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DESIGN AND IMPROVEMENT OF HYBRID METAL-GRAPHENE MICROSTRIP ANTENNA FOR INDOOR APPLICATIONS

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Master's Thesis

Supervisor

Asst. Prof. Dr. Oğuz KARAN

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The thesis titled DESIGN AND IMPROVEMENT OF HYBRID METAL-GRAPHENE MICROSTRIP ANTENNA FOR INDOOR APPLICATIONS prepared by ALI KAREEM NAJIM AL-ASADI and submitted on 27/12/ 2023 has been **accepted unanimously** for the degree of Master of Science in Electrical and Computer Engineering

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Ali Kareem Najim AL-ASADI

Signature

DEDICATION

Firstly, I express my gratitude to Allah Almighty for endowing me with the power of the mind, good health, strength, guidance, knowledge, and skills that enabled me to complete this study.

This thesis is dedicated wholeheartedly:

To my beloved father, Dr. Kareem Al-Asadi, who serves as my constant source of inspiration. He has consistently reminded me that every success in my life is a cherished gift for him.

To my mother, Rajaa Al-Aboodi, whose unwavering support has been a testament to pure and nurturing love.

In memory of my dear brother, Dr. Mohammed Kareem, whose soul was taken by a tragic car accident. I dedicate my success to him, knowing that if he were here, he would have been my foremost supporter.

To my elder brother, Major Anmar Kareem Al-Asadi, an officer whose presence provides me with strength, resilience, and happiness. Words fall short in describing his significance. I extend my heartfelt thanks for being a constant pillar of support. My success is dedicated to you.

Lastly, to my friends who have served as my most enthusiastic cheerleaders throughout this journey.

ABSTRACT

DESIGN AND IMPROVEMENT OF HYBRID METAL-GRAPHENE MICROSTRIP ANTENNA FOR INDOOR APPLICATIONS

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In recent years, wireless communications have gained significant prominence in our daily lives, offering a convenient and efficient means of transmitting information without the need for physical connections. This advancement has revolutionized the way tasks are performed and communication is carried out, facilitating seamless interactions over substantial distances using electromagnetic waves. The distinct advantage of wireless communication lies in its accessibility and adaptability, particularly in locations where conventional wired connections are impractical. As the reliance on wireless networks has grown, there has been a surge in connected devices and applications. However, this has led to network congestion, subsequently affecting data transmission speed. To counteract this challenge, network operators have explored solutions like utilizing higher frequencies to cater to the increasing demand for faster data transmission. The antenna plays a pivotal role within wireless communication systems, acting as a vital component. Among the various antenna types, microstrip antennas have gained prominence. Yet, they often exhibit limitations such as low gain and restricted bandwidth. Addressing these concerns becomes imperative. This study focuses on the enhancement of microstrip patch antennas (MPAs), specifically from rectangular and circular patches. The goal is to optimize their performance for operation at 62 GHz, catering to personal network applications within indoor environments.

The simulation and optimization processes are carried out using CST Antennas modeling software.

To enhance the bandwidth of the MPAs, a creative approach involving graphene flakes is employed. These flakes are strategically placed within engraved slots on the antenna patch. This introduces tunability to the antenna's frequency response, making it adaptable to applied voltages. Various slot shapes are explored to assess their impact on antenna performance. The simulation results highlight the effectiveness of this approach. The antennas exhibit robust performance and noteworthy tuning capabilities across multiple frequency bands, including 62 GHz, 59.545 GHz, 58.02 GHz, 53.21 GHz, and 57.965 GHz. This work underscores the potential of graphene-based modifications in enhancing antenna performance and expanding their applications in the realm of wireless communication.

Keywords: Microstrip Antenna, Indoor Communications, Graphene, Reconfigurable Antenna, Antenna Optimization.

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ABBREVIATIONS

TDMA	:	Time Division Multiple Access
CDMA	:	Code Division Multiple Access
LTE	:	Long Term Evolution
IoT	:	Internet of Things
WSN	:	Wireless Sensor Networks
WPT	:	Wireless Power Transfer
mm-waves	:	Millimeter Waves
BW	:	Bandwidth
MPA	:	Microstrip Patch Antenna
MPAs	:	Microstrip Patch Antennas
RFID	:	Radio Frequency Identification
GPS	:	Global Positioning System
MAs	:	Microstrip Antennas
RL	:	Return Loss
CVD	:	Chemical Vapor Deposition
CNTs	:	Carbon Nanotubes
GNPs	:	Graphite Nanoplatelets

1. INTRODUCTION

In this chapter, a brief overview for the general definition of the wireless communications, millimetre wave (mm-wave) technology, its features and various utilizations are presented. Additionally, the chapter includes a literature review, problem statement and thesis objectives.

1.1 WIRELESS COMMUNICATIONS

Over recent past years, communication technology has undergone a number of evolutions. Whereas, the fastest swelling field of the communications industry among all communication techniques has been wireless communication. Perhaps it is accurate to declare that numerous impressive wireless communication improvements have been made in the area of mobile and cellular communications, that affect the users' daily lives in a direct manner. It is a technology that has completely changed how we interact and communicate with one another. It has made it possible for people to communicate instantly around the world, allowing us to collaborate and share ideas in real time. We can now access the internet and other digital services while on the go thanks to wireless transmission, which enables us to stay connected and productive wherever we are. Emitting electromagnetic waves underpin wireless transmission technology. An antenna produces these waves, which move through the atmosphere at the speed of light [1]. They are capable of transmitting a variety of data types, including voice, data, video, and images. Wireless transmission systems employ a variety of encoding and decoding techniques to guarantee that the information is transmitted accurately and securely. The adaptability and mobility of wireless transmission are two of its main advantages. Wireless systems can be used anywhere within the range of the antenna, in contrast to wired systems, which are restricted by the length of the cable [2]. This enables us to access the internet and other digital services while on the go using mobile devices like smartphones and laptops. Additionally, wireless transmission has created new opportunities in industries like healthcare, education, and entertainment. For instance, it has enabled remote patient monitoring, enabling doctors to monitor their health from a distance. Students can now access educational materials from any location, giving them the freedom to learn at their own pace and on their own schedule. Wireless transmission has made it possible for us to stream music and films on demand in the entertainment sector, giving us immediate access to a sizable library of content. In determination, wireless transmission is a technology that has revolutionized the ways in which we interact with the environment, communicate, and access information. With regard to almost every aspect of our lives, its adaptability, mobility, and versatility have created new possibilities [3]. The utilizing of such networks offers many of the benefits that will be presented in the followed sections, one of the most significant features represented by the transmission of information to large area without the need for the physical media. Figure 1.1 shows the arrangement of different implementations within the wireless network [4].

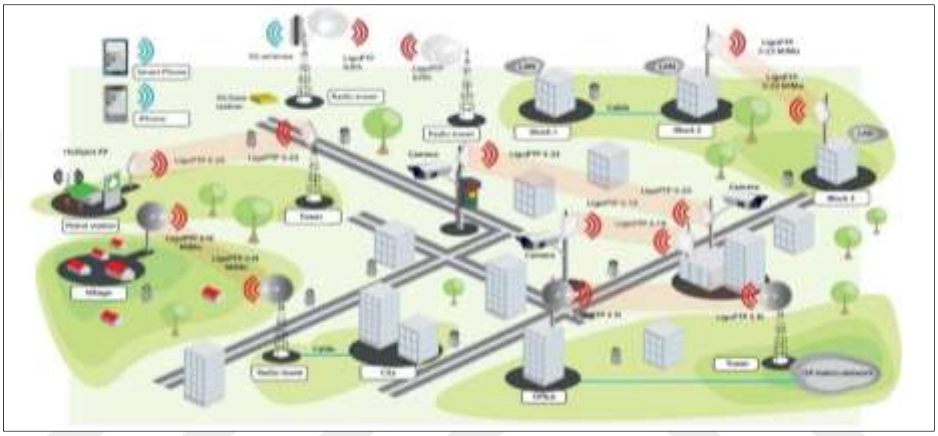


Figure 1.1: Structure of Different Application Within Wireless Network.

1.2 ADVANCEMENTS IN WIRELESS COMMUNICATIONS

The evolution of wireless communications from 1G to 6G has been a transformative journey, marked by significant technological advancements and remarkable improvements in communication capabilities. It all began with the launch of 1G, the first-generation cellular networks, in the early 1980s, which employed analog technology for voice communication. However, 1G had limitations in terms of call quality and capacity. The subsequent generation, 2G, emerged in the 1990s, introducing digital communication and enabling not only clearer voice calls but also the revolutionary feature of text messaging. 2G networks used Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) technologies [5]. The turn of the millennium brought 3G networks, which launched in the early 2000s, offering significant improvements in data transfer speeds and enabling internet access on mobile devices. This leap allowed users to access basic online services and opened the door for mobile browsing and email communication on-the-go. With 4G, which arrived in the late 2000s, mobile broadband reached new heights. Utilizing Long Term Evolution (LTE) technology, 4G provided faster data transmission, smoother video streaming, and the seamless use of various mobile applications. This generation laid the foundation for the rise of the mobile internet and smartphone usage. Following the success of 4G, the much-anticipated 5G made its commercial debut in the 2010s. 5G networks introduced an unprecedented level of performance, boasting significantly higher data rates, lower latency, and enhanced capacity. Operating on millimeter-wave frequencies, 5G revolutionized industries with its potential for IoT (Internet of Things) applications, smart cities, augmented and virtual reality experiences, and ultra-reliable communication for mission-critical applications. As the world continues to witness the transformative power of 5G, research and development efforts are already underway for the next frontier, 6G. Although still in its conceptual phase, 6G aims to further push the boundaries of wireless communications. Envisioned to operate at even higher frequencies, 6G promises to deliver data speeds exceeding 1 terabit per second, enabling unprecedented levels of connectivity and paving the way for futuristic technologies like holographic communications, advanced artificial intelligence, and seamless integration with the physical world [6]. The historic evolution of wireless communications has significantly impacted society, transforming the way people communicate, access information, and conduct business. Each generation has built upon its predecessor, bringing us closer to a hyper-connected world where information is transmitted instantly, and the potential for innovative applications seems limitless. As 6G research progresses, the future of wireless communications holds the promise of unlocking unimaginable possibilities in the digital age and beyond. Figure 1.2 shows the historic to future evolution for wireless communications [7].

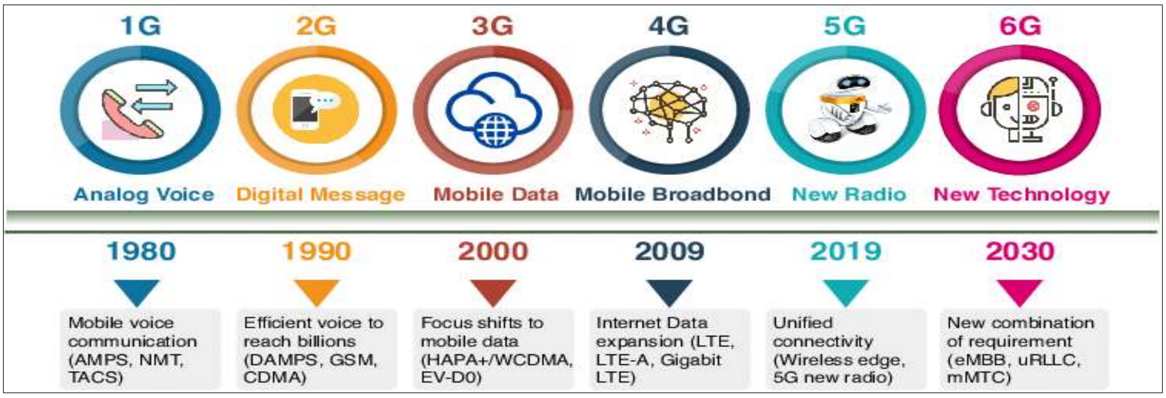


Figure 1.2: Historic to Future Evolution for Wireless Communications 1G to 6G.

1.3 FEATURES AND CHARACTERISTIC OF WIRELESS COMMUNICATIONS

Wireless transmission is a highly adaptable and dependable technology because it possesses a number of distinctive features and traits. Mobility, adaptability, scalability, and ease of deployment are a few of the key characteristics of wireless transmission [8], [9]:

1.3.1 Mobility

One of the most important aspects of wireless transmission is mobility. This indicates that devices are not physically bound to a cable or wire and are free to move about the coverage area. This feature makes it the perfect choice for mobile devices because it allows users to access the network from anywhere that is within the wireless signal's range.

1.3.2 Flexibility

Another important aspect of wireless transmission is flexibility. Users can access products and services from anywhere on the network thanks to seamless integration with existing wireless networks. Because of this, companies can boost their productivity without spending money on expensive optimization services.

1.3.3 Scalability

Another important aspect of wireless transmission is scalability. It allows networks to expand and evolve to meet evolving demands. As a result, web pages can easily be updated or extended to accommodate more users or more devices, without the need for significant changes in services.

1.3.4 Simplicity of Deployment

Another important aspect of wireless transmission is ease of use. It is easy to install and maintain as it requires little in the way of physical infrastructure. Given the difficulty of installing wires or cables in remote or inaccessible locations, this makes it an ideal solution.

1.3.5 Security

Another important aspect of wireless transmission is security. Wireless networks are susceptible to security threats such as data theft and hacking. Wireless transmission systems use security measures such as encryption and authentication to mitigate these risks to protect against unauthorized access and guarantee data confidentiality.

1.4 MODERN IMPLEMENTATIONS OF WIRELESS TRANSMISSION

The ability to communicate and exchange information without being bound to a physical connection has completely changed how people interact with technology. Wireless communication has many different contemporary uses, and those uses are growing as technology progresses. In this article, we'll examine some of the most important wireless communications applications used today, along with their advantages and difficulties [10], [11].

1.4.1 Mobile Communications

One of the most common uses for wireless technology is mobile communications. People can now communicate with one another from almost anywhere in the world thanks to the widespread use of smartphones and other mobile devices. Users of mobile communication systems can make calls, send texts, and access the internet while they are on the go thanks to a network of base stations that wirelessly transmit and receive data.

1.4.2 Internet of Things (IoT)

The network of gadgets that are connected to the internet and have the ability to communicate with one another is known as the IoT. A crucial IoT enabler, wireless communication enables devices to connect and exchange data without the need for physical connections. Wearable tech, automated factories, and smart homes are a few examples of IoT applications.

1.4.3 Wireless Sensor Networks (WSN)

The term WSN refers to a grouping of sensors that communicate wirelessly with one another and a central hub. Applications for WSNs are numerous and include monitoring the environment, industrial automation, and healthcare. They are frequently used in circumstances where using wired connections is impractical or impossible, such as in isolated or dangerous settings.

1.4.4 Wireless Power Transfer (WPT)

WPT is a technology that enables wireless charging of devices without the use of wires or other physical connections. WPT is being used in an increasing number of industries, such as consumer electronics, medical devices, and electric vehicles. The system uses electromagnetic induction or magnetic resonance to transmit power wirelessly.

1.4.5 Wireless Ad-Hoc Networks

Without the need for pre-existing infrastructure, wireless ad-hoc networks are networks that are created on an as-needed basis. When conventional network infrastructure is unavailable, such as during disaster response scenarios, these networks are typically used. Examples of applications include public safety, emergency response, and military communication. The IoT and mobile communications are just a couple of the many contemporary applications that wireless communication technology is a critical enabler for. Wireless communication will likely see an increase in the number of applications it can be used for as technology develops, making it a crucial technology for the future. However, in order to fully realize the potential of this technology, there are also difficulties related to wireless communication, such as problems with security, dependability, and spectrum availability.

1.5 MM-WAVES

The mm-waves are high-frequency electromagnetic waves that have a wavelength of between 1 and 10 mm. They are part of the radio frequency spectrum and are typically used in wireless communications for short-range, high-bandwidth applications. The mm-waves have a number of advantages over lower-frequency radio waves, including higher data rates, shorter latency, and reduced interference. However, they also have some disadvantages, including shorter range and susceptibility to atmospheric absorption. One of the key advantages of mm-waves is their ability to transmit data at very high speeds. This makes them ideal for applications that require large amounts of data to be transmitted quickly, such as high-definition video streaming, virtual reality, and augmented reality. In addition, mm-waves have shorter latency than lower-frequency radio waves, which means that data can be transmitted more quickly between devices. Another advantage of mm-waves is their ability to reduce interference. This is because they operate at a higher frequency than lower-frequency radio waves, which means that there is less interference from other wireless devices operating in the same frequency range. However, mm-waves have a shorter range than lower-frequency radio waves, which means that they are typically used for short-range, high-bandwidth applications. One of the key challenges associated with mm-wave technology is atmospheric absorption. This is because mm-waves are more easily absorbed by atmospheric gases such as oxygen and water vapor, which can limit their range and effectiveness. However, advances in antenna and beamforming technology have made it possible to overcome some of these challenges and to use mm-waves in a wider range of applications. Finally, mm-waves are an important technology in wireless communications because they provide high data rates, low latency, and minimal interference. Although they have some drawbacks, such as a shorter range and vulnerability to atmospheric absorption, technological advancements are making it possible to get around these obstacles and use millimetre waves in more and more applications. As a result, millimetre wave technology is likely to play a bigger part in wireless communications in the future [11], [12]. The spectrum of wireless mm-waves is presented in Figure 1.3.

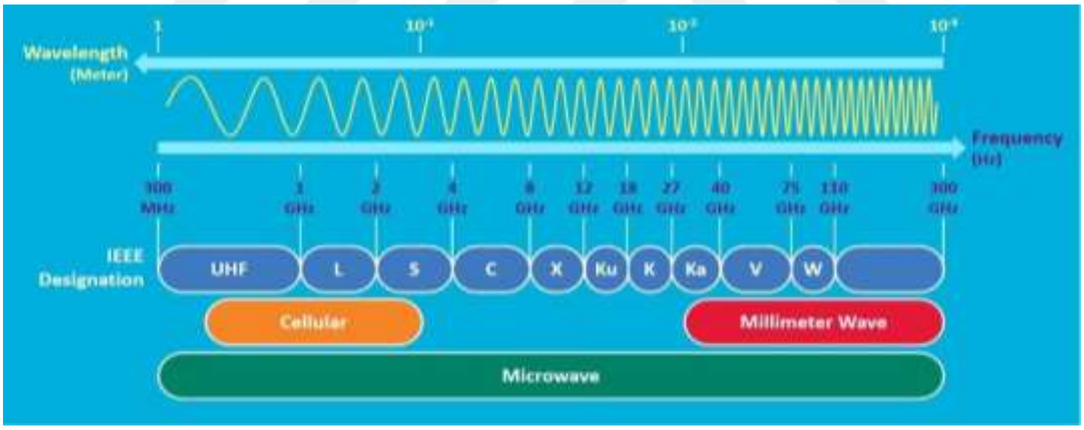


Figure 1.3: Spectrum for mm-waves.

1.6 APPLICATIONS OF MM-WAVES

The mm-waves, in general, have a wide range of applications in wireless communications, particularly in applications that require a high-bandwidth transmission over a short distance. In the realm of communications, some of the most important applications of mm-waves include the following [13], [14]:

1.6.1 5G Wireless Networks

Millimeter waves are a critical component of 5G wireless networks, which are designed to offer significantly higher data rates and lower latency than previous generations of wireless networks. The mm-waves are used in the high-frequency bands of the radio spectrum to transmit large amounts of data quickly and efficiently.

1.6.2 Wireless Backhaul

The mm-waves are used for wireless backhaul, which is the process of transmitting data between base stations and other network infrastructure. the mm-waves are particularly useful for wireless backhaul because they can transmit data at very high speeds over short distances, making them ideal for connecting small cells and other network components.

1.6.3 Point-to-Point Communication

The mm-waves are used for point-to-point communication, which involves transmitting data between two fixed points. This is particularly useful for applications such as WLANs and building-to-building connections, where high data rates and low latency are critical.

1.6.4 Automotive Radar

The mm-waves are used in automotive radar systems to detect objects and obstacles in the road ahead. These systems use the high-frequency bands of the radio spectrum to transmit and receive signals, allowing the vehicle to detect obstacles even in adverse weather conditions.

1.6.5 Security Screening

The mm-waves are used in security screening systems, such as airport body scanners, to detect hidden objects on a person's body. These systems use the high-frequency bands of the radio spectrum to create a three-dimensional image of the person's body, allowing security personnel to detect hidden objects that may pose a threat.

In determination, mm-waves are a critical component of modern wireless communications, offering high data rates, low latency, and several other benefits. They are used in a wide range of the, including 5G wireless networks, wireless backhaul, point-to-point communication, automotive radar, and the security screening. As technology continues to advance, it is likely that mm-waves will play an increasingly important role in the future of wireless communications. Figure 1.4 presents various applications of mm-waves.

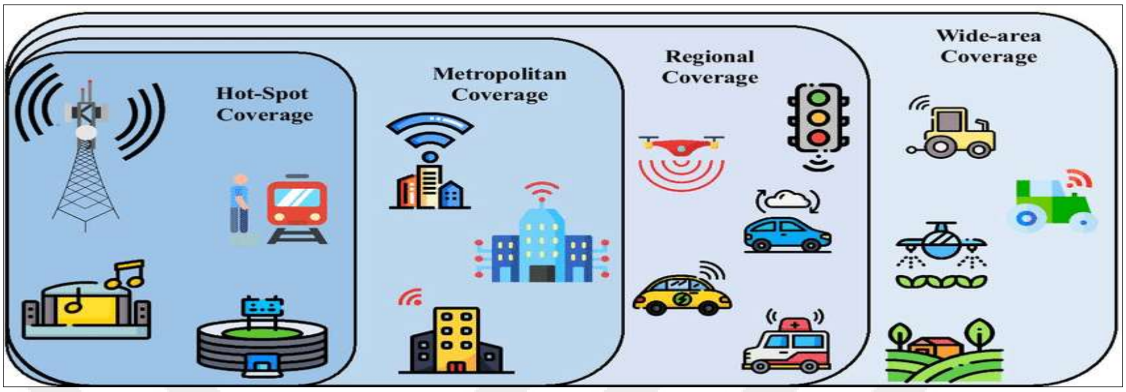


Figure 1.4: General Applications for the mm-waves.

1.7 MM-WAVES FOR INDOOR APPLICATIONS

The mm-waves are increasingly being used for indoor wireless communication due to their ability to provide high data rates and low latency. Indoor environments can present a number of challenges for wireless communication, including interference from other wireless devices and obstacles such as walls and furniture. The mm-waves are well-suited to indoor environments because they operate at higher frequencies than traditional radio waves, allowing them to penetrate some obstacles more effectively. Additionally, mm-waves can be used to create directional beams that can be steered to avoid obstacles and interference. This makes mm-waves an ideal technology for indoor applications such as WLANs, smart homes, and the IoT. However, one of the main challenges of using mm-waves for indoor communication is their shorter range, which means that they may require a larger number of access points to provide adequate coverage. Nonetheless, as the demand for high-speed wireless communication in indoor environments continues to grow, mm-waves are likely to play an increasingly important role in the future of indoor wireless communication. A personal network is a small, localized wireless network that is designed for personal use. These networks typically consist of a small number of devices, such as smartphones, tablets, and laptops, and are used to share files, access the internet, and communicate with other devices within the network. Personal networks can be created using a variety of wireless technologies, including Wi-Fi, Bluetooth, and Near Field Communication, and recently by means of the mm-waves. They are often used in homes, small offices, and other environments where a small, localized network is needed. Personal networks offer a number of advantages, including ease of use, low cost, and flexibility. They are also highly customizable, allowing users to tailor the network to their specific needs and preferences. As the number of wireless devices continues to grow, personal networks are likely to become increasingly popular as a way to connect and communicate within small, localized environments. The mm-waves can be considered a perfect solution when utilized within the range of the personal network in the different institutions because it is offered a higher speed of data transmission up to 1 Gbps. Whereas, recently the ambition of the users is to obtain a higher data transmission rate. The use of mm-waves in the personal network in large companies leads to minimizing the delay time of transmission and the use of the traditional ways, Figure 1.5 presents the structure of the personal network [15], [16].

Figure 1.5: General Structure for Small Personal Network.

1.8 BENEFITS AND DRAWBACKS OF MM-WAVES

There are several advantages characterized the utilization of the mm-waves and on the other hands there are several drawbacks that are presented in the following subsections.

1.8.1 Benefits

The mm-waves as mentioned previously are electromagnetic waves with wavelengths between 1 and 10 millimeters. Here are some advantages of using millimeter waves [17], [18]:

1.8.1.1 High bandwidth

The mm-waves have a high BW, allowing for the quick transmission of large amounts of data. They are therefore perfect for use in scenarios requiring high data rates, such as 5G mobile networks.

1.8.1.2 Low interference

The mm-waves have a frequency range that is higher than that of conventional wireless technologies, making them less likely to interfere with other wireless signals. Because of this, they are excellent for use in densely populated areas.

1.8.1.3 Small antenna size

Because mm-waves have a short wavelength, they can transmit and receive signals with antennas that are smaller than those needed for conventional wireless technologies. They are therefore perfect for use in compact devices like wearables and smartphones.

1.8.1.4 Enhanced security

The mm-waves have a short range, making it less likely for unauthorized parties to intercept or eavesdrop on them. Because of this, they are perfect for use in applications where security is an issue.

1.8.1.5 Non-ionizing radiation

Because mm-waves are non-ionizing, there is no chance that they will cause cancer or any other ionizing radiation-related health issues. They are therefore a secure option for use in procedures like security screening and medical imaging. In general, mm-wave technology is advantageous for a variety of applications, from mobile networks to medical imaging. They can offer high-speed data transfer, minimal interference, improved security, and a secure option for use in a variety of applications when used properly.

1.8.2 Drawbacks

While mm-waves offer numerous benefits, there are also some disadvantages to their use. Here are some of the potential drawbacks of using mm-waves [19], [20]:

1.8.2.1 Short range

The short range of mm-waves is one of their main drawbacks. They can only move a short distance before being stopped by obstructions like trees and buildings. This implies that in order to maintain a connection over a larger area, multiple antennas may be necessary.

1.8.2.2 High attenuation

Atmospheric gases, water vapor, and other obstructions quickly absorb millimetre waves. This may lead to significant attenuation, which can weaken the signal and make it challenging to keep a steady connection. The electromagnetic waves known as mm-waves have frequencies ranging from 30 to 300 gigahertz. Measuring the absorption of oxygen is one possible use for mm-waves. The phenomenon of oxygen molecules in the atmosphere absorbing and dispersing mm-wave radiation is referred to as oxygen absorption of mm-waves. The amount of mm-wave radiation absorbed by oxygen molecules can be used to calculate the atmospheric oxygen concentration. Numerous applications, such as environmental monitoring, atmospheric research, and industrial process control, can benefit from this. It is crucial to remember that precise oxygen absorption measurement using mm-waves necessitates careful calibration and interference source correction. Figure 1.6 shows the oxygen absorption for the mm-waves at different frequencies.

1.8.2.3 Clear line-of-sight

Is necessary for mm-waves to travel between the transmitting and receiving antennas. It follows that structures and trees can block the signal and interfere with connections. As a result, mm-waves may be less useful for use in crowded urban areas.

1.8.2.4 Cost of equipment

Compared to conventional wireless technologies, millimetre wave generation and detection technology is more expensive. As a result, installing and maintaining millimetre wave systems may become more expensive.

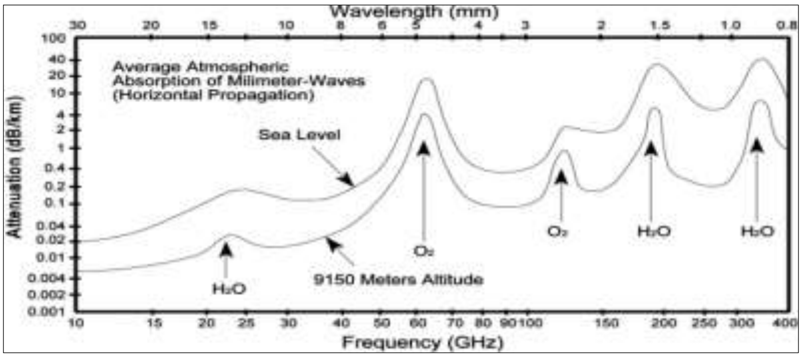


Figure 1.6: Oxygen Absorption for mm-waves.

1.8.2.5 Health concerns

Despite the fact that millimetre waves are non-ionizing and generally regarded as safe, some people have expressed worry about the long-term effects on their health. To fully comprehend the effects of millimetre wave exposure on health, more study is required.

When assessing the use of millimetre waves in various applications, it is important to carefully consider their drawbacks. Despite their many benefits, their effectiveness in some situations may be constrained by their short range, sensitivity to attenuation, and need for line-of-sight. It may also be necessary to consider the expense and potential health risks linked to millimetre wave technology.

1.9 LICENSE-FREE FREQUENCY

The 60-GHz band has, during the recent years, gained increased academic and commercial interest mainly due to the relatively large amount of license-free and little-used frequency spectrum located in the vicinity of 60GHz. The exact location of these free frequency bands varies locally but the 59–62GHz band overlaps around the world and is therefore a true worldwide license-free band. Compared to licensed spectrum bands, these bands typically have lower power limits and shorter ranges, but they also have a number of benefits. Applications for license-free spectrum include Wi-Fi networks, Bluetooth gadgets, cordless phones, and wireless audio equipment. Additionally, because anyone can experiment and innovate without the need for pricey licenses, new wireless technologies are made possible. Despite its advantages, using a license-free spectrum can be difficult because it may be interfered with by other devices using the same frequency bands. In order to address these problems and guarantee that license-free spectrum remains a practical option for wireless communications, rules and technical standards have been developed [21]. The license-free spectrum covers a wide range of frequency from 57 to 66 GHz, as exhibited in Figure 1.7.

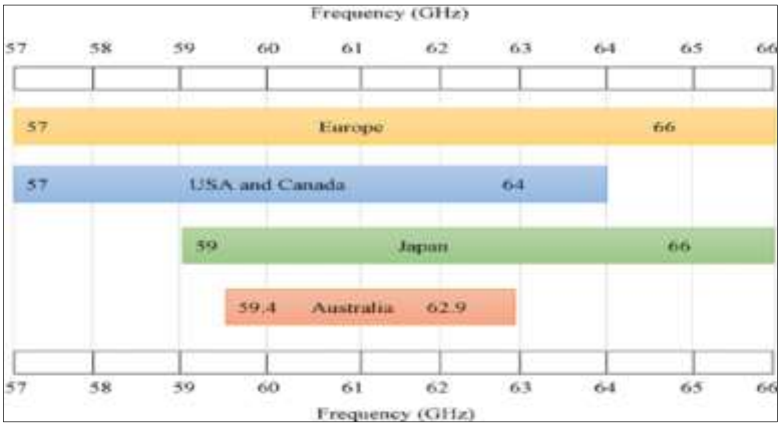


Figure 1.7: License-free Frequency Bands.

1.10 RELATED STUDIES

Numerous studies have explored the utilization of unlicensed frequency spectrum for personal networks in the past. Furthermore, extensive research and development have focused on enhancing the performance of MPAs, some of these studies are listed below:

a) The researchers of this article [22] have previously constructed and simulated a small, wideband MPA. The researchers adopted an inset feed strategy to obtain an excellent connection between the antenna and the source. The virtual MPA was designed for operation in the 60 GHz unlicensed band. To improve the gain, the bandwidth, and the total efficiency of the simulated MPA, the researchers added slots carved inside the antenna patch.

b) In this particular study, the researchers have laid the groundwork for a MPA based on the graphene that can operate within three distinct frequency bands. These frequency bands have been identified as highly promising for future wireless communication applications. The use of Graphene as a material offers several unique advantages, with one of the most notable being its ability to exhibit variable electrical conductivity based on specific requirements. The authors have integrated Graphene into the MPA patch by using it as inserted slots. By manipulating the chemical potential of the Graphene, the resonant frequency of the MPA can be adjusted, allowing it to function at frequencies ranging from 300 GHz to 410 GHz. These frequencies fall within the mm-wave band and represent a significant technological advancement. Overall, the authors have successfully demonstrated the potential of Graphene-based MPA in wireless communication applications [23].

c) The authors of this study have created, simulated, and produced a compact MPA array designed for use at 60 GHz. This particular MPA array structure is utilized to enhance both gain and frequency BW in related applications. To achieve optimal performance, the authors used the parallel with series feeding in conjunction with a different feeding method. The resulting MP antenna array has been shown to have good performance with an $S_{11} < -10$ dB, aligning with the globally available, unlicensed 60 GHz spectrum. The successful implementation of this MPA array represents a significant advancement in the field of wireless communication, and its potential applications are numerous [24].

d) The researchers in this study have presented two practical examples of the implementation of MPA at 28 GHz and 60 GHz. The simulated antennas used in the experiments were composed of a copper patch, ground plane, and substrate, that were fed utilizing the quarter-wave line feeding method. Throughout the design process, the researchers encountered several challenges and limitations that needed to be addressed to ensure optimal antenna performance. The study also details the steps taken to reconcile performance specifications and the fabrication process. The authors' comprehensive analysis and findings represent a significant contribution to the field of wireless communication, providing valuable insights for future research and development [25].

e) This article details the development of a compact single MPA and MPA in the form of array for use at 60 GHz. The researchers employed an enhancement approach utilizing a mushroom-like EBG organization to address the surface wave interference typically observed in such applications. This interference can lead to undesirable side lobes, lower MPA gain, and reduced efficiency. The implementation of EBG organization helps to reduce the effect of these waves. The introduced MPA design features a dielectric substrate, fully ground plane, and rectangular patch with mushroom cells integrated. After adding the mushroom cells, the researchers evaluated the MPA performance and observed significant improvements in side lobe levels, directivity (from 5.77 dB to 10 dB), and efficiency (from 80% to 95%). These findings demonstrate the potential of EBG structures in enhancing the performance of MPAs, and their implementation in this study represents a significant contribution to the field of wireless communication [26].

1.11 PROBLEM FORMULATION

The huge growth in the development of applications that employ wireless transmission has led to the occurrence of crowding, which in turn leads to making the data transfer speed slow. Therefore, wireless network developers from time to time develop the structure of wireless networks. Based on previous studies, the use of licensed spectrum provides a very high data transfer speed and thus meets the aspirations of users and avoids data traffic congestion. The MPAs are very popular for the utilize due to their many advantages, but they suffer from limited bandwidth and low gain. This is what we will try to solve through this work.

1.12 THESIS CONTRIBUTION

This study is introduced to eliminate and minimize the reported problems in the literature regarding data crowding and the related issues with MP antennas. The general contributions in this work can be listed as following:

a) Designing, investigating, simulating, and optimizing of MPA operated at 62 GHz which is chosen for applications within the indoor environment, short-range communications, and for the future of the following generation of the mobile communications.
b) Employing the graphene material as an engraved slot in the MPA patch makes the antenna able to tune frequency as required.

1.13 THESIS OUTLINES

The proposed work is generally prepared to cover four fundamental chapters; the organization of each chapter is listed as follows:

a) Chapter Two: In this chapter of the thesis, we present a comprehensive exploration of antennas, encompassing their fundamental principles, essential parameters, diverse types, and a specific focus on microstrip antennas. We delve into the advantages and disadvantages inherent to microstrip antennas, followed by an in-depth examination of microstrip antenna analysis and design methodologies. Additionally, we delve into various antenna-feeding approaches.

b) Chapter Three: Within this chapter, a comprehensive depiction of graphene material unfolds, encompassing its definition, fundamental applications, manufacturing processes, and intricate conductivity modelling.

c) Chapter Four: This particular chapter of the thesis elucidates the foundational methodology employed in designing the envisaged MPAs in both rectangular and circular configurations, along with the integration of graphene material. Additionally, this chapter unveils the attained outcomes as derived from the CST analysis.

d) Chapter Five: This chapter presents the conclusion from this study and the suggested developments.

2. THEORY OF ANTENNAS AND PRINCIPAL PARAMETERS

This functional chapter covers the fundamentals of antennas, parameters, types, MPAs, MPAs analysis, and MPAs feeding methods.

2.1 THEORY OF ANTENNAS

An antenna is a device that transmits and receives electromagnetic waves. Antennas are available in a variety of shapes and sizes. It is capable of converting electrical energy into electromagnetic waves and vice versa. Antennas are used for a variety of purposes, including radio and television signal broadcasting, cellular communication, satellite communication, radar, and wireless networking. The two primary elements that make up an antenna are the radiating element, which is part of the antenna that actually radiates or receives electromagnetic waves, and the feed line, which is the cable or transmission line that connects the radiating element to the transmitter or receiver. Electromagnetic waves are transmitted and received using antennas. The size and shape of the radiating element, as well as its orientation, determine the characteristics of the electromagnetic waves that are either transmitted or received. Antennas can be classified using a variety of parameters such as operating frequency range, polarization, radiation pattern, and others. Common antenna types include dipole antennas, patch antennas, horn antennas, parabolic antennas, and Yagi antennas. Patch antennas are yet another popular type. The proper design and installation of an antenna are required to ensure that it will function as intended when used. Location, elevation above ground, the nature of the environment around it, and the presence of nearby objects are all factors that can affect an antenna's performance. An antenna's performance can be maximized by ensuring that it is properly tuned and that its impedance is matched [27].

2.2 ANTENNAS HISTORY

In the literature, the researchers such as James Clerk Maxwell and Heinrich Hertz were among the first to develop a theory of electromagnetic waves in the latter half of the nineteenth century. At this point, antennas began to take shape. Nonetheless, the development of useful antennas did not begin until the early twentieth century. Guglielmo Marconi invented one of the first antennas, which became known as the Marconi antenna, in the early 1900s. This antenna served as a wireless telegraphy antenna. This antenna was constructed from a single wire strung between two poles. It was designed to send and receive Morse code signals over extremely long distances. The Yagi-Uda antenna is a highly sophisticated antenna that was developed as a result of advances in radio technology in the 1930s and 1940s. These developments resulted in the development of the Yagi-Uda antenna. A driven element and several passive elements are laid out in a specific pattern to produce directional radiation from the Yagi-Uda antenna. During WWII, the invention of parabolic reflector antennas coincided with the development of radar systems. A concave metal dish is used to focus electromagnetic waves in these antennas. These antennas could detect and track enemy aircraft and ships. The widespread use of television broadcasting and satellite communication after WWII enabled advancements in antenna technology. Two examples of more advanced and specialized antenna designs that emerged during this time period are the log-periodic antenna and the helical antenna. These two antennas are known as log-periodic antennas. Antennas are used in a wide range of devices and applications today, such as radio telescopes, interstellar communication, cell phone towers, and satellite dishes. Engineers can now design and optimize antennas with unprecedented precision using today's sophisticated computer modeling and simulation tools. This results in even greater improvements in both performance and efficiency. To summarize, antennas have come a long way since their inception, with many theoretical and practical innovations along the way. From Marconi's first antenna to the most cutting-edge models available today, antennas have played a critical role in the advancement of modern communication and technology [28]. The most common utilized antenna types are shown in following Figure 2.1.

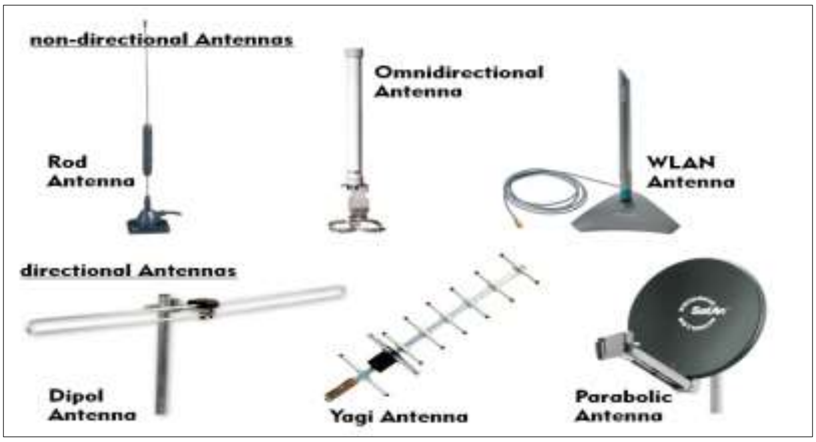


Figure 2.1: Different Type of Commonly Used Antennas.

To summarize, define, and outline the various applications of different antennas, the following information is provided [29]:

a) Dipole Antenna: A simple and commonly used antenna with two conductive elements (half-wavelength each) oriented in a straight line. Used for radio and television broadcasting, Wi-Fi, and various short-range communication systems.
b) Monopole Antenna: Consists of a single conductive element over a conducting surface (ground plane). Widely used in devices like smartphones, walkie-talkies, and wireless routers.
c) Yagi-Uda Antenna: A directional antenna with multiple elements in a linear array, including one driven element, one or more reflectors, and one or more directors. Often used for long-range point-to-point communication and television reception.
d) Patch Antenna: A compact, planar antenna with a low profile, usually etched on a dielectric substrate. Commonly used in mobile devices, GPS systems, and RFID tags.
e) Horn Antenna: A flared waveguide that emits and receives radio waves in a directional beam. Utilized in radar systems, satellite communication, and microwave links.
f) Parabolic Reflector Antenna: Consists of a curved dish reflector and a feed antenna at its focal point. Used in satellite communication, radio telescopes, and long-range point-to-point links.
g) Helical Antenna: A three-dimensional, wire antenna with a helix shape. Commonly found in satellite communication, GPS, and amateur radio applications.
h) Log-Periodic Antenna: A wideband, directional antenna with multiple elements, each designed for specific frequency ranges. Used in television antennas, cellular networks, and Wi-Fi routers.
i) Loop Antenna: A loop of wire or a coil that receives or radiates electromagnetic waves. Commonly used in AM radio receivers and RFID systems.
j) Microstrip Antenna: A type of patch antenna formed on a printed circuit board with a metal patch on one side and a ground plane on the other. Popular in wireless communication devices, radar systems, and satellite links.

2.3 ORGANIZATION OF THE MICROSTRIP ANTENNAS

The history of MAs dates back to the 1950s when researchers began exploring new ways to design and implement antennas for various applications. The concept of the MAs was independently proposed by two groups - D.E. Kerr from the UK and R.S. Munson from the United States - in the early 1950s. However, it wasn't until the 1970s that MAs gained significant attention and popularity due to advancements in integrated circuit technology. The development of printed circuit boards and planar transmission lines allowed for the easy fabrication of MAs on dielectric substrates, making them cost-effective and compact. Since then, MAs have become a prominent choice in wireless communication systems, satellite technology, radar applications, and other modern electronic devices due to their low profile, ease of integration, and versatility. Their historical evolution continues to influence the advancement of wireless communication technologies in the present day. Such antennas can also be constructed using printed circuits by etching copper-clad dielectrics into various shapes or arrangements. This technology allows for the creation of diverse antenna types. Among them, patch antennas have gained popularity due to their numerous advantages, including their ability to be easily customized to fit different surfaces. Generally, the MAs are constructed from an insulating material called substrate on its face a conductive material is engraved from a uniform or nonuniform shape called a patch and on its bottom the ground plane is engraved which is usually from conductive material. In recent years, MAs have seen increased usage. As shown in Figure 2.2, patch antennas come in various basic shapes and can be further modified for different applications [30].

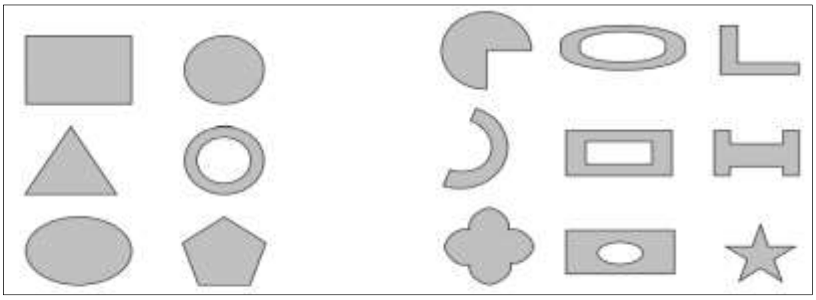
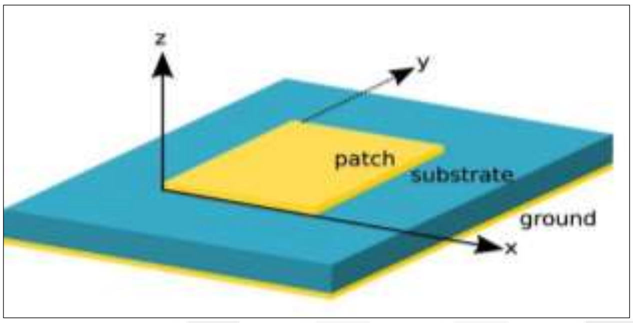
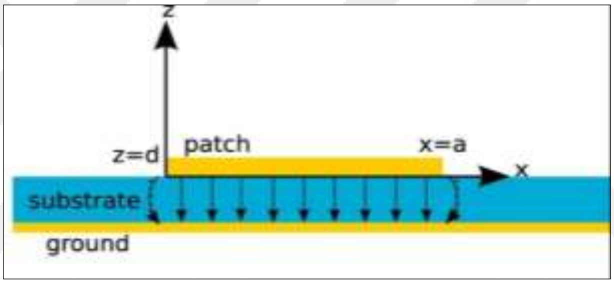


Figure 2.2: Different Patch Shapes.

By combining different patch shapes and feeding arrangements, the number of possible MPA antenna designs multiply, as depicted in Figure 2.3, which showcases a well-known MPA with radiation in the x-direction. The resonance frequency can be adjusted by varying the patch length (l), while the width (w) significantly influences the radiation resistance. It's worth noting that antennas employing microstrip elements typically have a narrow bandwidth, which may be a crucial consideration depending on the specific application.



(a) Front view



(b) Side view

Figure 2.3: General Form for the MA.

2.3.1 Antenna Substrate

The size and performance of a planar antenna are directly affected by the properties of the antenna substrate. In particular, two critical substrate characteristics, the constant for the dielectric ($\in_r$) and substrate thickness (h), play a pivotal role during the manufacturing process. There exist both lower and upper limits for the antenna substrate thickness. At the lower end, a thin substrate reduces radiation and fringing fields while enhancing Q and decreasing bandwidth due to increased capacitance to the ground. Conversely, the substrate thickness is constrained at the upper end to avoid undesirable substrate mode excitation. Additionally, as the antenna substrate thickness increases, the radiation efficiency of the antenna decreases. The width of a 50-ohm microstrip line also expands with substrate thickness and might even surpass the width of the microstrip antenna itself [30].

The substrate's $\in_r$ also significantly impacts the antenna's performance. Lower values of $\in_r$ result in decreased capacitance to the ground, leading to a higher fringing field and increased radiated power. On the other hand, a higher $\in_r$ value leads to more energy storage within the substrate and subsequently less power radiated from the patch antenna to the ground plane. As a result, various substrates with dielectric constants ranging from 2.2 to 12 can be employed to fabricate microstrip antennas, offering a wide range of design possibilities to suit different applications. The MPA primarily emits radiation due to the fringing fields that occur between the edge of the patch and the ground plane. For optimal antenna performance, it is preferable to use a thick dielectric substrate with a low dielectric constant. This choice enhances efficiency, increases bandwidth, and improves radiation characteristics. However, it also leads to a larger antenna size. On the other hand, in the quest to design a compact MPA, higher dielectric constants must be employed, which results in reduced efficiency and narrower bandwidth. Consequently, a trade-off must be made between antenna dimensions and antenna performance [31].

2.3.2 Features and Limitations of MPA

Researchers and engineers have shown significant interest in MPA and MPA arrays, utilizing them extensively in RF and microwave systems like communications, radar, navigation, remote sensing, and biomedical systems. The MPA exhibits versatility, existing in various forms such as patch, dipole, slot, or travelling-wave structures, tailored to specific applications. Among these, patch or patch-like radiators have been extensively investigated due to their distinctive qualities. These radiators offer several crucial benefits [32]:

a) The MPAs typically maintain the form of the low profile, with their thickness usually being less than 0.03 times the operating wavelength in free space (λ_0).
b) The MPA is known for its lightweight construction, typically fabricated employing a dielectric substrate with copper or any conductive materials affixed to it.
c) The MPA surrenders an excellent conformability to substrates, as it can be created on both planar and non-planar surfaces, allowing it to seamlessly adhere to the shape of the dielectric substrate it is mounted on.

d) The cost-effectiveness of the MPA is deemed a substantial benefit, primarily because it is normally created employing a budget-friendly printed circuit technique. Although the substrate constitutes the more expensive element of the antenna, the overall manufacturing process remains relatively economical.
e) Versatility is a key attribute of the microstrip patch antenna, offering flexibility in various aspects such as impedance, resonant frequency, radiation pattern, polarization, and operating mode. This adaptability stems from the ability to choose different shapes and feeding arrangements. Additionally, numerous techniques, including the incorporation of shorting pins, varactor diodes, patch loading, slotting, and introducing parasitic elements, can be applied to enhance and modify the antenna's performance.
f) The MPA has the capability to support both types of the linear and the circular polarization.
g) It is possible to design such an antenna compactly, fitting for personal mobile communication purposes.

Despite the wonderful characteristics of this type of antennas, there are many limitations that affect these antennas, which we list as follows [33]:

a) This type of antenna has a very low gain or more expressly poor gain.
b) This type of antenna has a restricted bandwidth.
c) This type of antenna suffered from the unwanted radiation emitted from antenna feeds and connections.
d) This type of antenna has limited efficiency because of the various loss.
e) With the exception of tapered slot antennas, most end-fire radiators exhibit subpar performance.
f) Limited power tolerance or reduced capacity for handling high power.
g) The majority of MPA emits radiation into the half-space.
h) High-performance arrays demand intricate feed structures.

The MPA quality factor represents its losses, and a high Q value results in a restricted bandwidth and low efficiency. MPA typically has an ultimately high Q. To reduce the quality factor, one can increase the dielectric substrate's thickness. However, this leads to a higher portion of power being converted into surface waves, which causes unwanted power loss and degrades antenna performance as the waves scatter at the dielectric bends. To mitigate surface waves, photonic bandgap structures can be employed. Another way to address issues like lower gain and power handling capacity is to use an array configuration for the antenna elements.

2.3.3 Fringing Effect in MPA

Due to the finite dimensions of the rectangular patch along its length and width, fringing effects occur at the edges of the patch. This phenomenon is depicted in Figure 2.4 for the two radiating slots of the microstrip antenna, both along the length and width. The degree of fringing is determined by the patch dimensions and the substrate height. In the primary E-plane (xy-plane), fringing is influenced by the ratio of the w to the substrate height (h) (w/h) and the $\in_r$ of the substrate. Although fringing is reduced in microstrip antennas with $w/h << 1$, it remains a relevant factor to consider, as it impacts the resonant frequency of the antenna. The same considerations apply to the width of the patch [34].

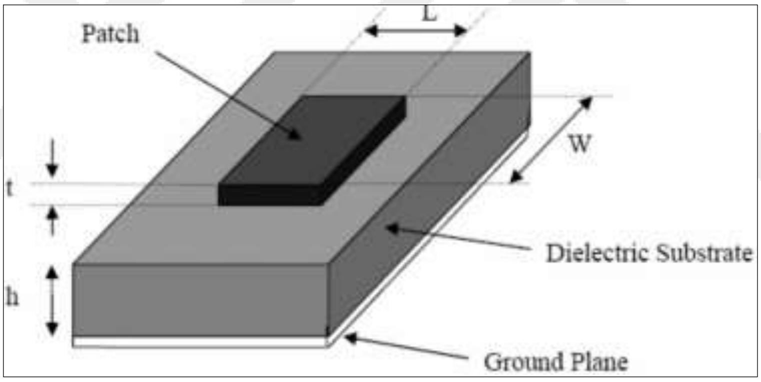
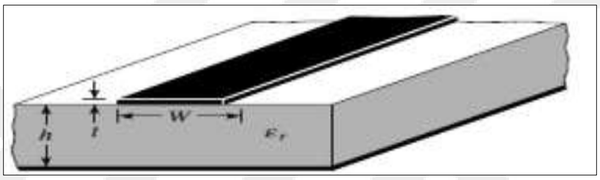
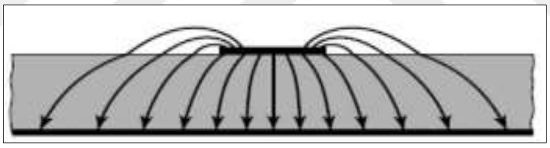


Figure 2.4: Basic Structure for the MPA.

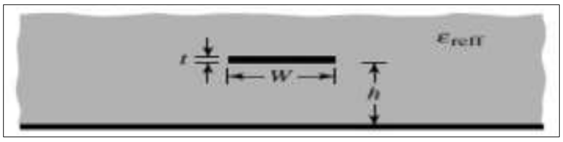
In Figure 2.5(a), we observe a microstrip line, and its corresponding electric field lines are illustrated in Figure 2.5(b). This microstrip line comprises two dielectrics, typically the substrate and air, making it a non-homogeneous structure. As depicted, a majority of the electric field lines are confined within the substrate, while some portions extend into the air. Due to the small values of W/h and $\in_r$, the electric field lines primarily concentrate within the substrate. This fringing effect causes the microstrip line to appear wider electrically than its actual physical dimensions. Because some waves propagate through the substrate and others through the air, an effective dielectric constant ($\in_{reff}$) is introduced to account for the impact of fringing and wave propagation in the line. To define the effective dielectric constant, we can consider a scenario where the center conductor of the microstrip line, maintaining its original dimensions and height above the ground plane, is embedded within a single dielectric material, as illustrated in Figure 2.5(c). The effective dielectric constant is determined as the dielectric constant of a uniform dielectric material that would yield the same electrical characteristics, particularly the propagation constant, as the actual microstrip line shown in Figure 2.3(a), when the center conductor is embedded within the single dielectric material as shown in Figure 2.3(c). In a configuration where there is air above the substrate, the $\in_{reff}$ typically falls within the range of $1 < \in_{reff} < \in_r$. For practical employments where the dielectric constant of the substrate significantly exceeds unity ($\in_r <<$ 1), the value of $\in_{reff}$ tends to be closer to the actual $\in_r$ of the substrate [34].



(a) Microstrip Line



(b) Field lines over the Microstrip Line



(c) Illustration for the Effective Permittivity

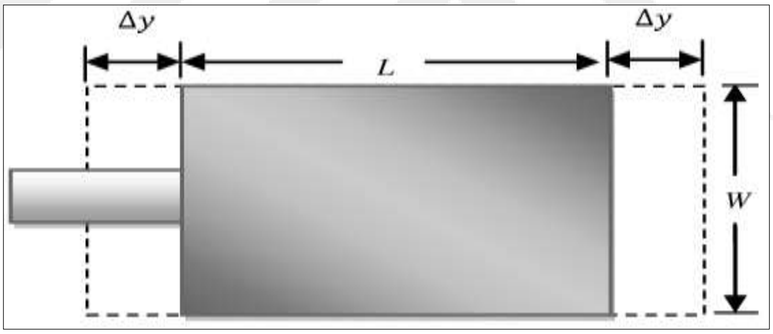
Figure 2.5: Microstrip Line with its Field and the Representation for the Effective Permittivity.

The effective dielectric constant is determined to be the dielectric constant of a uniform dielectric material, which would result in the line shown in Figure 2.5(c) having the exact electrical characteristics, particularly the propagation constant, as the real line depicted in Figure 2.3(a). The effective dielectric constant is frequency-dependent. With an increase in the operating frequency, a greater portion of the electric field lines concentrates within the substrate. Consequently, the microstrip line starts to exhibit characteristics resembling a homogeneous line with only the substrate dielectric. As a result, the effective dielectric constant approaches the value of the substrate's dielectric constant. The initial values of the effective dielectric constant at low frequencies are termed static values, and for cases where the ratio of width to height (w/h) is less than 1, they are given by [34]:

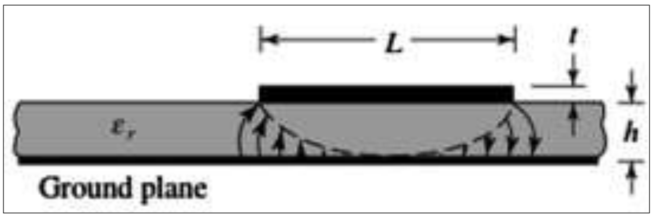
$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{\frac{-1}{2}} \tag{2.1}$$

2.3.4 Effective Patch Length

Due to the influence of fringing effects, the MPA appears to be larger in electrical size than its actual physical dimensions. In the principal E-plane (xy-plane), this phenomenon is depicted in Figure 2.6, where the patch's length dimensions are extended on both ends by a distance Δy. The value of Δy is determined by the ϵ_{reff} and the W/h ratio of the patch [34].



(a) Front View



(b) Side view

Figure 2.6: Patch Length Expansion.

A widely used and practical approximate relationship for the normalized extension of the length is can be interpreted as follows [34]:

$$\frac{\Delta y}{h} = 0.412\frac{\left(\epsilon_{reff} + 0.3\right)\left[\frac{w}{h} + 0.264\right]}{\left(\epsilon_{reff} - 0.258\right)\left[\frac{w}{h} + 0.8\right]} \tag{2.2}$$

Subsequently, to determine the primary and actual length of the antenna patch, considering that the effective length is typically greater than the actual length due to fringing effects on both edges of the patch as described above, we can utilize the following equation [35]:

$$L_{eff} = \frac{v_o}{2f_o\sqrt{\epsilon_{reff}}} \tag{2.3}$$

$$L = L_{eff} - 2\Delta y \tag{2.4}$$

Where:

L_{eff}: is describes the effective length;

v_o: is describes the light in the free space;

f_o: is describes the frequency of the operation; and

Δy: is describes the length expansion.

2.3.5 Feeding Methods

Various techniques can be employed to feed Microstrip patch antennas, and these methods can be broadly classified into two categories: contacting and non-contacting methods. In the contracting approach, the RF power is directly delivered to the radiating patch through a connecting element, such as a microstrip line. On the other hand, the non-contacting method involves power transfer between the microstrip line and the radiating patch through electromagnetic field coupling. Among the five most popular feed techniques used, we have the microstrip line, the coaxial probe, the coplanar waveguide (in both contacting or direct methods), and aperture coupling and proximity coupling (both non-contacting and indirect methods).

2.3.5.1 Microstrip line feeding method

The configuration of this particular feed technique is illustrated in Figure 2.7, where a conducting strip is directly connected to the edge of the microstrip patch. The conducting strip is narrower in width compared to the patch, and this feed arrangement offers the advantage of enabling the integration of the feed on the same substrate, resulting in a planar structure. The inset carved in the patch serves the ambition of aligning the impedance of the feed line to the patch, eliminating the condition for the use of the extra matching components. This convenient feeding scheme is achieved through precise control of the inset position, simplifying both fabrication and modelling while ensuring impedance matching. Nonetheless, when the dielectric substrate thickness is increased, issues like surface waves and spurious feed radiation arise, limiting the antenna's bandwidth. Additionally, the feed radiation results in undesirable cross-polarized radiation [36].

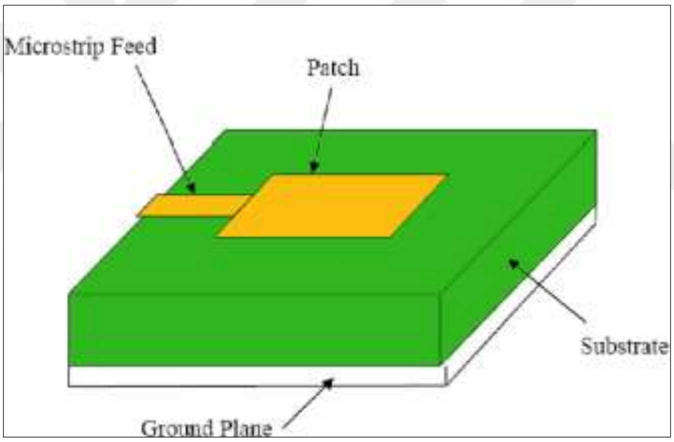


Figure 2.7: Layout of Line Feed for MPA.

2.3.5.2 Coax feeding method

The coaxial feed, commonly referred to as the probe feed, is a popularly used method for the requirements of the feeding for the MPAs. In Figure 2.8, it is evident that the inner conductor of the coaxial connector spreads through the dielectric and is soldered to the radiating patch. Meanwhile, the ground plane is soldered to the outer mesh of the conductor, as demonstrated in Figure 2.8.

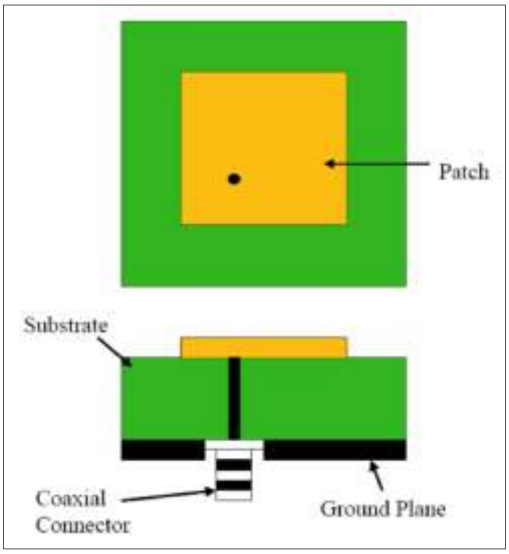


Figure 2.8: Coaxial Method for Feeding MPA.

The principal advantage of the using the coax feed method is its flexibility in putting the feed at any desired position in the patch, enabling effective impedance matching. This feeding scheme is simple to manufacture and displays low spurious radiation. However, it does have some drawbacks. The foremost restriction is its narrow BW, and it becomes difficult to model when operated with a dense type of the substrates as it involves drilling a hole in the substrate and the connector protrudes, affecting its planarity for substrates with thickness (h) greater than 0.02 times the free space wavelength (λo). Additionally, thicker substrates lead to longer probe lengths, causing the input impedance to be more extra inductive and resulting in matching issues. It is evident from the above discussion that both microstrip line feed and coaxial feed face numerous disadvantages when dealing with thick dielectric substrates, where broad bandwidth is desired. To address these concerns, non-contacting feed techniques, which will be discussed in the next subsections, offer solutions to overcome these limitations [37].

2.3.5.3 Aperture coupled feeding method

This feeding way is categorized as the non-conducting scheme, Figure 2.9 depicts how the ground plane is employed in this particular feeding strategy to separate the radiating patch and the microstrip feed line from one another. By use of a slot or aperture that is present in the ground plane, the interaction that is to take place between the patch and the feed line can be established.

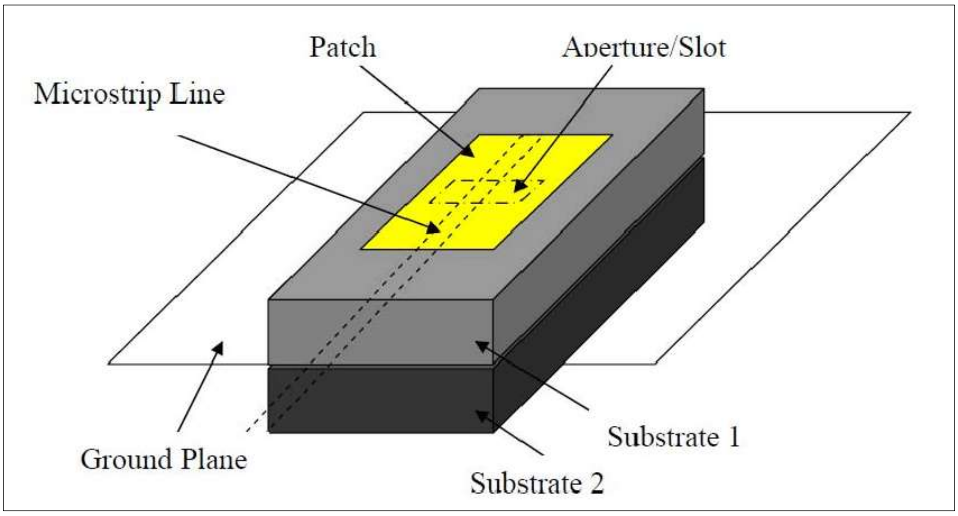


Figure 2.9: Layout for the Aperture Coupled Scheme.

Regularly, to achieve reduced cross-polarization resulting from a symmetric configuration, the coupling aperture is positioned centrally beneath the patch. The extent of coupling between the feed line and the patch depends on the aperture's shape, size, and location. The ground plane serves to separate the patch and feed line, effectively minimizing spurious radiation. For optimal patch radiation, a high dielectric material is employed for the bottom substrate, while a thick substrate with a low dielectric constant is used for the top layer. However, this feed technique comes with a notable drawback – its complex fabrication process involving multiple layers, leading to increased antenna thickness. Additionally, the feeding strategy offers limited bandwidth [37].

2.3.5.4 Proximity coupled feeding method

The electromagnetic coupling way, depicted in Figure 2.10, represents a specific type of feed technique. In this setup, pair of the dielectric substrates are utilized: one is positioned beneath the radiating patch, while the other is placed above the feed line. The feed line is situated between these pair substrates. One significant importance of this approach is its ability to eliminate unwanted feed radiation, leading to optimizing the antenna performance. Additionally, the configuration allows for a relatively broad bandwidth due to the overall increase in the MPA thickness. Another notable benefit of this scheme is the freedom to select different dielectric materials for the patch and the feed line, optimizing their individual performances according to specific requirements [38].

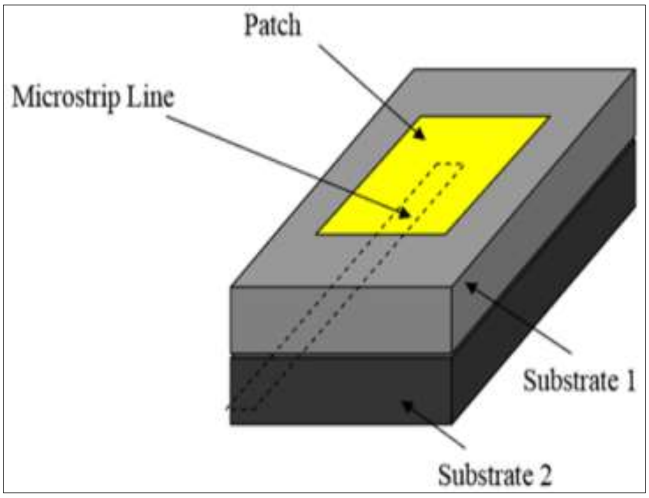


Figure 2.10: Layout for the Proximity Coupled Scheme.

2.4 FUNDAMENTAL PARAMETERS FOR MPA

To comprehensively assess the performance of MPAs and other antenna types, it is crucial to have a clear understanding of several major parameters. These parameters will be elaborated upon in the following subsections to provide a detailed interpretation. By thoroughly examining these key factors, we can gain valuable insights into the overall efficiency, gain, radiation pattern and effectiveness of MPAs and other antennas.

2.4.1 Radiation Pattern

In a general manner, an antenna can be split into three major regions: the reactive field region, the near-field region, and the far-field region. Each of these regions plays a distinct role in the overall behaviour of the antenna. The reactive field region is specified close to the antenna, where the field patterns undergo rapid changes with distance. Within this region, both the radiating energy and the reactive energy coexist, fluctuating towards and away from the antenna. This phenomenon gives rise to an energy-storage reactance without any energy dissipation. As we move further away from the antenna, the reactive fields become less significant, and the radiated energy becomes dominant. In the far-field region, the radiated energy is the primary factor, resulting in a variation of power with direction, independent of distance [38]. A visual representation of these antenna regions can be seen in Figure 2.11.

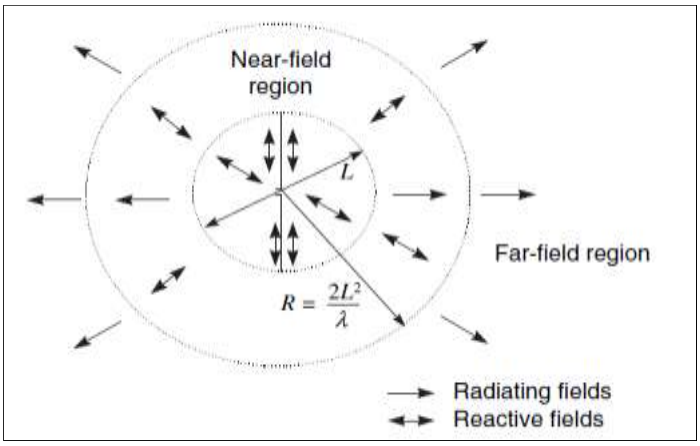


Figure 2.11: Radiation Pattern for General Antennas.

A graphical depiction or mathematical function can be used to describe the amount of power that is radiated from an antenna in relation to the spatial coordinates. This is referred to as the radiation pattern of the antenna. This pattern can be described as having both narrow peaks that are focused and wide peaks that are directed. When it comes to directional antennas, the primary lobe, which is also referred to as the main lobe, displays the most amount of radiation intensity. On the other hand, there are other lobes, such as the side, minor, and back lobes, even though monopoles and dipoles do not have these types of lobes. When it comes to sending antennas, these additional lobes signify the loss of energy, whereas for receiving antennas, they may indicate the presence of noise-causing sources. Please refer to Figure 2.12, which depicts the radiation pattern of a standard antenna, for further information and clarification [38].

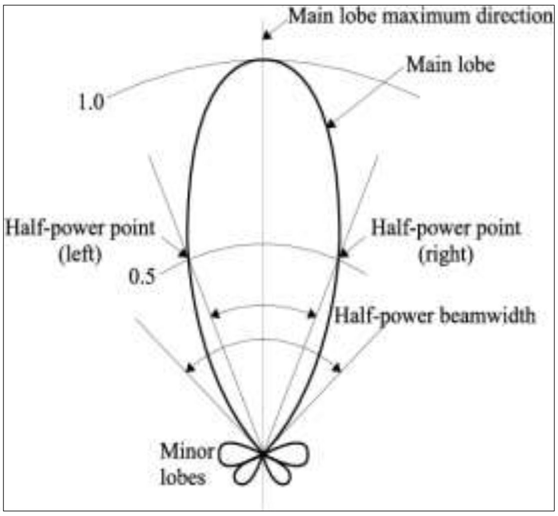


Figure 2.12: Structure for the Radiation Pattern of Different Antennas.

2.4.2 Directivity

An antenna's directivity can be inferred from its radiation pattern thanks to their close relationship. Even though there is no such thing as an isotropic antenna in the real world, it is nevertheless useful to analyse the directional features of antennas by using it as a reference. This is because an isotropic antenna, in theory at least, would emit the same amount of radiation in each of the three dimensions of space. In actual use, each and every type of genuine antenna emits more radiation in some directions than in others. The directivity of an antenna may be calculated by dividing the power density of the antenna in the direction of its maximum radiation in three-dimensional space by the average power density of the antenna. This will give you an answer as to which direction the antenna will radiate the most power. The directivity of an isotropic radiator is exactly 0 or 1 dB depending on the direction. To illustrate, the directivity of a half-wave dipole antenna is either 1.64 or 2.15 dB, depending on the configuration [38].

2.4.3 Gain

When compared to a theoretical antenna, the capacity of an antenna to emit more or less power in particular directions is referred to as its gain. Antennas come in a variety of shapes and sizes. An isotropic antenna would, in principle, emit radiation in a consistent manner in all directions; but, in practise, such an antenna does not exist. In spite of this, the isotropic antenna model is used as a point of reference when calculating the gain of real antennas. In comparison to isotropic antennas, omnidirectional antennas typically have a gain that is 2.1 decibels higher. Because of this, they are able to emit more power in a horizontal direction, but at the expense of transmission efficiency above and below the antenna. This results in a pattern that looks like a donut. However, directional antennas have the potential to reach gains that are greater than 20 dB. These antennas direct the radiation they emit in particular directions, thus removing sizeable chunks from the omnidirectional pattern produced by an omni antenna. As a consequence of this, they are able to significantly extend the range that the signal can be projected. However, one of the drawbacks of high-gain antennas is that they are sensitive to wind-induced position displacement, which can have a negative impact on the performance of the antennas. Yagi antennas, dish antennas, Luneberg lenses, and phased arrays are some examples of the many different configurations that can be used to aid efficient directional RF signal transmission. When it comes to achieving directional gain and improving signal transmission capabilities, each of these designs offers their own set of distinct advantages. Specifically, the gain is associated with the directivity, mathematically the gain can be described as [39]:

$$G = eD \tag{2.5}$$

Where:

G: is describes the antenna gain;

e: is describes the antenna efficiency; and

D: is describes the antenna directivity.

2.4.4 Return Loss (RL)

The RL serves as a critical parameter for assessing the performance of an antenna. It quantifies the antenna's ability to efficiently transfer power from the source to the antenna. The Return Loss is directly influenced by impedance matching and adheres to the principles of the maximum power transfer theory. Mathematically, the RL is defined as the ratio of the incident power on the antenna to the power reflected from the antenna. It can be expressed in terms of power using the following equation [39]:

$$RL = 10\, log_{10} \frac{P_{in}}{P_{ref}} \text{ (dB)} \tag{2.6}$$

Where:

RL: is describes the return loss;

P_{in}: is describes the incident power; and

P_{ref}: is describes the reflected power.

Alternatively, the RL for the antenna can be expressed in terms of the reflection coefficient (г) through the following equation:

$$RL = -20\log_{10}|\Gamma| \tag{2.7}$$

2.4.5 Bandwidth

As per the standard definition, BW refers to a range of frequencies within a wavelength that is specifically designated for a particular communication purpose. When a signal is transmitted or received, it is done over this specified range of frequencies. The allocation of this frequency range to a particular signal ensures that other signals do not interfere with its transmission. Essentially, BW represents the span of frequencies between the upper and lower limits over which a signal is transmitted. Once a BW is assigned for a specific use, it cannot be utilized by others. The entire spectrum is divided into various BW, each of which is allocated to different transmitters to ensure efficient and interference-free communication [40]. The BW practically can be obtained from the RL plot at $RL = -10$ dB, as shown in Figure 2.13.

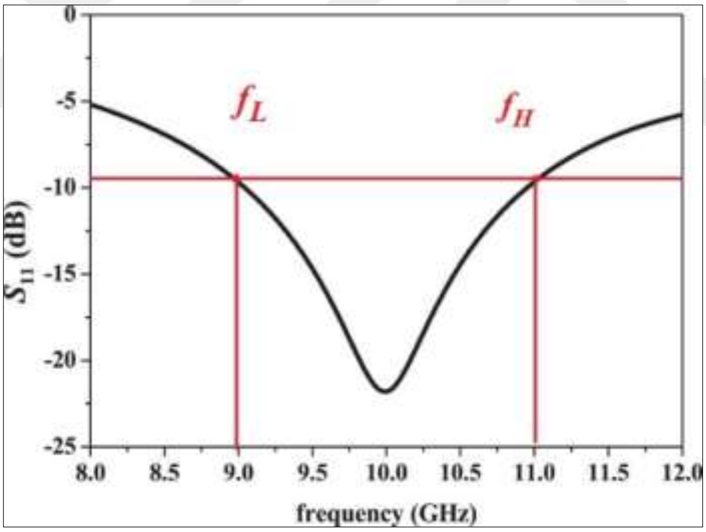


Figure 2.13: Determination of Antenna BW by using RL Plot.

3. GRAPHENE MATERIAL DEFINITION AND CHARACTERISTICS

In this chapter, we delve into an extensive exploration of graphene, covering its fundamental theory, wide-ranging applications, diverse types, and unique characteristics. Throughout the chapter, we aim to provide a comprehensive understanding of this remarkable material and its potential implications in various fields. From its inception in the scientific community to its current cutting-edge applications, we shed light on the significant advancements and discoveries related to graphene. Additionally, we discuss the distinct properties that make graphene stand out among other materials, showcasing its versatility and potential for transformative innovations.

3.1 GRAPHENE MATERIAL THEORY

The extraordinary two-dimensional substance known as graphene is made up of a single sheet of carbon atoms that are organized in a hexagonal lattice, as demonstrated in Figure 3.1. It is frequently referred to as the "wonder material" due to the exceptional qualities it possesses as well as the great potential it has for a variety of uses. Investigating the atomic structure of graphene as well as its electrical features is necessary in order to comprehend the theory that behind its singular properties. Graphene's flawless honeycomb pattern is formed by its hexagonal lattice structure, which results in each carbon atom being connected to three of its neighbouring carbon atoms. Graphene contains carbon-carbon bonds that are extraordinarily stable and demonstrate sp2 hybridization. As a consequence, graphene has a planar structure that possesses an incredible strength-to-weight ratio. Graphene is one of the strongest materials known according to its extraordinary mechanical capabilities, which are made possible by to its unique arrangement, which is even stronger than steel [41].

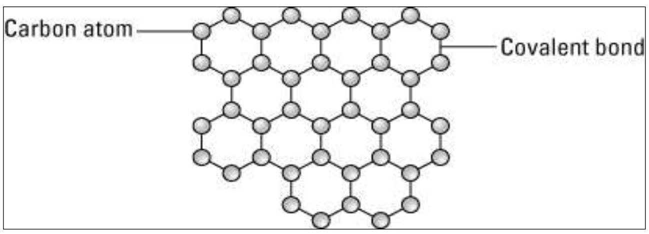
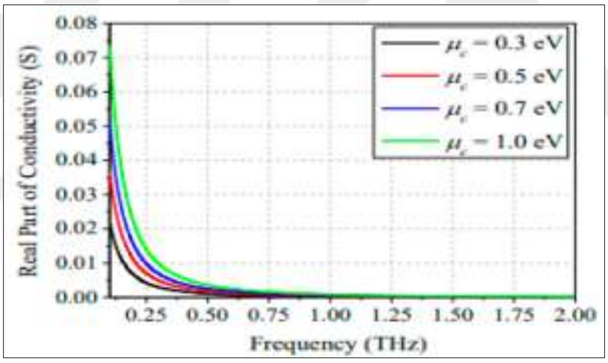
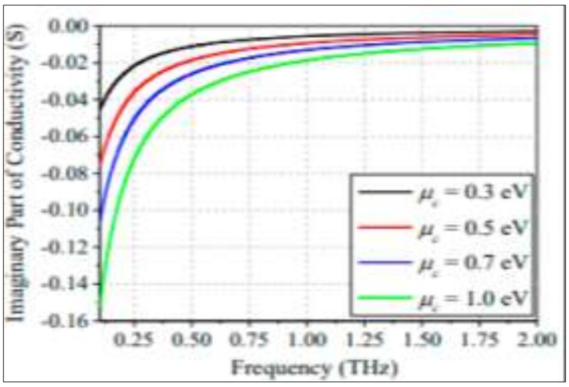


Figure 3.1: Physical Structure for Graphene.

The planar structure of graphene and the delocalization of electrons withing its hexagonal lattice are responsible for its one-of-a-kind electrical capabilities. The electrons have a high degree of mobility and operate in the same way as massless Dirac fermions, demonstrating a linear relationship between energy and momentum dispersion. Within the electronic band structure of graphene, a Dirac cone is used to depict this behaviour. This cone illustrates how the energy of electrons varies linearly with their momentum. Graphene's excellent electrical conductivity is a result of its straight dispersion, which sets it apart from majority of other materials in its class. Graphene's charge carriers have the ability to traverse over extended distances without scattering, which contributes to the material's high electron mobility. This feature has enormous repercussions for electronic devices, where components based on graphene have the potential to outperform those based on standard semiconductors [42]. The super conductivity for this material is appeared significantly in the higher frequency bands, as demonstrated in Figure 3.2.



(a) Real portion



(b) Imaginary portion

Figure 3.2: Characteristic for Conductivity of Graphene.

In addition, graphene has exceptional thermal conductivity, which allows for effective heat dissipation and makes it a desirable option for use in thermal management applications. Graphene's optical qualities are just as remarkable as its other properties. Because it absorbs just about 2.3% of the light that falls on it across a wide range of wavelengths, it has the potential to be used as a material for transparent electrodes in displays, solar cells, and other optoelectronic devices. Furthermore, the amazing mechanical, electrical, and thermal properties of graphene can be further tweaked and increased through functionalization, doping, and the introduction of defects in the lattice. This opens up new pathways for tailoring the properties of graphene to specific applications. In a nutshell, the theory behind graphene material is founded on the fact that it possesses a singular atomic structure, which in turn gives rise to exceptional electrical, mechanical, and optical capabilities. Because of these properties, graphene is an extraordinarily versatile material that has the potential to shape the future of nanotechnology and materials science. Graphene might be used to develop game-changing applications in fields like as electronics, energy storage, sensors, and many more as will explained in the next subsection [42].

3.2 GRAPHENE MANUFACTURING

Graphene is a critical component in the creation of a wide range of cutting-edge products. Graphene, with its one-of-a-kind structure as a two-dimensional lattice of carbon atoms, can serve as a useful starting point for the development of innovative composite materials with superior properties that can be adjusted to specific needs. One particularly significant application of graphene's function as a building block is its use as a component in composites, as shown in Figure 3.3 [43].

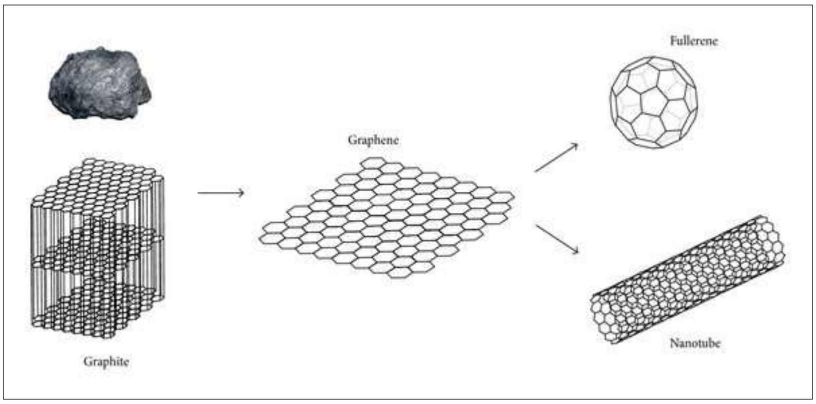


Figure 3.3: Graphene as Building Block for other Materials.

The mechanical, electrical, and thermal properties of composites created by distributing graphene sheets or functionalized graphene in matrices made of polymers, metals, ceramics, or other materials improve significantly. Because of their enhanced strength, hardness, and electrical conductivity, graphene-reinforced composites are appealing for use in a variety of applications, including aviation, automobile manufacturing, and building construction. Furthermore, the surface of graphene can be modified by adding a range of chemical groups, allowing for the precise tailoring of features such as hydrophobicity, adhesion, or catalytic activity. This functionalization paves the way for the development of composite materials with specific desirable properties [43].

Graphene is required as an intermediary stage in the creation of a variety of high-tech carbon-based items. Whereas, graphene may be transformed into a range of other carbon structures using processes such as chemical vapor deposition (CVD) and graphene oxide reduction. Carbon nanotubes (CNTs) and graphite nanoplatelets (GNPs) are two examples of these structures. These derivatives have some of the extraordinary qualities of graphene, but in more than one dimension, and they may be combined into high-performance materials designed for specialised uses [43].

Graphene has the potential to be employed as a material in electronic devices due to its exceptional electrical characteristics. Graphene-based transistors and sensors have recently shown considerable promise due to the material's exceptional carrier mobility and sensitivity. Furthermore, the flexibility of graphene as a structural component extends to numerous energy storage strategies. Graphene is a suitable material for use as an electrode in supercapacitors and lithium-ion batteries due to its large surface area, high electrical conductivity, and great mechanical strength [43].

In other words, graphene is a critical component in the production of a wide range of cutting-edge electronics. The use of graphene in electronic and energy storage devices, as well as its inclusion into composites and transformation into other carbon-based materials, all demonstrate graphene's revolutionary importance in material science and technology. Graphene and its derivatives are expected to have a growing impact on a variety of industries in the future years.

3.3 GRAPHENE UTILIZATIONS

Graphene, with its exceptional properties, has sparked immense interest in a plethora of applications across various industries. One of the most promising and revolutionary areas where graphene finds utility is in electronics and optoelectronics. Graphene's high electrical conductivity, along with its nearly transparent nature, makes it an ideal candidate for flexible, transparent electrodes in touchscreens, displays, and solar cells. Its unique electronic band structure allows for the development of ultra-fast transistors and high-performance electronic devices. Figure 3.4 shows some of the applications that are based on this material [44].

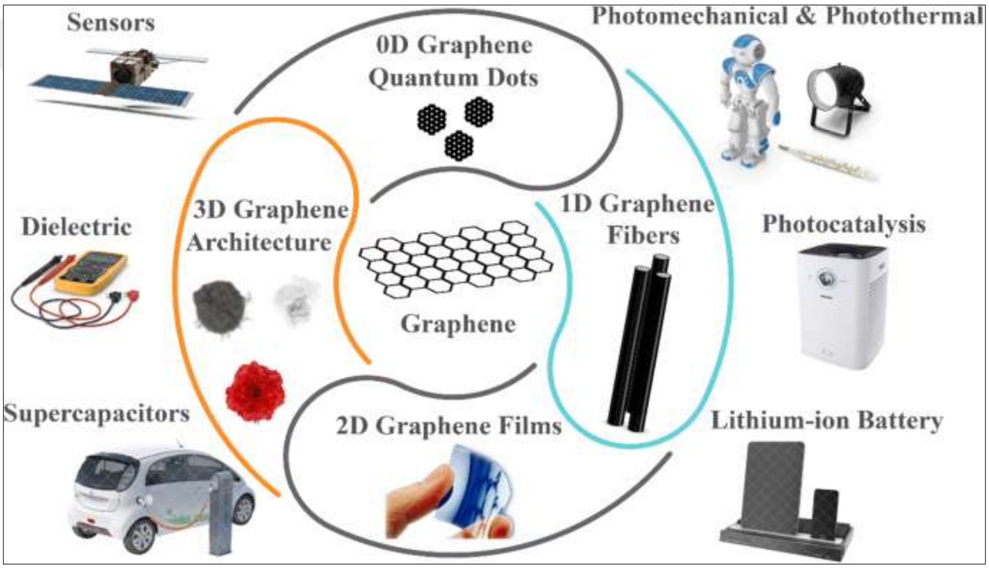


Figure 3.4: Some Utilizations for Graphene.

The field of energy storage is also revolutionized by graphene. Graphene-based materials are integrated into supercapacitors, where their high surface area and electrical conductivity enhance energy storage capabilities. Moreover, graphene's use in lithium-ion batteries leads to higher energy storage capacity, faster charging, and improved durability [44], [45].

Graphene's mechanical strength and flexibility make it valuable in the development of advanced composite materials. Reinforcing polymers, metals, and ceramics with graphene leads to composites with enhanced mechanical properties and conductivity, enabling applications in aerospace, automotive, and construction sectors.

Beyond electronics and energy storage, graphene's biocompatibility and large surface area have significant implications for biomedical applications. It is utilized in drug delivery systems, biosensors, and imaging agents, promising advancements in targeted therapy and disease diagnostics. Environmental applications also benefit from graphene's attributes. Graphene-based membranes are employed in water purification, desalination, and gas separation due to their superior permeability and selectivity.

In the field of sensors, graphene's high sensitivity to changes in its environment makes it an excellent candidate for gas sensors, biosensors, and wearable health monitoring devices. Additionally, graphene's thermal conductivity renders it useful in thermal management applications, such as heat sinks and thermal interface materials. As the scientific community continues to unravel the full potential of graphene, its utilizations are expected to expand even further, shaping the future of technology, healthcare, and sustainability. The remarkable versatility of graphene as a material building block is driving innovation and opening doors to a new era of materials science and engineering.

3.4 GRAPHENE BENEFITS AND LIMITATIONS

Because graphene possesses outstanding qualities, it is capable of delivering a myriad of benefits; nevertheless, it is also subject to some constraints. Both of these features are discussed in this section, and the benefits of graphene can be listed as follows [46]:

a) Graphene is one of the strongest materials known due to its extraordinary mechanical strength and flexibility. Its tensile strength exceeds that of steel, making it an excellent choice for uses that prioritize portability without sacrificing durability.
b) Graphene's extraordinary electrical conductivity is a result of its distinctive electronic band structure. This quality makes it a promising candidate for use in ultra-fast electronics, transparent display electrodes, and advanced energy storage systems.
c) Graphene's superior thermal conductivity makes it a promising candidate for use in thermal management in electronics and other heat-sensitive devices.
d) Graphene is so close to transparent that it transmits virtually all of the light that hits it—roughly 97.7 percent. Because of this quality, it can be used in optoelectronic devices including touch screens, solar cells, and light sources.

e) Because of its high surface area, graphene can be used in a wide variety of applications, including medicine delivery, gas storage, and sensors.
f) Graphene's biocompatibility and promising uses in biomedical fields including drug delivery systems and biosensors pave the way for exciting new medical discoveries.
g) Graphene can maintain its performance and integrity in severe environments and chemical processes since it is chemically stable and generally inert.

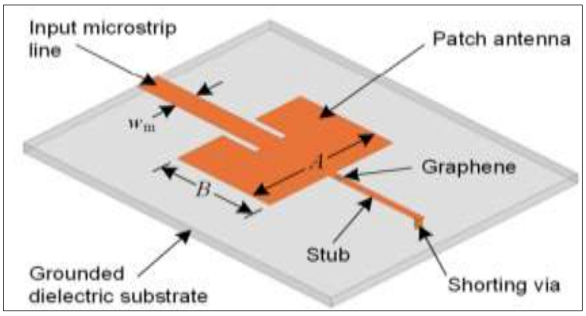
Despite the many promising uses and benefits of graphene, further research and development are needed to overcome its limitations. Graphene has the potential to revolutionize a wide range of sectors as researchers and engineers learn more about it and find ways to mass-produce it. Opposed to the perfect characteristic for this material, there are several limitations and defects the material, which are [47]:

a) High production costs and limited scalability hinder graphene's widespread commercial applications. Despite the necessity for large-scale production methods to reduce prices, scalability remains a problem.
b) Complexity of Synthesis: Graphene synthesis that allows for precise control over its properties can be difficult and time-consuming, necessitating specialized equipment and knowledgeable personnel.
c) Being only one atom thick, graphene is easily broken or scratched during handling or while being incorporated into devices.
d) Due to its unusual electrical structure, graphene cannot be used directly in digital electronics due to the absence of a band gap. Band gap engineering in graphene is still in the works.
e) Environmental Risks: There are ecological risks associated with the mass manufacture and possible disposal of graphene-based materials.
f) Because of safety concerns, graphene and its derivatives need to be extensively studied before they are used widely in biomedical applications.
g) The unique features of graphene and the necessity for compatibility with other materials make it difficult to integrate graphene into current technologies and manufacturing processes.

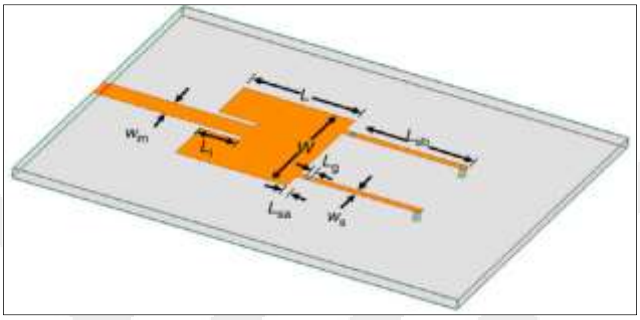
3.5 GRAPHENE BASED ANTENNAS

Graphene is a promising material for improving antenna performance because to its exceptional electrical conductivity, mechanical strength, and flexibility. Graphene has the potential to vastly enhance antennas in terms of signal reception, transmission efficiency, and overall longevity if it is incorporated into antenna designs. Graphene's remarkable electrical conductivity makes it a promising new material for antennas. Due to its high electron mobility and low resistivity, electrical signals can be conducted efficiently, resulting in lower signal losses, better radiation efficiency, and multiple bands, as shown in Figure 3.5. Researchers have showed the ability to obtain better gain and broader bandwidth by adding graphene elements into antenna systems, meeting the ever-increasing needs for quicker, more reliable wireless communication. Graphene's mechanical toughness and adaptability also aid in the creation of antennas that can wrap around irregular surfaces. This quality is very useful in situations when conventional, stationary antennas wouldn't work. The use of flexible graphene-based antennas opens up new opportunities for communication and connectivity in a wide range of contexts, as they can be easily integrated into wearable devices, IoT sensors, and even on irregularly shaped objects [48].

Graphene's use in antenna technology also fits nicely with the movement towards smaller and more compact devices. Since graphene is atomically thin, it can be easily integrated into the tiny substrates often employed in current antennas, allowing for the development of ultra-compact and lightweight antenna systems without sacrificing performance. This is especially helpful for applications where space is at a premium, including compact communication devices and portable gadgets. The graphene's use into antenna design has the potential to radically alter the landscape of wireless communication. Because of its high mechanical strength, low weight, and high electrical conductivity, it can be used in a various of methods to improve antenna performance and open up new avenues of connectivity. As this field of study develops further, novel graphene-based antenna solutions that meet the ever-evolving needs of our interconnected world will become a reality [48].



(a) MPA with Single Stub with Graphene



(b) MPA with Pair Stub with Graphene

Figure 3.5: The Structure for the Graphene-based MPA.

3.6 MATHEMATICAL MODELLING OF GRAPHENE CONDUCTIVITY

The remarkable conductivity exhibited by graphene facilitates the efficient transmission of energy and radiation. Furthermore, the inherent tunability of graphene grants the capability to manipulate not only the resonant frequency of the antenna but also its radiation traits. Additionally, the compact nature of MPAs crafted from graphene deems them highly compatible for assimilation within a multitude of nanoscale devices and systems. As previously stated, the controllable and adjustable nature of graphene's superconductivity can be harnessed by the applying of a DC voltage across the graphene sheet, as visually depicted in Figure 3.6 [49].

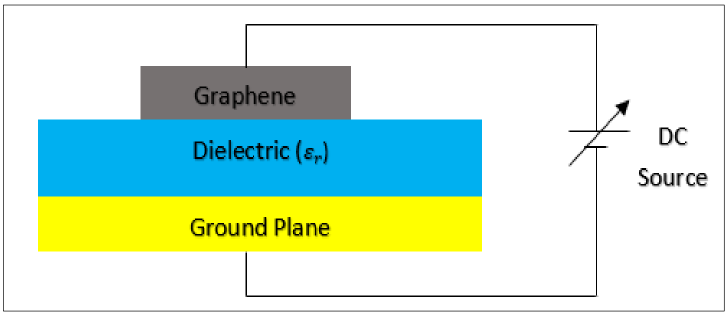


Figure 3.6: Graphene Tuning Process.

To mathematically describe the characteristics of graphene, a Drude-like formulation can be employed, as illustrated by the series of equations outlined in references [50] and [51]:

$$\sigma(\omega,\mu_c,\gamma,T) = \frac{Je^2(\omega - j2\gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega - J2\gamma)^2}\int_0^\infty \in \left(\frac{\partial f_d(\in)}{\partial \in} - \frac{\partial f_d(-\in)}{\partial \in}\right)d\epsilon - \int_0^\infty \in \left(\frac{\partial f_d(-\in) - f_d(\in)}{(\omega - J2\gamma)^2 - 4\left(\frac{\in}{\hbar^2}\right)}\right)d\epsilon\right] \quad (3.1)$$

$$f_d = \left(e^{\frac{(\in - \mu_c)}{K_B T}} + 1\right)^{-1} \quad (3.2)$$

Where:

f_d: is used to describe the allocation of the Fermi-Dirac;

ω: is used to describe the radian frequency;

γ: is used to describe the scattering rate;

μ_c: is used to describe the chemical potential;

T: is used to describe the ordinary inside temperature for the room;

ħ: is used to describe the reduced form of the Planck's constant; and finally,

K_B: is used to describe the Boltzmann constant.

The source of the primary constituent in the preceding equation (3.1) can be attributed to the intra-band phenomenon, while the subsequent term emerges from inter-band interactions. The presentation of the Kubo formula takes on an integral structure, presenting difficulties in both computation and fusion with the Finite-Difference Time-Domain approach. Nevertheless, there exists the potential to optimize the Kubo formula and condense the expression for intra-band conductivity, as elucidated in the subsequent manner [52]:

$$\sigma_{St} = \sigma_{intraband} + \sigma_{interband} \tag{3.3}$$

$$\sigma_{intraband}(\omega, \mu_c, \gamma, T) = \frac{-Je^2(\omega - j2\gamma)}{\pi\hbar^2}\left[\frac{\mu_c}{K_B T} + 2\ln\left(e^{\frac{(-\mu_c)}{K_B T}} + 1\right)\right]\frac{1}{\omega - J2\gamma} \tag{3.4}$$

The dominant factor dictating graphene's conductivity pertains chiefly to the intra-band component, which exhibits remarkable prevalence across an extensive spectrum of frequencies. Throughout the expansive frequency range, the tangible facet of intra-band conductivity vastly surpasses its imaginary counterpart. In regard to the inter-band conductivity, its representation can be given within the subsequent equation [52]:

$$\sigma_{interband}(\omega, \mu_c, \gamma, T) = \frac{-Je^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - (\omega - J2\gamma)\hbar}{2|\mu_c| + (\omega - J2\gamma)\hbar}\right)\frac{1}{\omega - J2\gamma} \tag{3.5}$$

Beyond the threshold of 1 THz, the inter-band conductivity assumes dominance, with its imaginary facet notably outpacing the real component. To find the impedance for the proposed frequency (i.e., 62 GHz) we can use the following equation that is constructed from the intra-band conductivity relation [53]:

$$Z_{surface} = \frac{1}{\sigma_{intraband}(\omega, \mu_c, \gamma, T)} \tag{3.6}$$

$$Z_{surface} = \frac{J\pi\hbar^2(2\pi f(\tau_l\tau_s) - j(\tau_l + \tau_s))}{q^2(\tau_l\tau_s)\left[\mu_c + 2k_B T ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right]} \tag{3.7}$$

In order to obtain the values for the τ_l and τ_s, the set of the following mathematical equations can be used [53]:

$$\tau_l = \frac{\mu_l \, \hbar\sqrt{n\pi}}{q \; v_f} \tag{3.8}$$

$$\tau_s = \frac{4\hbar^2 \, \rho_m {v_{ph}}^2 v_f}{\sqrt{n\pi} k_B T \; D^2} \tag{3.9}$$

Where:

$Z_{surface}$: is describes the surface impedance for graphene;

μ_l: is describes the mobility electron.

τ_l: is describes the long-term scattering;

τ_s: is describes the short-term scattering;

ρ_m: is describes the 2D mass density for graphene;

v_{ph}: is describes the sound velocity of longitudinal acoustic phonons in graphene; and finally,

D: is describes the deformation potential.

The creation of a reconfigurable MPA for indoor applications can be achieved by harnessing the potential of graphene material that is linked with DC voltage. As previously explored, graphene's exceptional electrical attributes stem from its atomic-thin nature, characterizing it as a 2D material. Notably, the conductivity of graphene stands as a malleable attribute, responsive to the modulation of diverse parameters. To effectively simulate graphene within the CST software, a series of essential steps need to be meticulously followed, as illustrated in Figure 3.7.

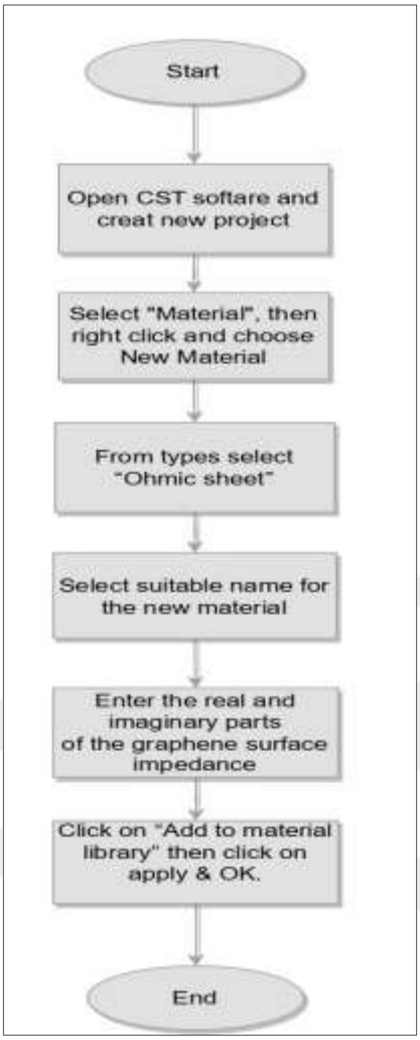


Figure 3.7: Steps for Adding Graphene as an Ohmic Sheet to CST.

4. DESIGN AND EVALUATION OF PROPOSED ANTENNA

This chapter will elucidate the essential procedures involved in designing a rectangular and circular reconfigurable MPA utilizing graphene, tailored for indoor applications operating at 62 GHz. Additionally, the outcomes attained upon the finalization of the designed antennas will be showcased in this chapter.

4.1 DESIGN OF STANDARD RECTANGULAR SHAPE MPA

This study introduces a compact MPA available in both rectangular and circular configurations. These MPA designs are intended for operation within indoors and within the area of institutions, catering to private networks functioning over the 62 GHz frequency range. Leveraging this frequency range facilitates swift, high-capacity data transfers among employees or individuals within the organization's internal network. This, in turn, leads to notable reductions in waiting times, latency, and overall workflow enhancement. To design the standard rectangular shape MPA many of the necessary parameters should be chosen as seen in Table 4.1.

Table 4.1: Principal Parameters for Standard MPA Design.

Parameter	**Value/Description**
MPA operating frequency (f_r)	62 GHz
Substrate type	Roger's RT-5880
Dielectric constant ($\in_r$)	2.2
Dielectric height (h)	0.1 mm

Upon finalizing the specification of the aforementioned elemental parameters, the computation of antenna dimensions commences. To achieve this, the straightforward transmission line analysis method elucidated in sections (2.3.2 and 2.3.3) is employed. The MATLAB software is employed to evaluate the equations pertinent to this method. With the dimensions in hand, the simulation phase is activated by constructing the three-dimensional configuration of the regular MPA within the CST software framework. Detailed dimensional attributes for the standard MPA, inclusive of the feeding mechanism, are visually represented in Figure 4.1.

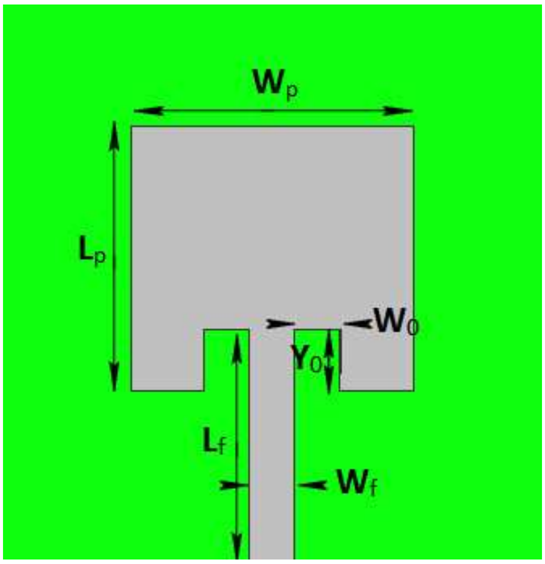


Figure 4.1: Dimensions for Standard Rectangular MPA.

Figure 4.2 illustrates the simulated configuration of the standard rectangular MPA, while Table 4.2 provides the computed dimensions corresponding to the rectangular-shaped conventional MPA.

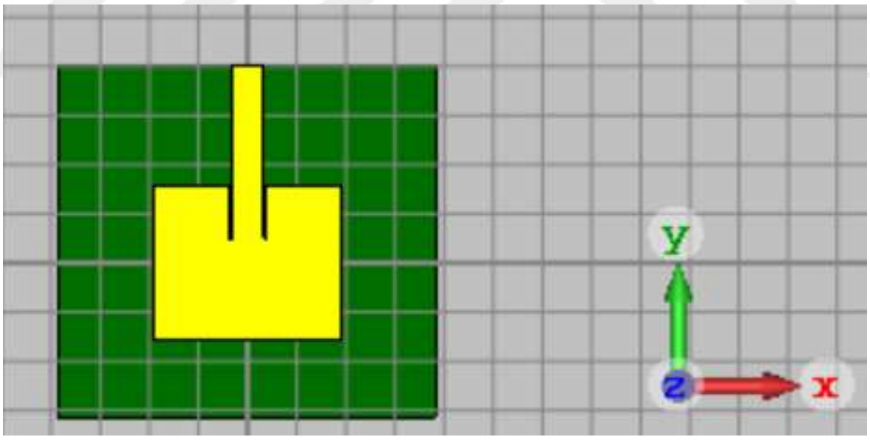


Figure 4.2: Standard MPA in CST.

During the calculation of antenna dimensions and the MPA evaluation process, a discrepancy and mismatching are observed in the resonant frequency, deviating from the intended 62 GHz frequency. This issue requires resolution, and one of the conventional approaches involves adjusting the antenna size (i.e., the dimensions). In this method, the specific dimensions for the patch and the feeding line are either decreased or increased to rectify the resonant frequency misalignment. The resulting adjusted antenna dimensions are outlined in Table 4.3.

Table 4.2: Equations-based MPA Dimensions.

Dimension	**Size in (mm)**
Patch Length (L_b)	1.7670
Patch Width (W_b)	1.9110
Ground Plane Length (L_g)	3.5344
Ground Plane Width (W_g)	3.8225
Feed Line Length (L_f)	1.7670
Feed Line Width (W_f)	0.3081
Feed Line in the Patch (Y_o)	0.5372
Gap Between Feed Line and Patch (W_o)	0.0371

Table 4.3: Modified MPA Dimensions.

Dimension	**Size in (mm)**
Patch Length (L_b)	1.535
Patch Width (W_b)	1.97
Ground Plane Length (L_g)	3.07
Ground Plane Width (W_g)	3.94
Feed Line Length (L_f)	1.76
Feed Line Width (W_f)	0.26
Feed Line in the Patch (Y_o)	0.6
Gap Between Feed Line and Patch (W_o)	0.05

4.2 DESIGN OF STANDARD CIRCULAR SHAPE MPA

In this section, a compact standard circular MPA is designed and simulated for indoor applications based on 62 GHz. In the same previous manner, to design the standard circular shape MPA many of the necessary parameters should be chosen as seen in Table 4.4.

Table 4.4: Principal Parameters for Standard MPA Design.

Parameter	Value/Description
MPA operating frequency (f_r)	62 GHz
Substrate type	Roger's RT-5880
Dielectric constant ($\in_r$)	2.2
Dielectric height (h)	0.1 mm

Upon finalizing the specification of the aforementioned elemental parameters, the computation of antenna dimensions commences. The same equations of sections (2.3.2 and 2.3.3) are employed to calculate the substrate, ground plane, and strip feed line. In order to find the circular patch dimensions, the following equation is used:

$$a_e = a\left\{1 + \left(\frac{2h}{\pi a \in_r}\right)\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}} \tag{4.1}$$

$$a = \frac{F}{\{1 + \frac{2h}{\pi \in_r F}[\ln\left(\frac{\pi F}{2h}\right) + 1.7726]\}^{\frac{1}{2}}} \tag{4.2}$$

$$F = \frac{8.791 \times 10^9}{f_o\sqrt{\in_r}} \tag{4.3}$$

Where:

a_e: is describes the effective radius of the circular patch; and

a is describes the radius of the antenna.

The MATLAB software is employed to evaluate the equations pertinent to this method. With the dimensions in hand, the simulation phase is activated by constructing the three-dimensional configuration of the standard MPA within the CST software framework. Detailed dimensional attributes for the standard circular MPA, inclusive of the feeding mechanism, are visually represented in Figure 4.3 while Table 4.5 shows the calculated and modified dimensions for the circular MPA.

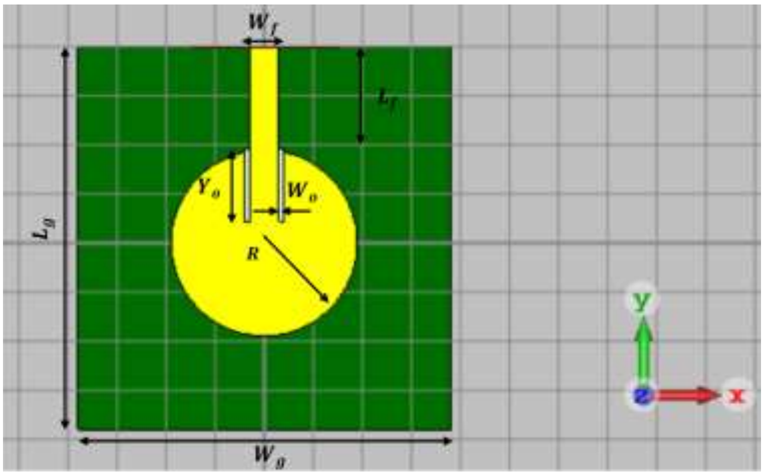


Figure 4.3: Dimensions for Standard Circular MPA.

Table 4.5: Circular MPA Dimensions.

Dimension	Calculated value	Modified value
Patch Radius (R)	0.9320 mm	0.95 mm
Length of the Ground Plane (L_g)	3.7280 mm	3.8 mm
Width of the Ground Plane (W_g)	3.7280 mm	3.8 mm
Length of the Strip Line (L_f)	1.7674 mm	1.7674 mm
Width of the Feed Line (W_f)	0.3081 mm	0.3 mm
Feeding Insert in the Patch (Y_o)	0.7264 mm	0.73 mm
Separation Between Strip Line and Patch (W_o)	0.0326 mm	0.05 mm

4.3 GRAPHENE BASED RECONFIGURABLE MPA

To exemplify the utilization of graphene material in reconfigurable antennas, the central focus lies in examining a key design known as a reconfigurable MPA. This work comprises a fusion of a copper rectangular and circular patch embedded with graphene flakes. The subsequent stage in the design procedure involves strategically determining the positions of these graphene flakes on the patch. This determination is guided by an analysis of the surface current distribution across the patch. The aim is to pinpoint locations with reasonable current density accumulation.

In this work, a distinctive property of graphene material comes into play—adujstable surface impedance associated to the DC voltage (V_{dc}). The graphene sheet, employed as voltage-controlled switches, are pivotal in manipulating the current distribution across the patch. As

V_{dc} increases, the impedance of the graphene flakes diminishes, facilitating the flow of current. Conversely, when V_{dc} decreases, the impedance of the flakes rises, allowing only minimal leakage currents to pass while the most value of the current is prevented from passing inside the flakes due to its high resistance. These switchable states can be defined into two operational modes: an "ON" state characterized by a larger patch size (at high V_{dc}) and an "OFF" state characterized by a reduced patch size (at low V_{dc}). This ingenious mechanism empowers the antenna to operate across multiple frequencies, contingent on whether it is in the ON or OFF state. For a visual representation of the current distribution across the rectangular and circular patch shapes, Figures 4.4 and 4.5 are created.

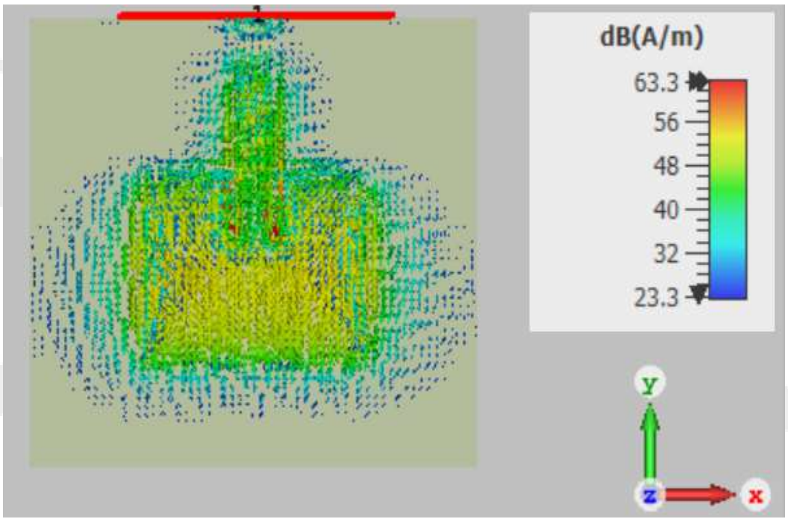


Figure 4.4: Current Allocation on Rectangular Shape MPA.

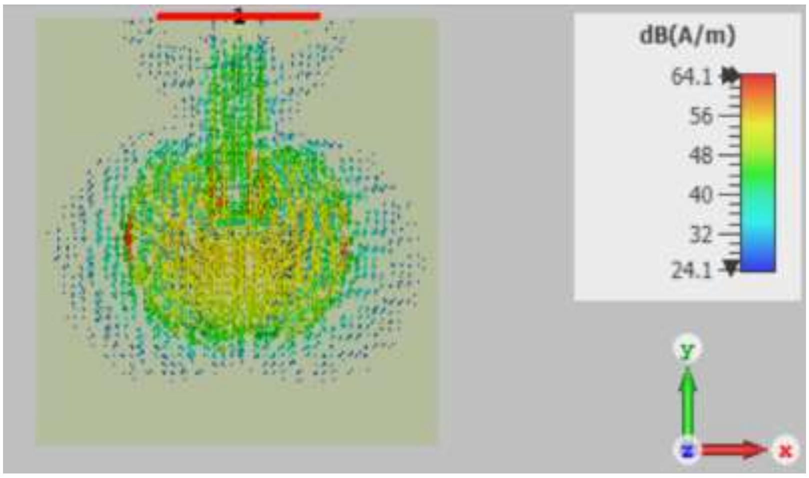


Figure 4.5: Current Allocation on Circular Shape MPA.

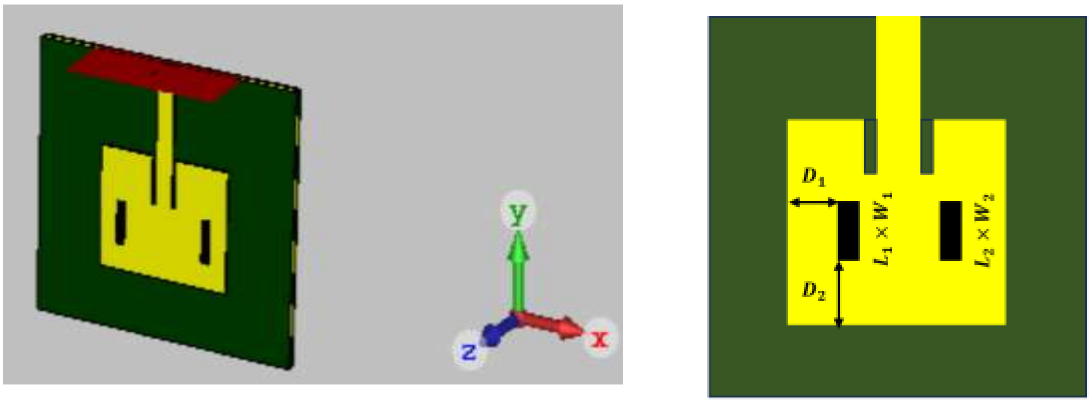
After monitoring the current allocation over the rectangular and circular MPA, the flakes of the graphene are etched to the position of the reasonable current in the form of uniform slots. By employing the graphene slots a frequency reconfigurable MPA will be generated. In this context, the shapes and location on the slots is govern the shifting in the resonant frequency.

The V_{dc} value can be readily applied to the graphene flakes, a process achievable via the antenna's feeding port. To effectively incorporate the graphene material into the CST software, the impedance of the flakes is derived using MATLAB software. This calculation is based on the set of equations outlined in section (3.6). The magnitude of the impedance of the graphene flakes is established by manipulating the density of charge carriers. This adjustment involves either minimizing or maximizing the density, as detailed in Table 4.6.

Table 4.6: Parameters and Constants for Graphene Impedance Modelling.

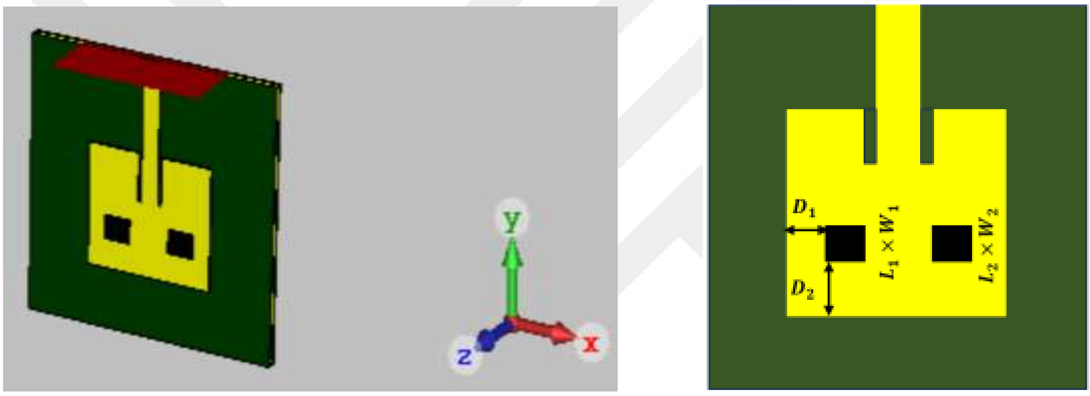
Parameters	**Description**	
μ_l(m^2/Vs)	2.7	
D (eV)	4	
T (K)	295	
f_o (GHz)	62	
Case	ON	OFF
V_B (V)	30	0.2
n (m^{-1})	3.48×10^{17}	6×10^{14}
Z_S	8.231+ 4.625i	2570+74.92i

In this work, a several shapes and positions for the graphene slots are etched in the rectangular and circular MPA. Figures 4.6-4.9 exhibits the simulated rectangular and circular MPA with graphene and Table 4.7 exhibits the position for the slots on the patch.



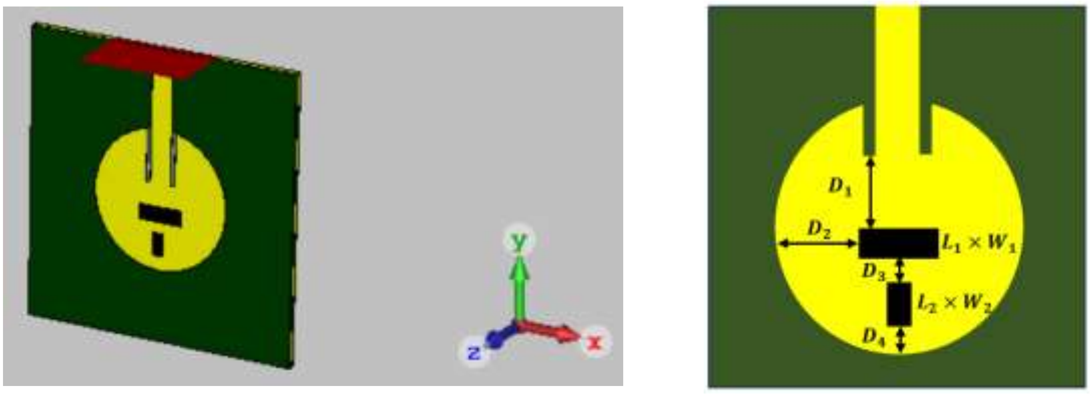
(a) Designed antenna (b) Schematic illustration

Figure 4.6: First Design for the Rectangular Shape MPA.



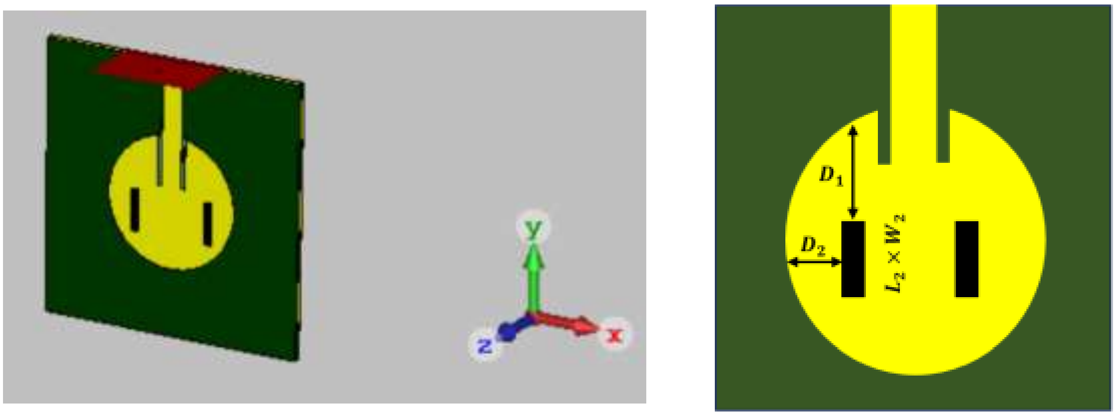
(a) Designed antenna (b) Schematic illustration

Figure 4.7: Second Design for the Rectangular Shape MPA.



(a) Designed antenna (b) Schematic illustration

Figure 4.8: First Design for the Circular Shape MPA.



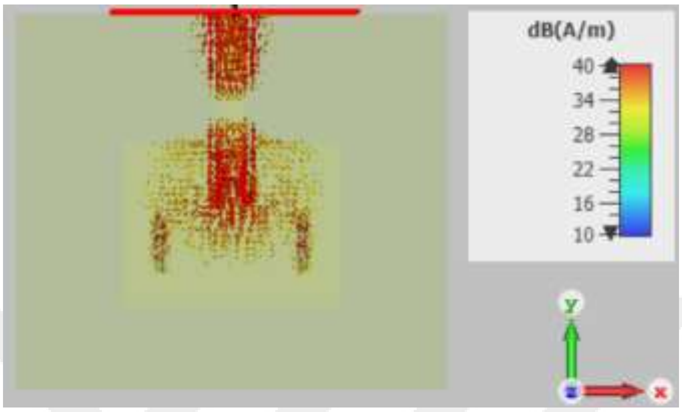
(a) Designed antenna (b) Schematic illustration

Figure 4.9: Second Design for the Circular Shape MPA.

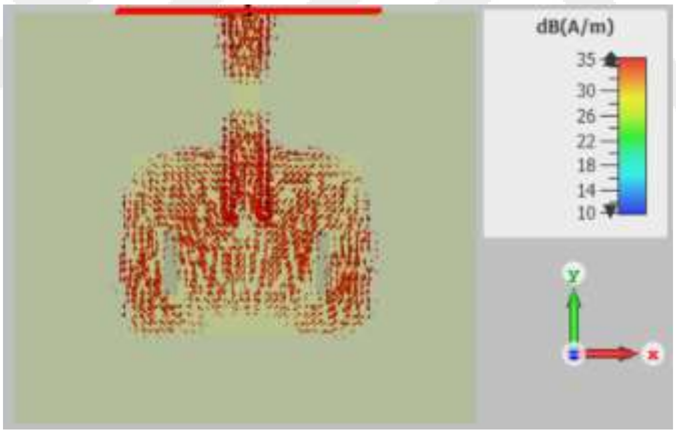
Table 4.7: Dimensions and Position for Slots on the Designed MPAs all in (mm).

Design	D_1	D_2	D_3	D_4	W_1	L_1	W_2	L_2
1st Rectangular MPA	0.26	0.32	0.26	0.32	0.12	0.54	0.12	0.54
2nd Rectangular MPA	0.24	0.36	0.24	0.36	0.4	0.3	0.4	0.3
1st Circular MPA	1.04	0.62	0.15	0.2	0.2	0.6	0.3	0.15
2nd Circular MPA	0.82	0.33	0.82	0.33	0.1	0.6	0.1	0.6

By designing various shapes for the MPA and arranging multiple slot configurations at different positions, we will achieve and demonstrate distinct frequency bands, as elaborated in the results section. When completing the design of the proposed graphene-based MPAs, a surface current monitor is created to observe the current distribution on the patch in both the ON and OFF states. In the ON case, the current is able to pass through the flake due to the low impedance. However, in the OFF state, the current is unable to pass due to the high impedance value, resulting in only leakage current being present on the flakes. This is illustrated in Figures 4.10-4.13.

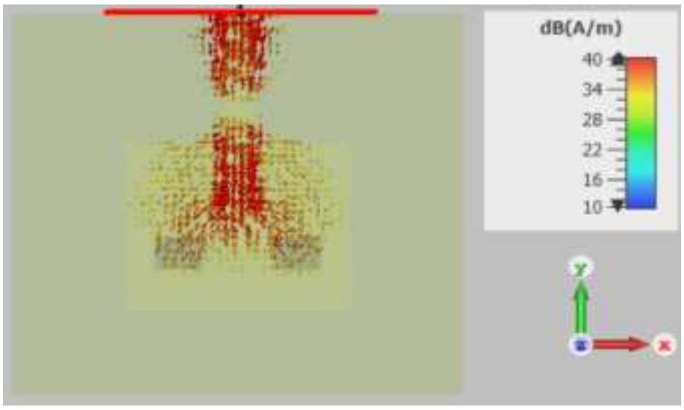


(a) ON case for 1st rectangular shape design

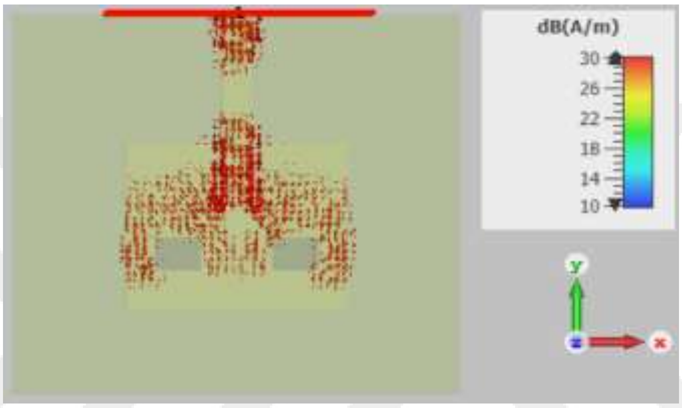


(b) OFF case for 1st rectangular shape design

Figure 4.10: Current Allocation for the 1st rectangular Design.

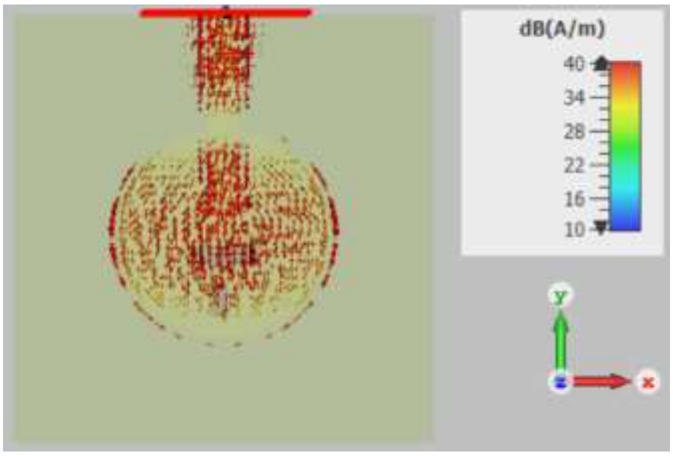


(a) ON case for 2nd rectangular shape design

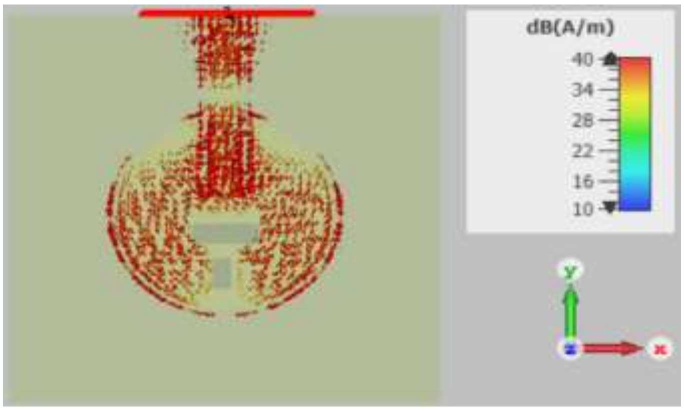


(b) OFF case for 2nd rectangular shape design

Figure 4.11: Current Allocation for the 2nd rectangular Design.

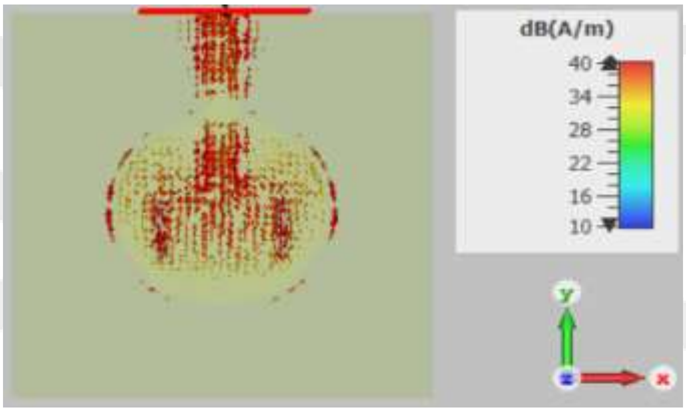


(a) ON case for 1st circular shape design

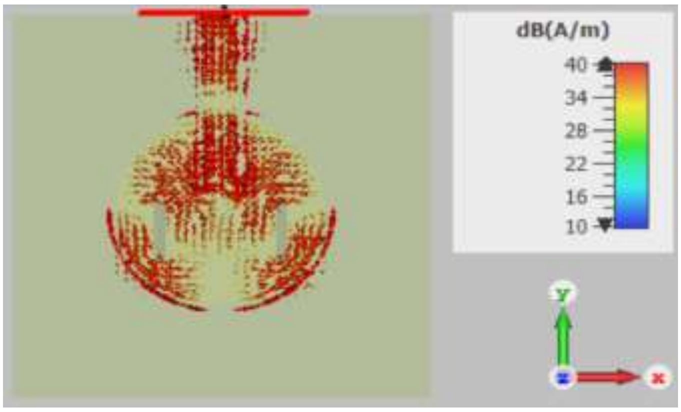


(b) OFF case for 1st circular shape design

Figure 4.12: Current Allocation for the 1st Circular Design.



(a) ON case for 2nd circular shape design



(a) OFF case for 2nd circular shape design

Figure 4.13: Current Allocation for the 2nd Circular Design.

As seen from the previous Figures 4.10-4.13, during the ON case there is a good current pass through the flakes of graphene that are filled a different shape of the engraved slots. While in the OFF case the current isn't able to pass due to the high resistance of the flakes and only the leakage current is available. By employing the ON and OFF cases a several bands of frequency can be reached.

4.4 RESULTS AND DISCUSSION

The subsequent subsections present the results obtained through the CST software for the proposed reconfigurable circular and rectangular MPAs. These results encompass parameters like S_{11}, bandwidth (BW), and antenna gain.

4.4.1 Simulated MPAs S_{11}

Return loss (S_{11}) holds significance in RF circuits, particularly when achieving impedance matching is a priority. It quantifies the ratio of a signal that undergoes reflection due to an impedance mismatch. Typically, an acceptable S_{11} value hovers around -10 dB. This indicates that the MPA effectively absorbs the majority of the applied power (approximately 90%), with only 10% being reflected in the opposite direction (toward the source). Figures 4.14 and 4.15 shows the S_{11} for the rectangular and circular MPA before the procedure for dimensions corrections.

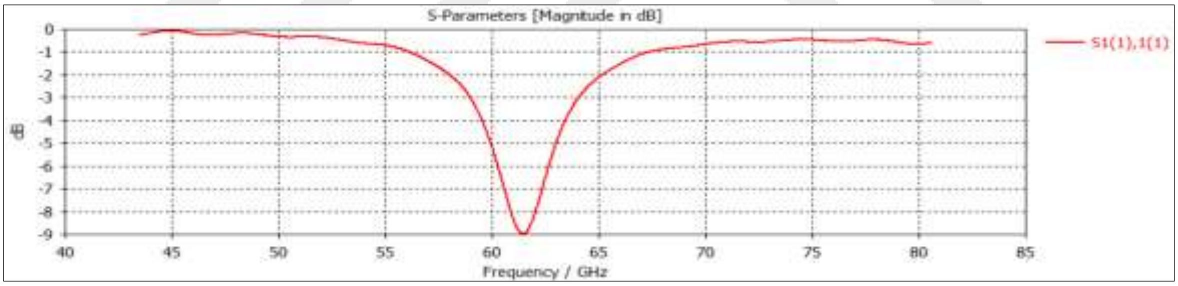


Figure 4.14: Achieved S_{11} for the Rectangular Design MPA.

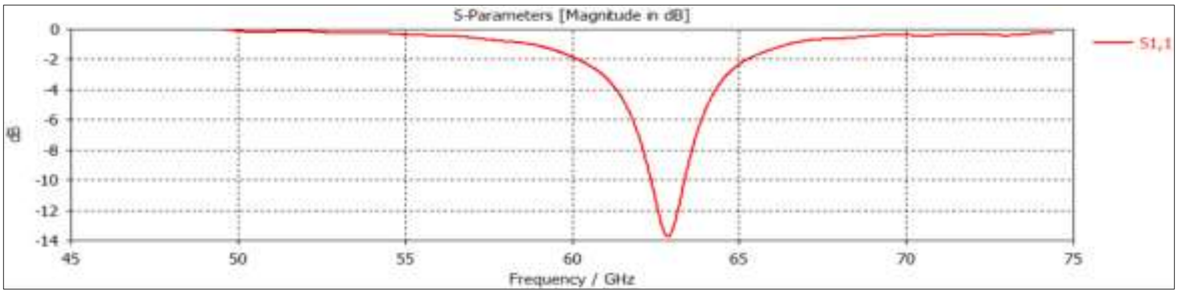


Figure 4.15: Achieved S_{11} for the Circular Design MPA.

As seen from Figures 4.14 and 4.15, that have shown above the center frequency isn't met with the required 62 GHz due to the mismatch issue in the impedance. In order to solve this problem, the procedure for correction the MPA dimensions should be applied. Figures 4.16 and 4.17 exhibits the S_{11} after modified the dimensions.

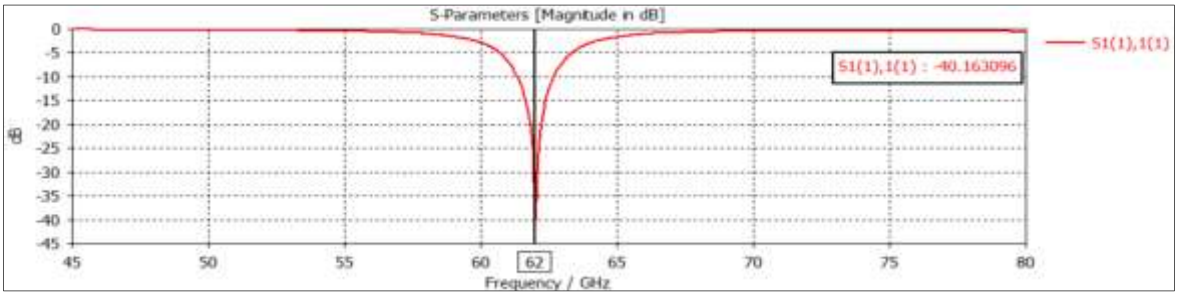


Figure 4.16: Achieved S_{11} for the Modified Rectangular Design MPA.

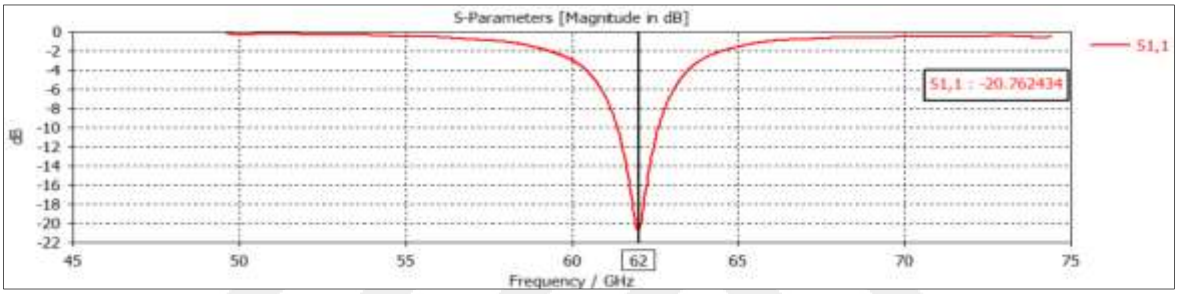


Figure 4.17: Achieved S_{11} for the Modified Circular Design MPA.

By employing a small flake from the graphene, a several bands of frequency are achieved by changing the position, shape of slot, and shape of antenna. Figures 4.18-4.25 shows the S_{11} for the rectangular and circular shape MPA at the ON/OFF cases.

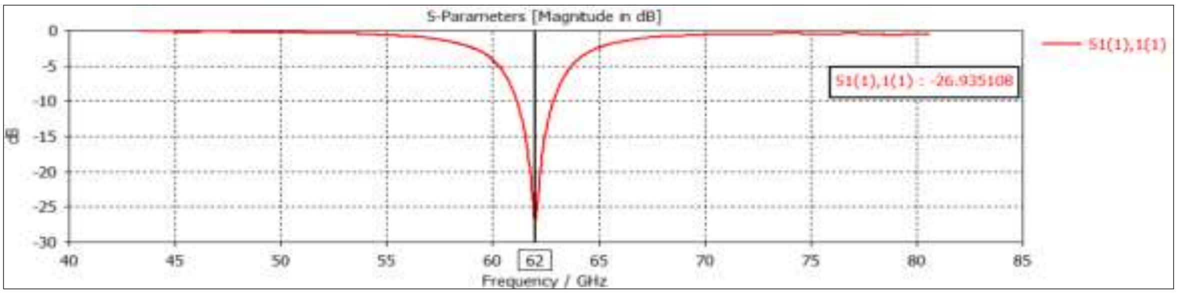


Figure 4.18: Achieved S_{11} for the 1st Rectangular MPA with Graphene at ON case.

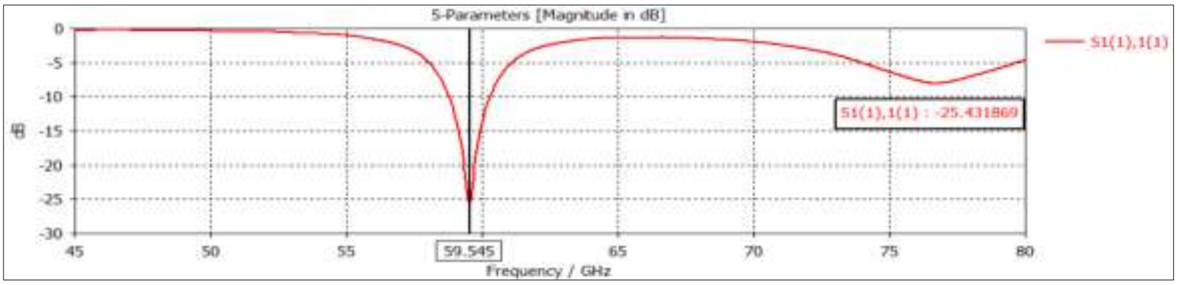


Figure 4.19: Achieved S_{11} for the 1st Rectangular MPA with Graphene at OFF Case.

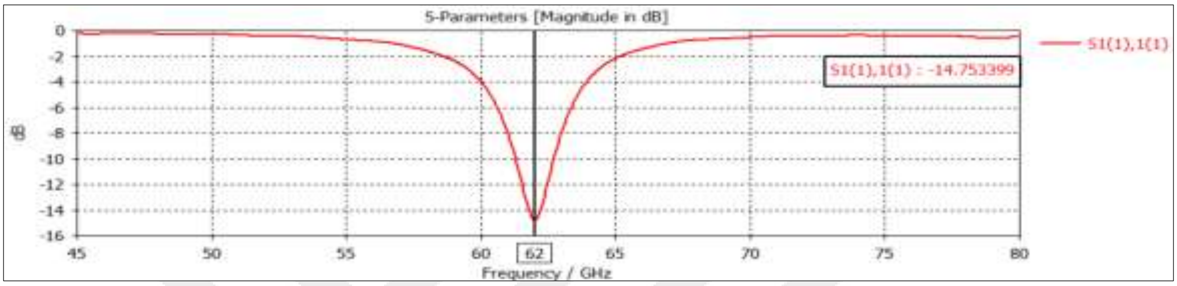


Figure 4.20: Achieved S_{11} for the 2nd Rectangular MPA with Graphene at ON Case.

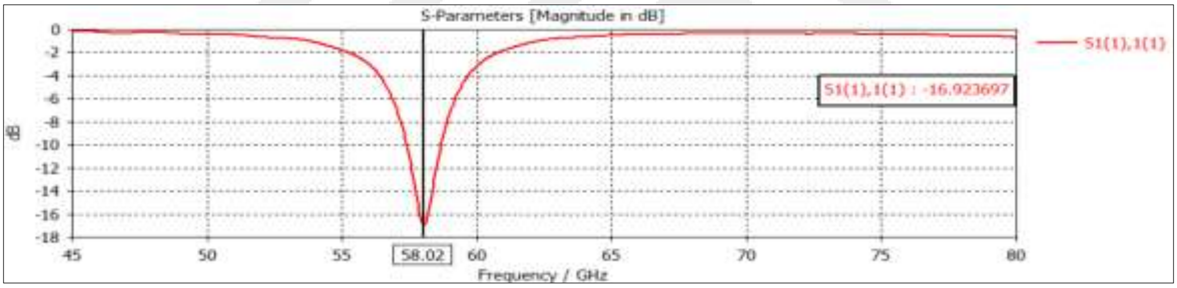


Figure 4.21: Achieved S_{11} for the 2nd Rectangular MPA with Graphene at OFF Case.

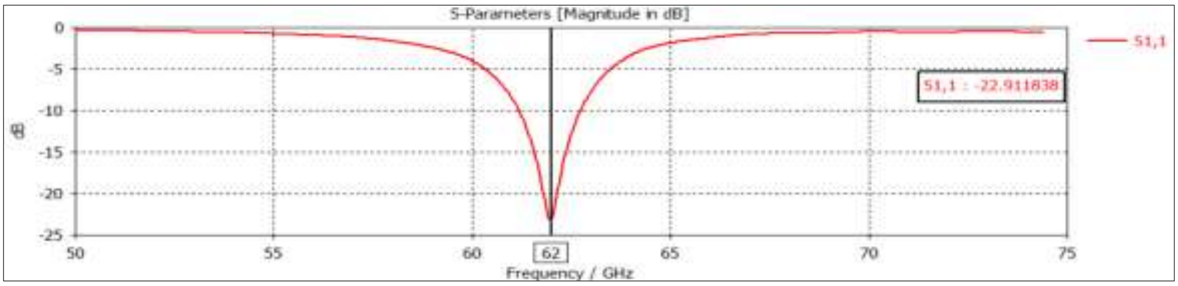


Figure 4.22: Achieved S_{11} for the 1st Circular MPA with Graphene at ON Case.

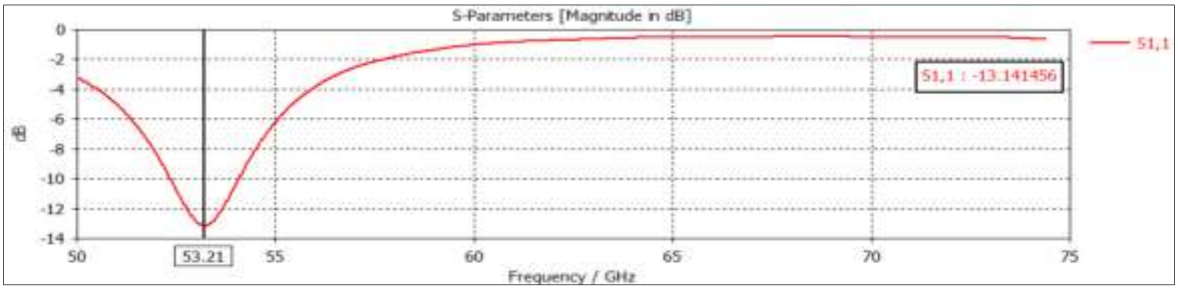


Figure 4.23: Achieved S_{11} for the 1st Circular MPA with Graphene at OFF Case.

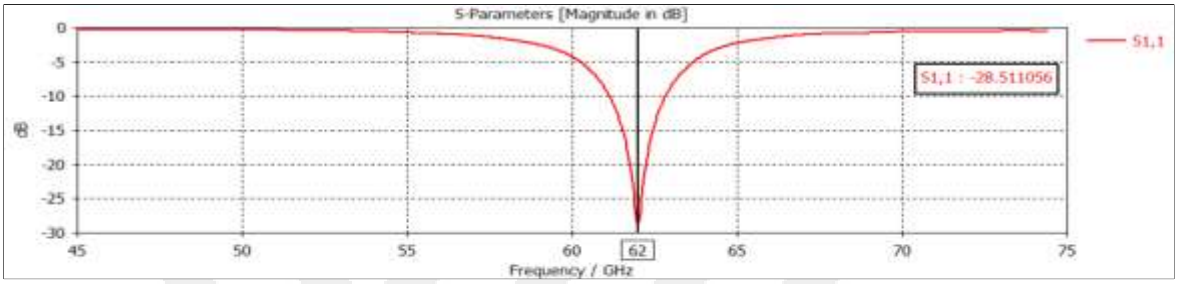


Figure 4.24: Achieved S_{11} for the 2nd Circular MPA with Graphene at ON Case.

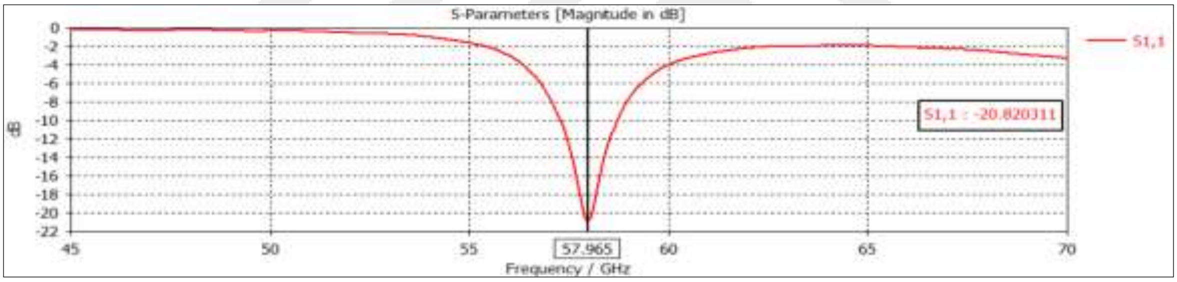


Figure 4.25: Achieved S_{11} for the 2nd Circular MPA with Graphene at OFF Case.

4.4.2 Simulated MPAs BW

The antenna BW refers to the range within which the antenna can operate effectively, delivering optimal performance. The antenna's bandwidth is typically determined by analyzing its S_{11} pattern. From the S-Parameters results, at S_{11}= -9.5 dB the BW can be calculated, Figures 4.26 and 4.27, respectively, exhibit the BW for the rectangular and circular shape MPA after the parameter correction procedure.

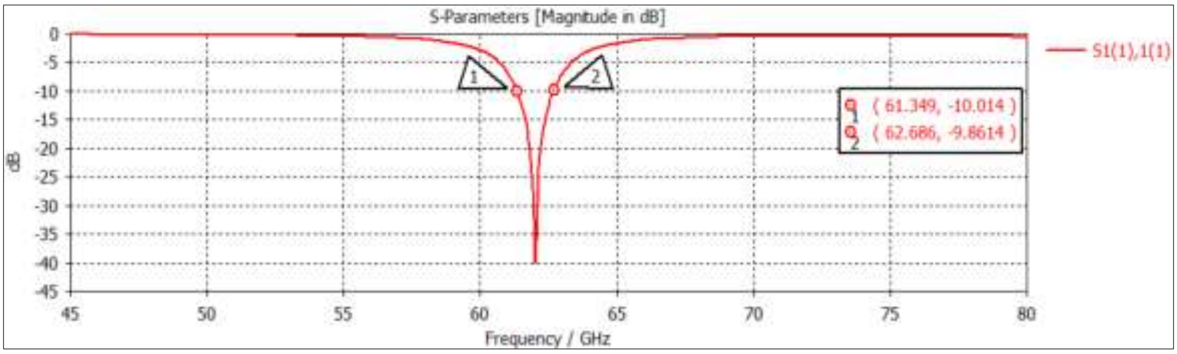


Figure 4.26: Achieved BW for the Corrected Dimensions Rectangular Shaped MPA.

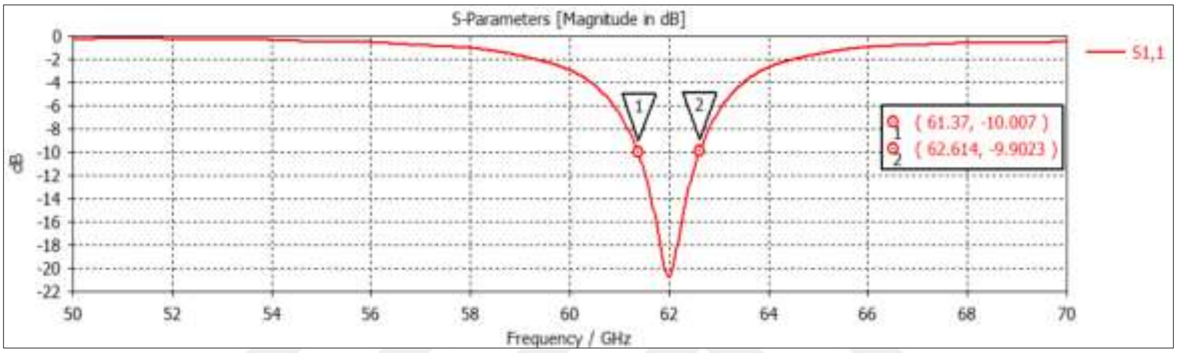


Figure 4.27: Achieved BW for the Corrected Dimensions Circular Shaped MPA.

After employing the flakes of the graphene as slots, dual bands are obtained from each design for ON and OFF cases. The S_{11} for each band are shown in Figures 4.28-4.35.

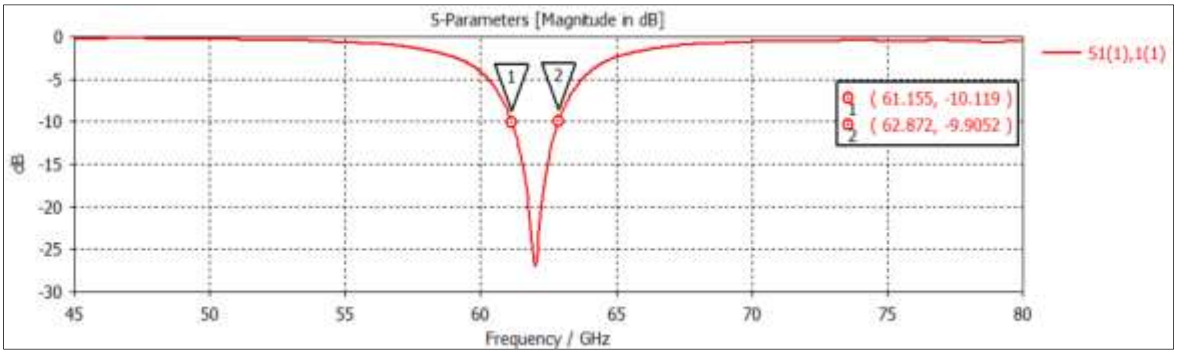


Figure 4.28: Achieved BW for the 1st Rectangular MPA with Graphene at ON Case.

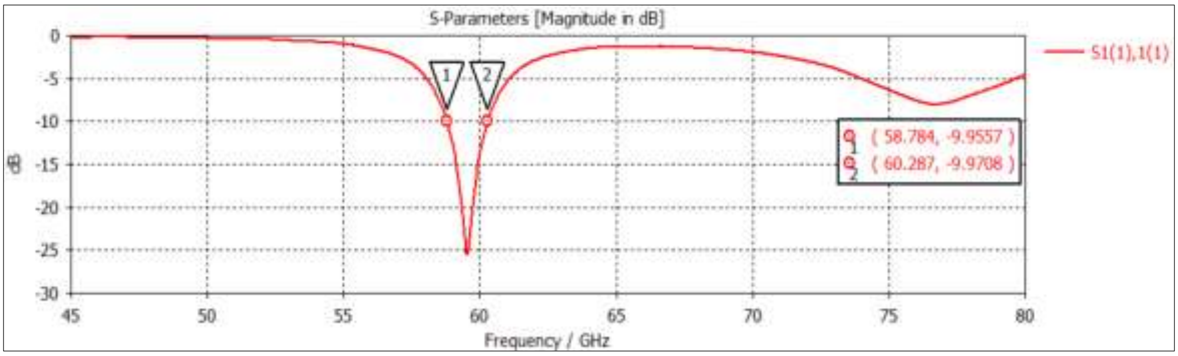


Figure 4.29: Achieved BW for the 1st Rectangular MPA with Graphene at OFF Case.

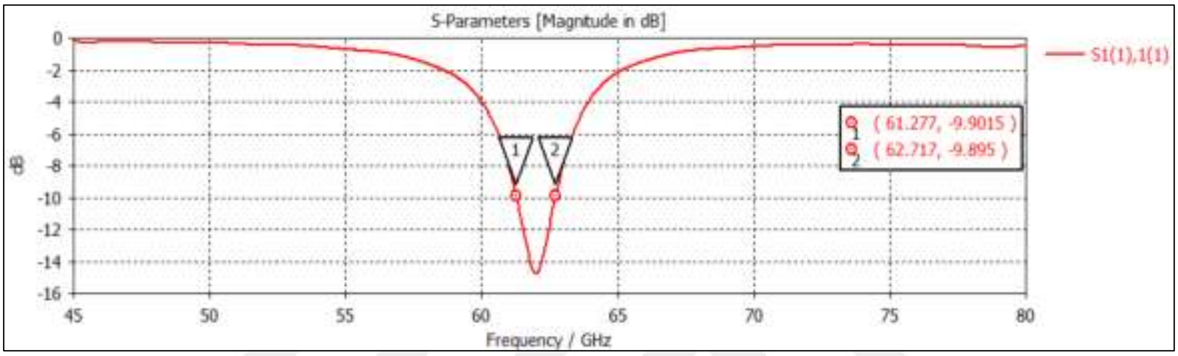


Figure 4.30: Achieved BW for the 2nd Rectangular MPA with Graphene at ON Case.

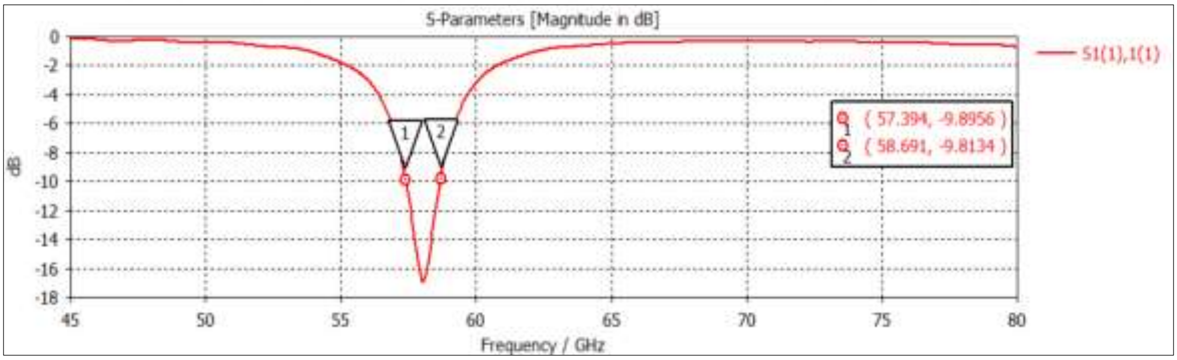


Figure 4.31: Achieved BW for the 2nd Rectangular MPA with Graphene at OFF Case.

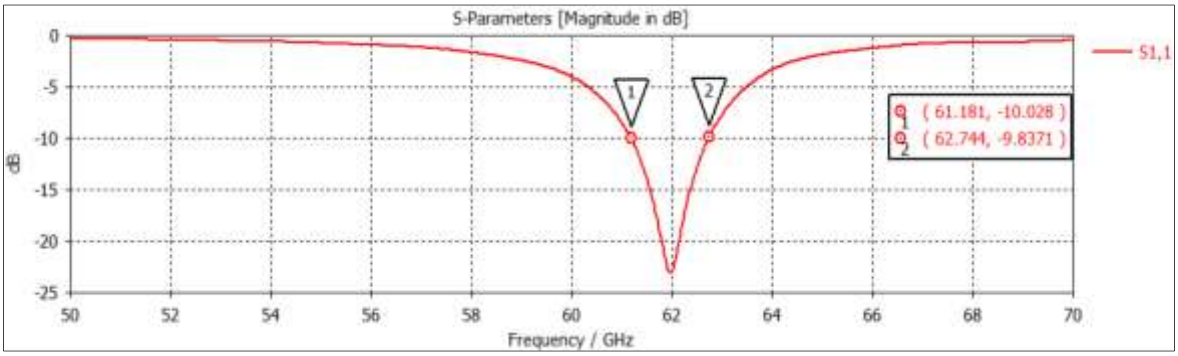


Figure 4.32: Achieved BW for the 1st Circular MPA with Graphene at ON Case.

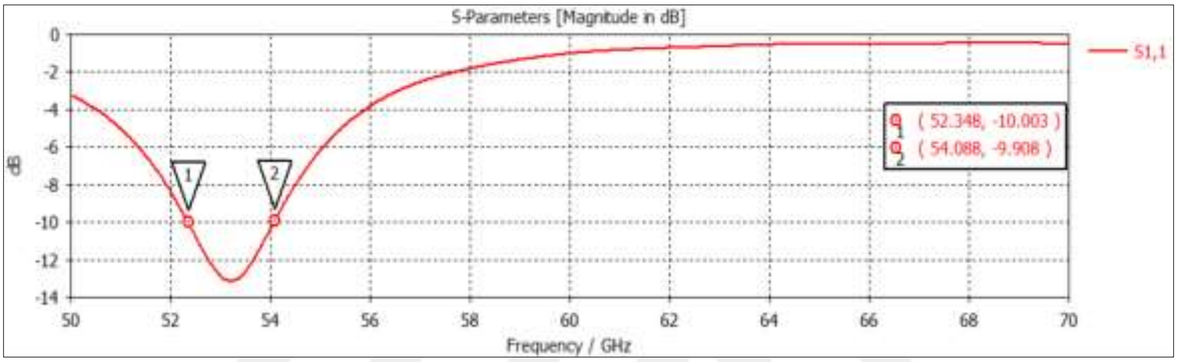


Figure 4.33: Achieved BW for the 1st Circular MPA with Graphene at OFF Case.

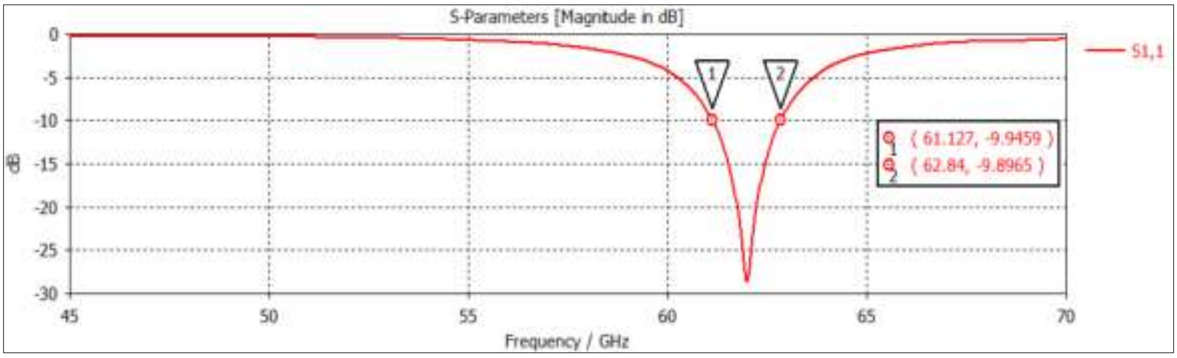


Figure 4.34: Achieved BW for the 2nd Circular MPA with Graphene at ON case.

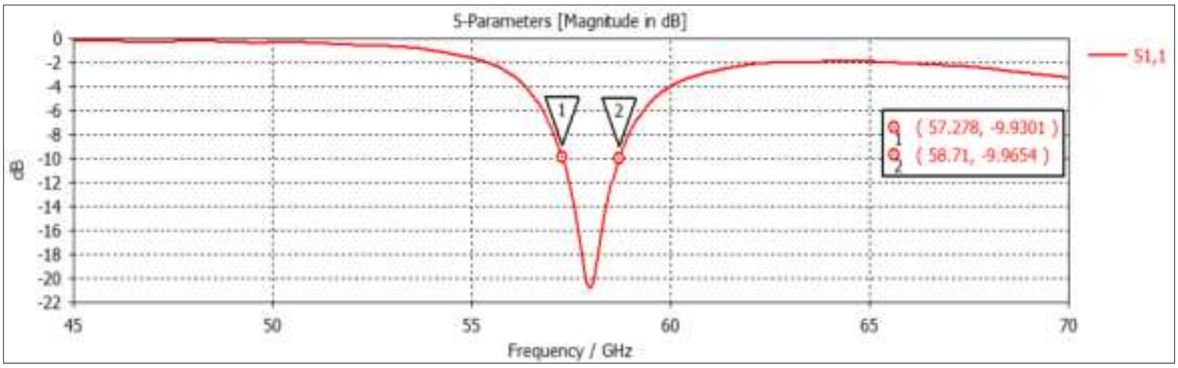


Figure 4.35: Achieved BW for the 2nd Circular MPA with Graphene at OFF Case.

In order to calculate the BW for the designed MPAs, we should subtract the lower frequency (f_1) from upper frequency (f_2), as presented in Table 4.8.

Table 4.8: Calculated BW for the Designed MPAs.

Design		f_1(GHz)	f_2(GHz)	BW (GHz)
Modified Rectangular Shape		61.349	62.686	1.337
Modified Rectangular Shape		61.37	62.614	1.244
1st rectangular design with graphene	ON	61.155	62.872	1.717
	OFF	58.784	60.287	1.503
2nd rectangular design with graphene	ON	61.277	62.717	1.44
	OFF	57.394	58.691	1.297
1st circular design with graphene	ON	61.181	62.744	1.563
	OFF	52.348	54.088	1.74
1st circular design with graphene	ON	61.127	62.84	1.713
	OFF	57.278	58.71	1.432

4.4.3 Simulated MPAs Gain

Another fundamental parameter that governs the MPA performance is the antenna gain. Antenna gain is the measure of an antenna's effectiveness in focusing and amplifying electromagnetic signals in a specific direction, improving signal strength and range compared to an isotropic radiator that radiates equally in all directions. The achieved gain for the MPAs is presented in Figures 4.36-4.45.

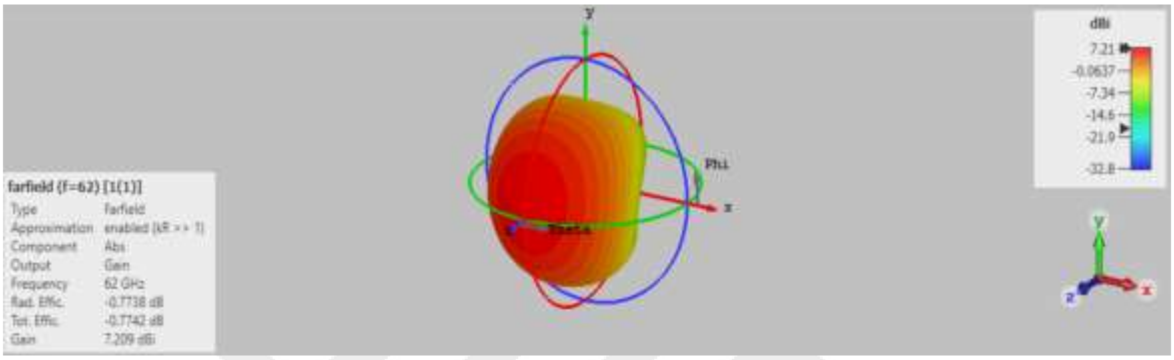


Figure 4.36: Achieved Gain for the Rectangular MPA.

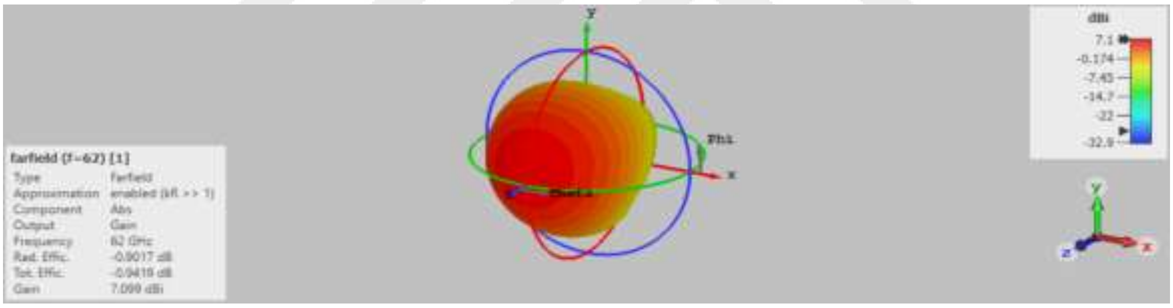


Figure 4.37: Achieved Gain for the Circular MPA.

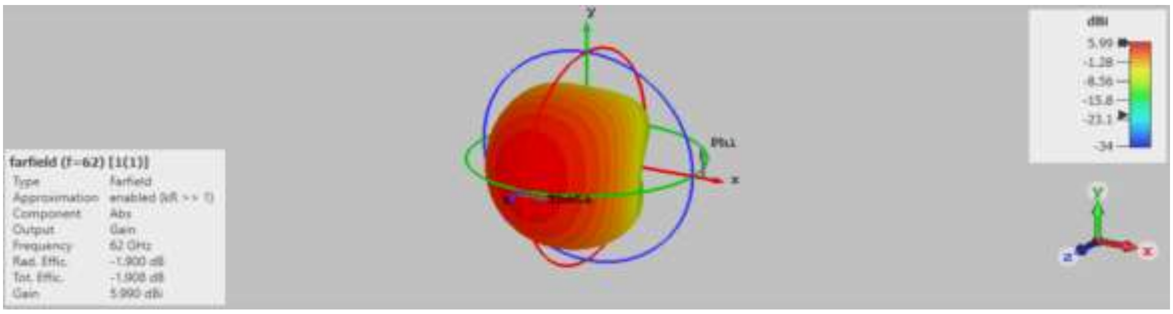


Figure 4.38: Achieved Gain for the 1st Rectangular MPA with Graphene at ON Case.

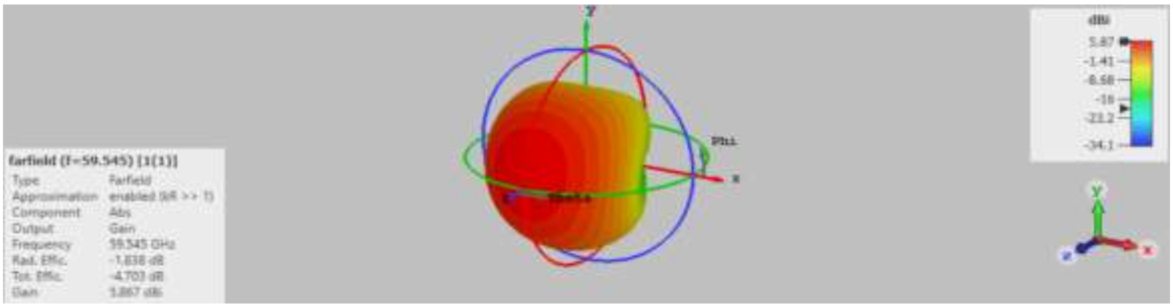


Figure 4.39: Achieved Gain for the 1st Rectangular MPA with Graphene at OFF Case.

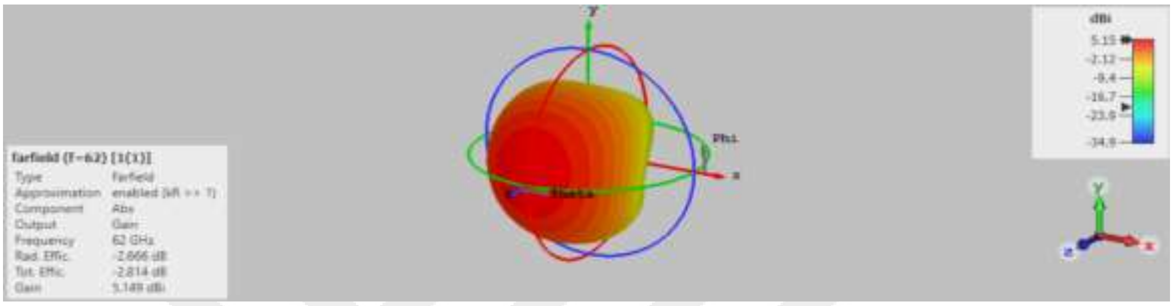


Figure 4.40: Achieved Gain for the 2nd rectangular MPA with Graphene at ON Case.

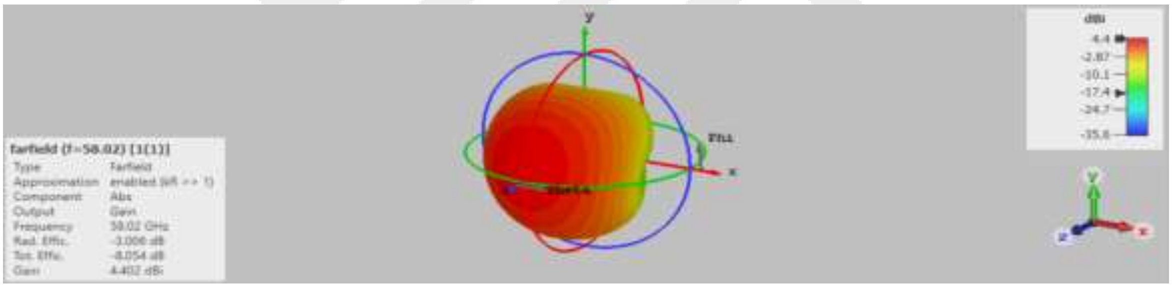


Figure 4.41: Achieved Gain for the 2nd Rectangular MPA with Graphene at OFF Case.

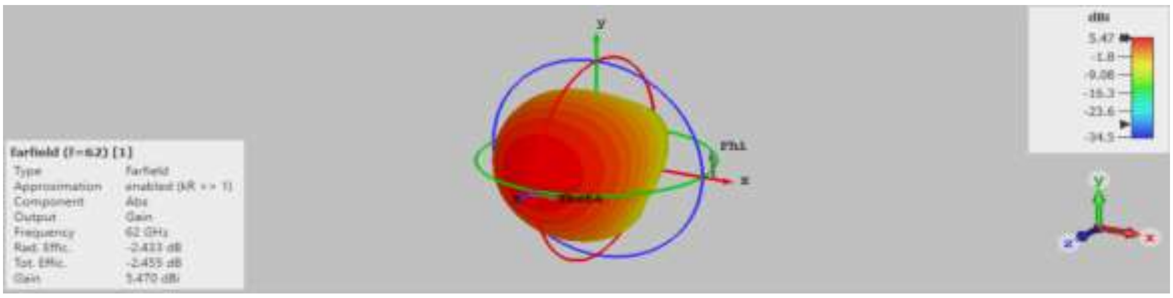


Figure 4.42: Achieved Gain for the 1st Circular MPA with Graphene at ON Case.

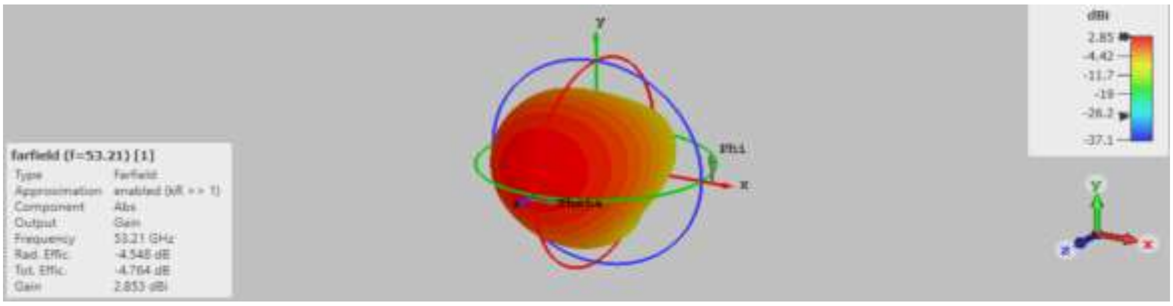


Figure 4.43: Achieved Gain for the 1st Circular MPA with Graphene at OFF Case.

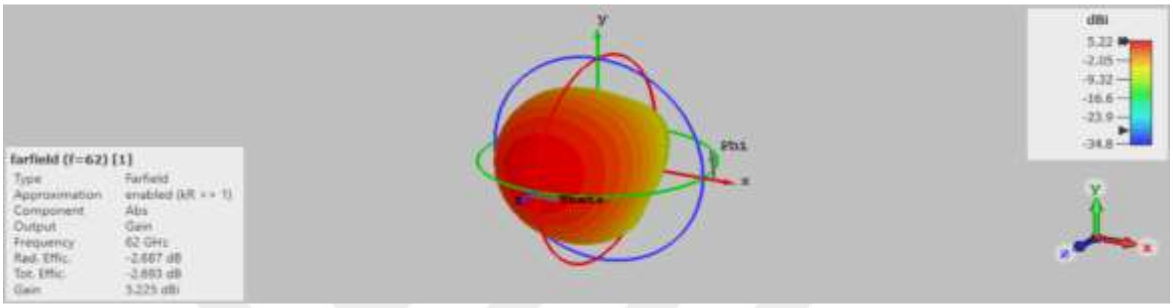


Figure 4.44: Achieved Gain for the 2nd Circular MPA with Graphene at ON Case.

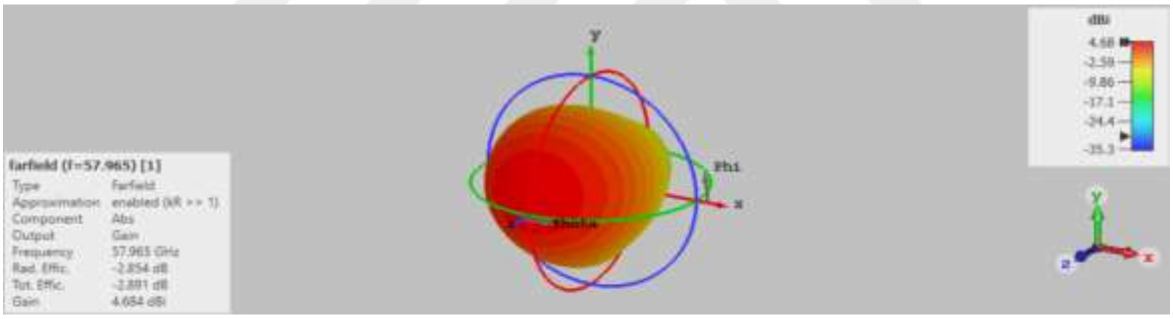


Figure 4.45: Achieved Gain for the 2nd Circular MPA with Graphene at OFF Case.

After concluding the presentation of the results, in order to effectively summarize and compare the attained outcomes across the previously simulated designs, Table 4.9 has been generated.

Table 4.9: Results Comparison for the Designed MPAs.

Design		f_o(GHz)	S_{11} (dB)	Gain (dBi)	BW (GHz)
Modified Rectangular Shape		62	-40	7.21	1.337
Modified Rectangular Shape		62	-20.76	7.1	1.244
1st rectangular design with graphene	ON	62	-26.93	5.99	1.717
	OFF	59.545	-25.43	5.87	1.503
2nd rectangular design with graphene	ON	62	-14.75	5.15	1.44
	OFF	58.02	-16.92	4.4	1.297
1st circular design with graphene	ON	62	-22.91	5.47	1.563
	OFF	53.21	-13.14	2.85	1.74
1st circular design with graphene	ON	62	-28.51	5.22	1.713
	OFF	57.965	-20.82	4.68	1.432

According to the total results that presented in Table 4.9, the MPA gain is affected and drops slightly at f_o=62 GHz when adding the graphene material because this material has a low conductivity in such bands of frequency and increased at the higher frequencies. While the achieved S_{11} is good and the BW is the better due to the tuning capability.

5. CONCLUSION AND FUTURE ADVISE

5.1 CONCLUSION

Over the recent years, wireless communications have undergone a significant evolution, emerging as an indispensable element of everyday life. This transformation has triggered a substantial surge in applications interconnected through wireless networks. However, this rapid expansion has led to issues such as network congestion and a decline in data transmission speed. To address these challenges, a potential solution has been proposed involving the utilization of high frequencies, particularly unlicensed ones. These frequencies are favored due to their extensive coverage range and remarkable data transfer speeds. The majority of MPAs encounter a range of challenges, primarily stemming from their limited gain and narrow bandwidth. In this study, we have focused on the design and simulation of compact conventional rectangular and circular MPAs that integrate graphene slots. This design process was facilitated by leveraging CST antenna analysis software. The primary aim was to cater to personal indoor networks operating within the 62 GHz and less frequency spectrum. Leveraging the tunable conductivity of graphene, our research has successfully yielded multiple frequency bands. This achievement was realized by strategically configuring distinct shapes and positions for both the graphene slots and antenna patches. Remarkably effective operational frequency bands were obtained under both ON and OFF conditions. Specifically, for the rectangular and circular MPAs with various graphene slot configurations, center frequencies were recorded at 62, 59.545, 58.02, 53.21, and 57.965 GHz. Notably, the simulated MPAs demonstrated commendable gain, although a minor degradation was observed due to the inherent low conductivity of graphene in such bands of frequency. One of the standout features of this research is the enhanced tuning capability achieved through the integration of graphene.

5.2 FUTURE ADVISE

The realm of antenna science is expansive, characterized by a diverse range of design methodologies and optimization strategies. To further advance and enhance the performance of this study, numerous modifications can be introduced. These potential modifications are succinctly outlined as follows:

a) The challenge in this work lies in the small size of the antenna and the difficulty of integrating the graphene material with it. Therefore, it will be a good addition in the future when manufacturing and scientific measurement of return losses and gain.
b) Many of techniques can be used to enhance the MPA gain and other parameters such as array, frequency selective surfaces, and the metamaterials.
c) Etching the graphene in the ground plane to create a compact MPA with a large BW

REFERENCES

[1] A. Alsudani and H. M. Marhoon, "Design and Enhancement of Microstrip Patch Antenna Utilizing Mushroom Like-EBG for 5G Communications," Journal of Communications, vol. 18, no. 3, pp. 156-163, 2023.

[2] J. Wu and P. Fan, "A Survey on High Mobility Wireless Communications: Challenges, Opportunities and Solutions," in IEEE Access, vol. 4, pp. 450-476, 2016.

[3] T. Maiwald et al., "A Review of Integrated Systems and Components for 6G Wireless Communication in the D-Band," in Proceedings of the IEEE, vol. 111, no. 3, pp. 220-256, March 2023.

[4] S. Hassouna, M. A. Jamshed, J. Rains, J. U. R. Kazim, M. U. Rehman, M. Abualhayja, and Q. H. Abbasi, "A survey on reconfigurable intelligent surfaces: Wireless communication perspective," IET Communications, vol. 17, no. 5, pp. 497-537, 2023.

[5] S. Alraih, I. Shayea, M. Behjati, R. Nordin, N. F. Abdullah, A. Abu-Samah, and D. Nandi, "Revolution or evolution? Technical requirements and considerations towards 6G mobile communications," Sensors, vol. 22, no. 3, p. 762, 2022.

[6] A. F. M. Shahen Shah, "A Survey From 1G to 5G Including the Advent of 6G: Architectures, Multiple Access Techniques, and Emerging Technologies," 2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV, USA, 2022, pp. 1117-1123.

[7] C. Yeh, G. Do Jo, Y. J. Ko, and H. K. Chung, "Perspectives on 6G wireless communications," ICT Express, vol. 9, no. 1, pp. 82-91, 2023.

[8] P. Pandit, "Review on Characteristics of Wireless Communication Systems," Int. Res. J. Eng. Technol, vol. 6, pp. 1036-1041, 2019.

[9] D. J. Costello, "Fundamentals of Wireless Communication (Tse, D. and Viswanath, P.) [Book review]," in IEEE Transactions on Information Theory, vol. 55, no. 2, pp. 919-920, 2019.

[10] D. Tse and P. Viswanath, "Fundamentals of Wireless Communication," Cambridge University Press, 2005.

[11] Wong, K. D., "Fundamentals of wireless communication engineering technologies," John Wiley & Sons, 2011.

[12] X. Wang et al., "Millimeter Wave Communication: A Comprehensive Survey," in IEEE Communications Surveys & Tutorials, vol. 20, no. 3, pp. 1616-1653, third quarter 2018.

[13] H. Kou, "Wireless Communication System and Its Application in Big Data Remote Monitoring and Decision-Making," Mathematical Problems in Engineering, 2022.

[14] G. Chittimoju and U. D. Yalavarthi, "A comprehensive review on millimeter waves applications and antennas," in Journal of Physics: Conference Series, vol. 1804, no. 1, p. 012205, IOP Publishing, 2021.

[15] A. Moerman et al., "Beyond 5G Without Obstacles: mmWave-over-Fiber Distributed Antenna Systems," in IEEE Communications Magazine, vol. 60, no. 1, pp. 27-33, 2022.

[16] F. Fuschini, E. M. Vitucci, M. Barbiroli, G. Falciasecca and V. Degli-Esposti, "Ray tracing propagation modeling for future small-cell and indoor applications: A review of current techniques," in Radio Science, vol. 50, no. 6, pp. 469-485, June 2015.

[17] G. Chittimoju and U. D. Yalavarthi, "A comprehensive review on millimeter waves applications and antennas," in Journal of Physics: Conference Series, vol. 1804, no. 1, p. 012205, IOP Publishing, February 2021.

[18] S. Khan, M. Farasat, U. Naseem, et al., "Performance Evaluation of Next-Generation Wireless (5G) UAV Relay," Wireless Personal Communications, vol. 113, pp. 945-960, 2020.

[19] N. Ana-Maria, M. Alexandru and P. E. Cristian, "Study of millimeter waves in 5G," 2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), Bucharest, Romania, 2021, pp. 1-4.

[20] J. Min, Y. Li, X. Xia, H. Wang, P. Liu, T. Cao, and H. Ren, "Millimeter wave radar-based motion monitoring method in magnetic resonance imaging system," in Medical Imaging 2023: Physics of Medical Imaging, vol. 12463, pp. 525-532, 2023.

[21] B. M. Motlagh, S. E. Gunnarsson, M. Ferndahl and H. Zirath, "Fully integrated 60-GHz single-ended resistive mixer in 90-nm CMOS technology," in IEEE Microwave and Wireless Components Letters, vol. 16, no. 1, pp. 25-27, Jan. 2006, doi: 10.1109/LMWC.2005.861354.

[22] S. Sur, I. Pefkianakis, X. Zhang, and K. H. Kim, "Wifi-assisted 60 GHz wireless networks," in Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking, 2017, pp. 28-41.

[23] L. C. Paul, R. K. Pramanik, M. M. ur Rashid, M. N. Hossain, M. Z. Mahmud, and M. T. Islam, "Wideband Inset Fed Slotted Patch Microstrip Antenna for ISM Band Applications," in 2019 Joint 8th International Conference on Informatics, Electronics & Vision (ICIEV), IEEE, 2019, pp. 79-84.

[24] U. N. Nissan, G. Singh, P. Kumar, and N. Kumar, "High Gain Terahertz Microstrip Array Antenna for Future Generation Cellular Communication," in 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), IEEE, 2020, pp. 1-6.

[25] W. Yang, K. Ma, K. S. Yeo, and W. M. Lim, "A compact high-performance patch antenna array for 60-GHz applications," IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 313-316, 2015.

[26] D. A. Outerelo, A. V. Alejos, M. G. Sanchez, and M. V. Isasa, "Microstrip antenna for 5G broadband communications: Overview of design issues," in 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, IEEE, 2015, pp. 2443-2444.

[27] D. Guha and Y. M. Antar, Eds., "Microstrip and printed antennas: new trends, techniques and applications," John Wiley & Sons, 2011.

[28] T.K. Sarkar and M. Salazar-Palma, "Maxwell's Original Presentation of Electromagnetic Theory and Its Evolution," in Handbook of Antenna Technologies, Z. Chen, Ed., Singapore: Springer, 2015, pp. 1-15.

[29] A. Q. Khan, M. Riaz, and A. Bilal, "Various Types of Antennas with Respect to Their Applications: A Review," International Journal of Multidisciplinary Sciences and Engineering, vol. 7, no. 3, pp. 1-8, 2016.

[30] J. R. James, P. S. Hall, and C. Wood, "Microstrip Antenna: Theory and Design," vol. 12, IET, 1986.

[31] D. G. Fang, "Antenna Theory and Microstrip Antennas," CRC Press, 2017.

[32] R. Waterhouse, "Microstrip Patch Antennas," in Handbook of Antennas in Wireless Communications, CRC Press, 2018, pp. 6-1.

[33] K. F. Lee, K. M. Luk, and H. W. Lai, "Microstrip Patch Antennas," World Scientific, 2017.

[34] C. A. Balanis, "Antenna Theory: Analysis and Design," John Wiley & Sons, 2016.

[35] N. Sengottaiyan, P. Kalyanasundaram, S. M. Ramesh, R. Gurusamy, and V. Rajmohan, "Design of Novel Rectangular Microstrip Patch Antenna with Improved Gain and Performance Analysis," in 2023 International Conference on Sustainable Computing and Smart Systems (ICSCSS), Coimbatore, India, 2023, pp. 1377-1382.

[36] N. Kumar and N. Sharma, "The Various Feeding Techniques of Microstrip Patch Antenna Using HFSS," Int. J. Electron. Commun. Eng., vol. 6, no. 6, pp. 23-29, 2019.

[37] S. R. Saunders and A. Aragón-Zavala, "Antennas and Propagation for Wireless Communication Systems," John Wiley & Sons, 2007.

[38] H. J. Visser, "Antenna Theory and Applications," John Wiley & Sons, 2012.

[39] B. Biswas and A. Karmakar, "Printed Antennas for Future Generation Wireless Communication and Healthcare," CRC Press, 2023.

[40] P. K. Malik, Z. Lu, B. T. P. Madhav, G. Kalkhambkar, and S. Amit (Eds.), "Smart Antennas: Latest Trends in Design and Application," Springer, 2022.

[41] O. Azzaroni and W. Knoll (Eds.), "Graphene Field-Effect Transistors: Advanced Bioelectronic Devices for Sensing Applications," John Wiley & Sons, 2023.

[42] J. A. Carrasco, P. Congost-Escoin, M. Assebban, and G. Abellán, "Antimonene: A Tuneable Post-Graphene Material for Advanced Applications in Optoelectronics, Catalysis, Energy, and Biomedicine," Chemical Society Reviews, 2023.

[43] A. Kausar, I. Ahmad, M. H. Eisa, M. Maaza, and H. Khan, "Manufacturing Strategies for Graphene Derivative Nanocomposites—Current Status and Fruitions," Nanomanufacturing, vol. 3, no. 1, pp. 1-19, 2023.

[44] X. You, Q. Zhang, J. Yang, and S. Dong, "Review on 3D-printed Graphene-Reinforced Composites for Structural Applications," Composites Part A: Applied Science and Manufacturing, vol. 107420, 2023.

[45] A. G. Olabi, M. A. Abdelkareem, T. Wilberforce, and E. T. Sayed, "Application of Graphene in Energy Storage Device–A Review," Renewable and Sustainable Energy Reviews, vol. 135, p. 110026, 2021.

[46] H. Zhang, D. Yang, A. Lau, T. Ma, H. Lin, and B. Jia, "Hybridized Graphene for Supercapacitors: Beyond the Limitation of Pure Graphene," Small, vol. 17, no. 12, p. 2007311, 2021.

[47] V. B. Mohan, K. T. Lau, D. Hui, and D. Bhattacharyya, "Graphene-based Materials and Their Composites: A Review on Production, Applications and Product Limitations," Composites Part B: Engineering, vol. 142, pp. 200-220, 2018.

[48] M. Yasir, P. Savi, S. Bistarelli, A. Cataldo, M. Bozzi, L. Perregrini, and S. Bellucci, "A Planar Antenna with Voltage-Controlled Frequency Tuning Based on Few-Layer Graphene," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2380-2383, 2017.

[49] H. A. Abdulnabi, R. T. Hussein, and R. S. Fyath, "UWB Single Port Log Periodic Toothed Terahertz Antenna Design Based on Graphene Artificial Magnetic Conductor," Modern Applied Science, vol. 11, no. 3, pp. 86-97, 2017.

[50] H. A. Abdulnabi, R. T. Hussein, and R. S. Fyath, "0.1-10 THz Single Port Log Periodic Antenna Design Based on Hilbert Graphene Artificial Magnetic Conductor," ARPN Journal of Engineering and Applied Sciences, vol. 12, no. 4, pp. 1189-1196, 2017.

[51] F. M. Rasheed and H. A. Abdulnabi, "Multiband Graphene-Based MIMO Antenna in Terahertz Antenna Regime," in 2022 2nd International Conference on Computing and Machine Intelligence (ICMI), IEEE, April 2022, pp. 1-6.

[52] H. A. Abdulnabi, R. Talib, and R. S. Fyath, "Design and Characterization of THz Antenna Using Graphene-Based AMC," LAP LAMBERT Academic Publishing, 2023.

[53] R. H. Abd and H. A. Abdulnabi, "Reconfigurable Graphene-Based Multi-Input Multi-Output Antenna Design for THz Applications," Bulletin of Electrical Engineering and Informatics, vol. 12, no. 4, pp. 2193-2202, 2023.