessed: 31 July 2023).

[5] Learning, L. (no date) *Physics*, *Maxwell's Equations: Electromagnetic Waves Predicted and Observed | Physics*. Available at: https://courses.lumenlearning.com/suny-physics/chapter/24-1-maxwells-equations-electromagnetic-waves-predicted-and-observed/ (Accessed: 11 September 2023).

[6] *Marconi's first wireless transmission* (no date) *Marconi's First Wireless Transmission I Oxford Open Learning*. Available at: https://www.ool.co.uk/blog/marconis-first-wireless-transmission/#:~:text=On%20the%2012th%20December%201901,the%20curvature%20of%20the%20earth. (Accessed: 11 September 2023).

[7] Greedy, S. (2023) 'EEEE3087 Mobile Technologies Lecture 1 - EO1: Introduction ', *Introduction*. *Introduction*, Nottingham: University of Nottingham, 30 January.

[8] Mishra, H., Gupta, R. and Upadhyay, S.K. (2019) *Systematic review of congestion handling techniques for 802.11 wireless networks*, 16 September.

[9] Chandrappa, D.K. and Sebak, A.R. (2019) *Substrate integrated waveguide based millimeter wave antennas*. thesis.

[10] Aziz, I., Dancila, D. and Viikari, V. (no date) *Ultra-wideband millimeter-wave antenna arrays and front-end systems for high data rate 5G and high energy physics applications*. thesis.

[11] K. Carver and J. Mink, "Microstrip antenna technology," in IEEE Transactions on Antennas and Propagation, vol. 29, no. 1, pp. 2-24, January 1981, doi: 10.1109/TAP.1981.1142523.

[12] Bevelacqua, P. (no date) *Microstrip (patch) antennas*, *Microstrip Antennas: The Patch Antenna*. Available at: https://www.antenna-theory.com/antennas/patches/antenna.php (Accessed: 13 September 2023).

[13] *Dipole antenna* (2023) *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Dipole_antenna (Accessed: 13 September 2023).

[14] *Antenna (radio)* (2023) *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Antenna_(radio) (Accessed: 13 September 2023).

[15] Nunna, P.K., Kuchhal , P. and Varshney, A. (no date) ‘Wearables and Implantables in MICS- A Review’, *Alexandria Engineering Journal* [Preprint]. doi:https://doi.org/10.1016/j.aej.2023.07.060 .

[16] Undefined (2021) *UHF vs. VHF - 5 differences between two way radios, Amerizon Wireless*. Available at: https://www.amerizonwireless.com/blog/uhf-vs-vhf (Accessed: 13 September 2023).

[17] *Antenna theory - slot* (no date) *Online Courses and eBooks Library*. Available at: https://www.tutorialspoint.com/antenna_theory/antenna_theory_slot.htm#:~:text=Babinet’s%20principle%20states%20that%2D%20%E2%80%9CWhen,when%20there%20is%20no%20screen%E2%80%9D (Accessed: 13 September 2023).

[18] Alsager, A.F. (2011) *Design and Analysis of Microstrip Patch Antenna Arrays* . thesis. Available at: https://www.diva-portal.org/smash/get/diva2:1312395/FULLTEXT01.pdf (Accessed: 16 September 2023).

[19] *Slotted array antennas: Your guide to the top benefits* (2019) *Rantec Microwave Systems*. Available at: https://www.rantecantennas.com/blog/slotted-array-antennas-your-guide-to-the-top-benefits/ (Accessed: 16 September 2023).

[20] G. Q. Luo, Z. F. Hu, Y. Liang, L. Y. Yu and L. L. Sun, "Development of Low Profile Cavity Backed Crossed Slot Antennas for Planar Integration," in IEEE Transactions on Antennas and Propagation, vol. 57, no. 10, pp. 2972-2979, Oct. 2009, doi: 10.1109/TAP.2009.2028602.

[21] WatElectronics (2022) *Yagi Uda Antenna : Basics, working, design and its applications, WatElectronics.com*. Available at: https://www.watelectronics.com/yagi-uda-antenna/ (Accessed: 16 September 2023).

[22] Wu, Y. *et al.* (2016) *Graphene-based Yagi-UDA antenna with reconfigurable radiation patterns, AIP Publishing*. Available at:

https://pubs.aip.org/aip/adv/article/6/6/065308/22631/Graphene-based-Yagi-Uda-antenna-with (Accessed: 16 September 2023).

[23] Matan (2023) *Parabolic reflector antenna: How it works, application & advantages*, *Electricity*. Available at: https://www.electricity-magnetism.org/parabolic-reflector-antenna/ (Accessed: 16 September 2023).

[24] Ahmed, M. *et al.* (2014) 'A Review of Strategies for Parabolic Antenna Control', *Australian Journal of Basic and Applied Sciences* [Preprint]. Available at: https://www.ajbasweb.com/old/ajbas/2014/May/135-148-May14.pdf (Accessed: 16 September 2023).

[25] Dubey, N. (2023) *Horn antenna - electronics club antenna & wave propagation electronics club*, *Electronics Club*. Available at: https://electronics-club.com/horn-antenna/ (Accessed: 16 September 2023).

[26] Edu, O. (2023) *MM-WAVE HIGH GAIN ANTENNA ARRAY FOR 5G/6G WIRELESS COMMUNICATION ppt (interimppt)*.

[27] Afaz Uddin Ahmed, M. T. Islam, Rezaul Azim, Mahamod Ismail, Mohd Fais Mansor, "Microstrip Antenna Design for Femtocell Coverage Optimization", *International Journal of Antennas and Propagation*, vol. 2014, Article ID 480140, 8 pages, 2014. https://doi.org/10.1155/2014/480140

[28] *Yagi–Uda Antenna* (2023) *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Yagi%E2%80%93Uda_antenna (Accessed: 03 July 2023).

[29] Sreelakshmi, K. *et al.* (2017) 'Linear Array Yagi-UDA 5G antenna for vehicular application', *International Journal of Engineering & Technology*, 7(1.1), p. 513. doi:10.14419/ijet.v7i1.1.10158.

[30] *Horn antenna* (2023) *Wikipedia*. Available at:

https://en.wikipedia.org/wiki/Horn_antenna (Accessed: 03 July 2023).

[31] *Satellite television* (2023) *Wikipedia*. Available at:

https://en.wikipedia.org/wiki/Satellite_television (Accessed: 03 July 2023).

[32] *Parabolic antenna* (2023) *Wikipedia*. Available at:

https://en.wikipedia.org/wiki/Parabolic_antenna (Accessed: 03 July 2023).

[33] Khan, J. *et al.* (2022) 'Design of a millimeter-wave MIMO ANTENNA ARRAY FOR 5G communication terminals', *Sensors*, 22(7), p. 2768. doi:10.3390/s22072768.

[34] Bhavsar, T. (2023) *What is slot antenna? working and application of slot antenna.*, *Easy Electronics*. Available at: https://easyelectronics.co.in/slot-antenna/#:~:text=Low%20cost%3A%20Slot%20antennas%20can,where%20interference%20must%20be%20minimized (Accessed: 16 September 2023).

[35] Matan (2023) *Slot antenna: How it works, application & advantages*, *Electricity*. Available at: https://www.electricity-magnetism.org/slot-antenna/ (Accessed: 16 September 2023).

[36] Bevelacqua, P. (no date) *VSWR (Voltage Standing Wave Ratio)*, *VSWR*. Available at: https://www.antenna-theory.com/definitions/vswr.php (Accessed: 16 September 2023).

[37] *What is meant by the VSWR of an antenna?* (2023) *MobileMark*. Available at: https://www.mobilemark.com/about/faq/what-is-meant-by-the-vswr-of-an-antenna/#:~:text=A%20VSWR%20value%20under%202,for%20a%20frequency%20of%20interest. (Accessed: 16 September 2023).

[38] Gugle, G.L.E. (2023) 'RF Transmission/ Reception Feed line and Standing Wave Ratio (SWR) ', *Marine Corps Electricity and Electronic Training Series (MCEETS)*, 16

September. Available at: http://rfcec.com/RFCEC/Section-3%20-%20Fundamentals%20of%20RF%20Communication-Electronics/27%20-%20RF%20FEEDLINE/RF%20Feedline%20-%20Coaxial%20Cable%20VSWR%203%20(By%20Larry%20E.%20Gugle%20K4RFE).pdf (Accessed: 16 September 2023).

[39] F. Parment, A. Ghiotto, T. -P. Vuong, J. -M. Duchamp and K. Wu, "Air-Filled Substrate Integrated Waveguide for Low-Loss and High Power-Handling Millimeter-Wave Substrate Integrated Circuits," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 4, pp. 1228-1238, April 2015, doi: 10.1109/TMTT.2015.2408593.

[40] *Substrate-integrated waveguide* (2023) *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Substrate-integrated_waveguide (Accessed: 16 September 2023).

[41] Djerafi, T., Doghri, A. and Wu, K. (2015) ‘Substrate integrated waveguide antennas’, *Handbook of Antenna Technologies*, pp. 1–60. doi:10.1007/978-981-4560-75-7_57-1.

[42] Y. Shi, W. J. Wang and T. T. Hu, "A Transparent SIW Cavity-Based Millimeter-Wave Slot Antenna for 5G Communication," in IEEE Antennas and Wireless Propagation Letters, vol. 21, no. 6, pp. 1105-1109, June 2022, doi: 10.1109/LAWP.2022.3158418.

[43] Rayas-Sanchez, J.E. and Gutierrez-Ayala, V. (2008) ‘A general EM-based design procedure for single-layer substrate integrated waveguide interconnects with microstrip transitions’, *2008 IEEE MTT-S International Microwave Symposium Digest* [Preprint]. doi:10.1109/mwsym.2008.4632999.

[44] *Waveguide Frequency Bands with Interior Dimensions* (no date) *miwv.com*. Available at: https://miwv.com/images/Waveguide-Chart.pdf (Accessed: 16 September 2023).

[45] Arya, V. and Garg, T. (2022) 'Design and analysis of substrate integrated waveguide', *SSRN Electronic Journal* [Preprint]. doi:10.2139/ssrn.4159620.

[46] Khalid, N. (2018) *K-band Substrate Integrated Waveguide (SIW) coupler - iopscience*, *iopscience.iop.org*. Available at: https://iopscience.iop.org/article/10.1088/1757-899X/341/1/012014 (Accessed: 16 September 2023).

[47] *1.2.1.2. loss tangent* (no date) *Intel*. Available at: https://www.intel.com/content/www/us/en/docs/programmable/683883/current/loss-tangent.html#:~:text=Loss%20tangent%20(tan(%CE%B4)),the%20dissipation%20factor%20(Df). (Accessed: 16 September 2023).

[48] Balde, J. and Messner, G. (1987), "Low Dielectric Constant—The Substrate of the Future", *Circuit World*, Vol. 14 No. 1, pp. 11-14. https://doi.org/10.1108/eb043930

[49] (No date) *RT/duroid® 5880 laminates*. Available at: https://www.rogerscorp.com/advanced-electronics-solutions/rt-duroid-laminates/rt-duroid-5880-laminates (Accessed: 16 September 2023).

[50] Agrawal , M. (2020) *CST_SUBSTRATE integrated waveguide_introduction*, *YouTube*. Available at: https://www.youtube.com/watch?v=pSOOsPnPpiY&t=7s (Accessed: 02 July 2023).

[51] *The applications and advantages of ka-band frequency* (2022) *Cadence*. Available at: https://resources.system-analysis.cadence.com/blog/msa2022-the-applications-and-advantages-of-ka-band-frequency (Accessed: 16 September 2023).

[52] *Ka-Band vs. Ku-Band: Everything you should know* (2023) *Get SAT*. Available at: https://www.getsat.com/knowledge-base/ku-band-vs-ka-band/ (Accessed: 16 September 2023).

[53] Khair, N. Yusof, N. Wahab, Y. Bari, B. Ayob, N. and Zolkapli, M. Substrate-integrated waveguide (SIW) microwave sensor theory and model in characterising dielectric material: A review, Sensors International, Volume 4, 2023, 100244, ISSN 2666-3511, https://doi.org/10.1016/j.sintl.2023.100244. (https://www.sciencedirect.com/science/article/pii/S2666351123000189)

[54] Bharath, K. *et al.* (2022) 'High performance millimeter wave SIW slotted array antenna', *Progress In Electromagnetics Research C*, 125, pp. 15–23. doi:10.2528/pierc22072508.

[55] Keltouma , N. and Mehdi, D. (2013) 'Design of substrate integrated Waveguide single longitudinal slot antenna', *International Journal of Engineering Research & Technology (IJERT),* 2(11). Available at: https://www.ijert.org/research/design-of-substrate-integrated-waveguide-single-longitudinal-slot-antenna-IJERTV2IS110317.pdf (Accessed: 01 July 2023).