Design of 60GHz Antenna for 5G Communication Systems.

Talha Anwar, BSc. Eng

Submitted in fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

School of Engineering and Digital Sciences
Department of Electrical and Computer Engineering
Nazarbayev University

53 Kabanbay Batyr Avenue,
Nur-Sultan, Kazakhstan, 010000

Supervisors: Carlo Molardi, Galymzhan Nauryzbayev

April 2024

DECLARATION

I hereby declare that this work named "Design of 60GHz Antenna for 5G Communication Systems" is entirely my own creation, with the exception of the properly cited and quoted passages.

According to my understanding, this has not been part of or submitted for any other degree or certificate at Nazarbayev University or any other national or international institution either before or at the same time.

Name: TALHA ANWAR

Date: April 2024

ACKNOWLEDGEMENTS

I express my utmost gratitude to the divine being, Allah, for bestowing upon me abundant blessings and fortitude during the course of my research endeavor, culminating in its successful completion. I would like to extend my profound gratitude and genuine appreciation to my esteemed supervisors, Professor Dr. Carlo Molardi (lead supervisor, NU Kazakhstan), Professor Dr. Ikechi A. Ukaegbu (principal instructor), Professor Dr. Galymzhan Nauryzbayev (co-supervisor, NU Kazakhstan) and Professor Dr. Arjuna Marzuki (instructor, WOU Malaysia), I would like to express my heartfelt gratitude for acquainting me with the realm of antenna design. I express my gratitude for the consistent provision of motivation, constructive criticism, and patient guidance that you have extended to me throughout my research endeavor. This job would not have been feasible without the instruction and support provided. Dear Professor Dr. Hashmi, I would like to express my gratitude for your amazing direction, encouragement, and valuable talks during our interactions.

I appreciate my family and close friends for their unwavering support through the challenges and downs of my master's program and life. Thank you for believing in me and for everything you've given up so that I might succeed, Baba. I will always appreciate that help. Thank you, Mom, for always believing in me and cheering me on.

To all my friends, who enrich my life with their support, wisdom, and honesty, I offer my deepest gratitude. I want to express my gratitude to my three mentors, Engr. Muhammad Usman Younas, Engr. Ahamd Raza Arif, and Engr. Muhammad Arslan Sami, for all the wisdom they've shared with me over the years. I appreciate all the fun we have together both in and out of the University.

Finally, I'd like to express my gratitude to Prof. Dr. Mehdi Bagheri (My Academic Advisor), who was an invaluable resource throughout my master's program and was there for me when the going got tough. Please accept my sincere appreciation.

ABSTRACT

5G technology was developed to transform mobile communication through fast data rates, reduced latency, and enhanced network capacity. Transitioning to higher frequencies, especially in the millimeter wave region, has presented issues related to signal path and propagation loss. To address these limitations, a systematic examination is being conducted to explore the use of the 60GHz frequency band. This action aims to overcome existing challenges in implementing 5G and prepare the foundation for upcoming generations such as 6G. Utilizing 60GHz frequencies can enhance the capabilities and possibilities of wireless communication, leading to a more efficient and productive network.

This study presents a proposal for a microstrip patch array antenna consisting of four components, designed specifically for 5G wireless applications, with a particular emphasis on the utilization of the 60 GHz millimeter-wave spectrum. The emphasis of the design is on the choice of a single microstrip patch antenna as the primary radiating component using Rogger RT 5880, Teflon, and LTCC A6M as a dielectric substrate. The antenna is designed to function exceptionally well in a wide range of weather situations while simultaneously guaranteeing robustness and dependability.

This master thesis highlights the notable performance variations across Roggers RT5880, Teflon, and LTCC A6M substrates when designing single, two, and four-element patch antenna arrays for 5G communication systems at 60 GHz. The design approach makes use of Computer Software Technology (CST) Microwave Studio, which integrates different dielectric substrates Roggers RT5880, Teflon, and LTCC A6M characterized by a relative permittivity of 2.2, 2, and 5.9 respectively. LTCC A6M substrate offered high-quality antenna performance results when arranged in an elements array using single layer substrate. And Teflon offered better results when arranged in a single and two-elements array. However, the final results emphasize Roggers RT5880 as the best substrate material due to its outstanding characteristics like high gain, high directivity, broad bandwidth, input impedance matching, and compact size. The findings offer useful recommendations for enhancing antenna designs and selecting substrates, ultimately promoting the creation of high-performance antennas customized for modern wireless communication applications.

Table of Contents

LIST OF ABBREVIATIONS

EM	Electro-Magnetic
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
OFDMA	Orthogonal Frequency-division Multiple Access
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
EDGE	Enhanced Data GSM Evolution
ITM	Information Technology and Management
UMTS	Universal Mobile Telecommunications System
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
IoT	Internet of Things
LTE	Long Term Evolution
VSWR	Voltage Standing Wave Ratio
UHD	Ultra-High Definition
SKA	Square Kilometer Array
EHF	Extremely High Frequency
CST	Computer Simulation Technology
QoS	Quality of Service
Mbps	Megabits per second
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine-Type Communications
URLLC	Ultra-Reliable and Low Latency Communications
ITU	International Telecommunication Union
MIMO	Multi Input Multi Output
UHF	Ultra High Frequency
mm-waves	Millimeter waves
LTCC	Low Temperature Co-fired Ceramic
PTFE	Polytetrafluoroethylene
RF	Radio Frequency
SINR	Signal-to-Interference-plus-Noise Ratio
SLL	Side lobe level

uRLLC	Ultra reliable Low Latency Communication
WLAN(s)	Wireless Local Area Network
PIEA	Planar Inverted- R Antenna
PAA	Phased Array Antenna
PCB	Printed Circuit Board
M2M	Machine-to-Machine Communications
LMPs	Link Management Protocols
HPBW	Half Power Beamwidth
FNBW	First Null Beamwidth
EBG	Electromagnetic Band Gap
1D	One Dimensional
1G	First-Generation
2D	Two Dimensional
2G	Second-Generation
3D	Three Dimensional
3G	Third-Generation
4G	Fourth-Generation
5G	Fifth-Generation
6G	Sixth-Generation

LIST OF TABLES

LIST OF FIGURES

LIST OF PUBLICATIONS

T. Anwar, A. Marzuki and I. A. Ukaegbu, "Design of Wideband Microstrip Patch Antenna Array with Improved Feedline for 60GHz Wireless Applications," 2023 IEEE 17th International Conference on Application of Information and Communication Technologies (AICT), Baku, Azerbaijan, 2023, pp. 1-4, doi: 10.1109/AICT59525.2023.10313165.

1 Introduction

The general availability of 5G technology represents a significant turning point in the development of wireless communication, providing exceptional data rates, reduced latency, and the ability to support a wide range of networked devices and applications. The key to accessing these groundbreaking capabilities is the creation and use of high-performance antennas designed for operating in the millimeter-wave frequency ranges, namely inside the 60GHz spectrum. This research project aims to thoroughly investigate the complexities of antenna design and development, specifically focusing on creating a specialized 60GHz antenna designed for 5G systems. We seek to surpass the increasing need for efficient high-frequency communication solutions by exploring the complex characteristics of this particular frequency range. We aim to advance antenna technology through comprehensive investigation and assessment, enabling the optimal integration and use of 5G networks.

1.1 A Concise Historical Overview of Mobile Networks and Their Generations in Communication.

Almost every decade since 1980 has seen the release of a new version of cell phones. Upon examination of the initial generation (1G), it becomes evident that it was equipped with analog radio systems, to allocate available bandwidths into distinct frequency bands, utilized circuit switched networks, and possessed the capability to just transmit voice messages [1], [2]. However, the era of network connectivity encountered challenges pertaining to insufficient bandwidth, compromised security, and suboptimal hand-off mechanisms. The second generation (2G) of mobile telecommunications technology was developed and deployed for commercial usage in the year 1991 [3]. It was made because of the problems with 1G and the growing need for more cell phone capacity. The voice technology for this age was digital, and the time division multiple access (TDMA) scheme was used [4]. It was during 2G that new technologies like GSM (global system for mobile communications), GPRS (also called 2.5G), and EDGE (also called enhanced GPRS) were launched [3]. The circuit-switched domain was used for sending and receiving talk calls on 2G networks, while the packet switched domain was used for sending and receiving data [5]. Mobile networks of the third generation (3G), which was also known as IMT-2000, were put in place in 2000. Mobile phone service was made possible by this technology. The 3G technology platforms were CDMA-2000, wide CDMA, UMTS, and TD-SCDMA [6]. Digital broadband, global roaming, faster internet, and high quality of service (QoS) were all things that this age offered.

The fourth generation (4G) of mobile communication came out in 2010, and it is different from the generations that came before it because it is internet based [7]. OFDMA is a new way for 4G networks to connect. New technology standards for this generation include long term evolution (LTE) [8], [9]. Current LTE networks are reaching their limits and can't keep up with the expanding needs of modern wireless communications. Therefore, the arrival of 5G cellular technology has finally arrived.

Table 1-1: Shows a summary of how the four versions of cell phones compare to each other's [2], [3], [6], [10]

Generation	**1G**	**2G**	**3G**	**4G**
Time Duration	1980s	1991s	2000s	2010s
Launched by	Nippon Telegraph and Telephone	Radiolinia	NNT Docomo	Swedish-Finnish network operator
Country	Japan	Finland	Japan	Scandinavian
Data Speed	2.4 kbps	50 – 384 kbps	2000 kbps	100 Mbps +
Technique	Analog	Digital	Broadband Data	LTE
Operated Frequency	0.8 GHz	0.9 GHz	2.11 GHz	2.62 GHz
Services	Voice Calls	SMS, Voice Calls	Multimedia messaging, Video Call, and Internet	HD Video Streaming, online Games

1.2 Mobile Communication's Fifth Generation.

There is a huge increase in wireless data flow these days, and consumers with smartphones want better internet service wireless connectivity to accommodate services like streaming ultra-high definition (UHD) video. The emergence of contemporary technologies has created a need for high-speed data transmission, extensive bandwidth, and increased system capacity. Cellular networks like 4G and LTE advanced are having a hard time keeping up with these needs of modern wireless communication. As a response to the demands of contemporary wireless communication, the fifth iteration (5G) of mobile communication has been introduced. This latest version aims to provide services characterized by reduced latency, enhanced data rates, expanded bandwidth, and more connectivity options for numerous devices [11]. The main idea behind 5G is to make cell phone networks less sluggish while also being cheap.

The International Telecommunication Union has established stringent criteria for fifth generation that are beyond the feasible constraints of already accessible wireless technology. According to the statistics presented in Figure 1.1, it is anticipated that 5G networks will exhibit a latency not exceeding 1ms, spectrum efficiency of 10 bits/s/Hz, a data transmission rate of up to 1000 Mbps, a cost reduction of 10 times in contrast to 4G, with a top speed of up to 800 miles per hour, and the ability to support over 1 million connected users per km^2.

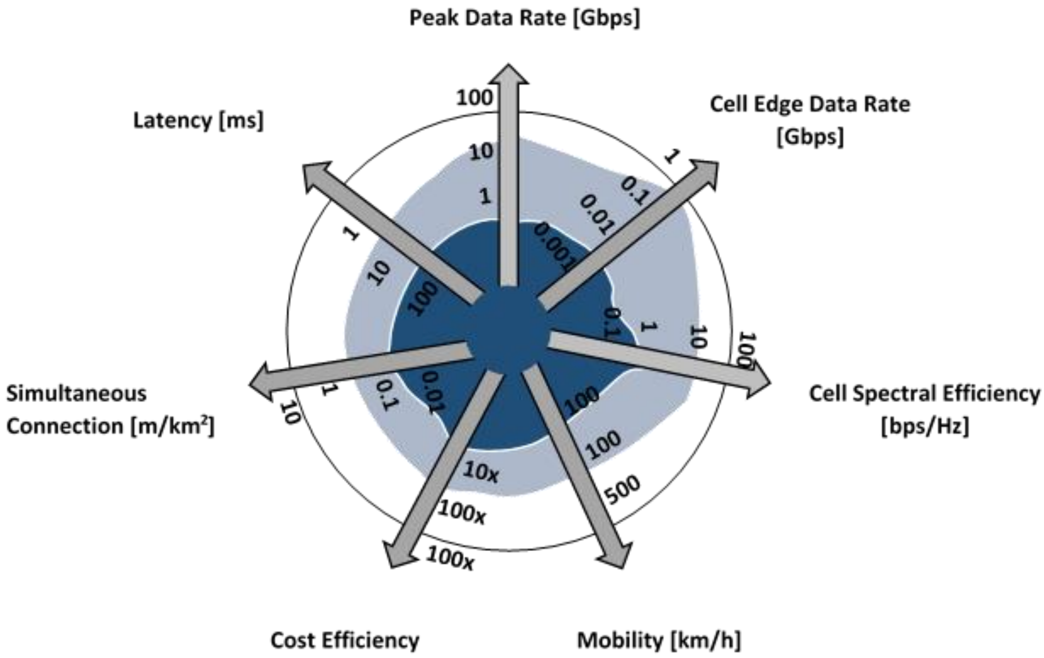

Figure 1.1: Predicted Feature of 5G Network [12]

Fifth generation (5G) networks aim to supply three distinct categories of use cases, specifically, advancements in extremely dependable connectivity with minimal delay, Large-scale machine-to-machine connectivity, and enhanced cellular internet connectivity [13]. The usage example of expanded mobile broadband illustrates the augmentation of network capacity. The program for enhanced mobile broadband effectively manages data files of considerable size, often reaching several terabytes, to accommodate the growing demand from consumers for more rapid data transfer.

Some examples of sub-uses for eMBB are hotspots in areas with a lot of people that need to cover indoors as well as outdoors and internet everywhere. The URLLC use case is concerned with establishing connections that exhibit high responsiveness, minimal latency, and remarkable reliability. Moreover, this application helps meet the needs of essential infrastructure in emerging economies. Some of these uses are smart energy systems and grids, self-driving cars, Industrial automation, and eHealth.

The mMTC use case talks about how machines can talk to each other over wired or wireless networks. This can happen with little or no help from humans. Machines can create data, share information, and act without any help from humans. More specifically, mMTC includes connecting and networking billions of machines wirelessly. It is seen as a key step in the evolution from IoT to Internet of Everything.

Important technologies such as millimeter wave band, massive (MIMO), complex networks, and antenna array beamforming all contribute to the 5G cellular communication network. These technologies collectively empower the network to operate at a superior performance level and effectively cater to a diverse array of applications. The user has not provided any text to rewrite [14].

New bands require to be used in order to meet the high standards for 5G networks. The frequency bands used by 5G networks can be broken down into three categories. First band, or low band, refers to frequencies lower than 1GHz. The second band, also called a mid-band, covers frequencies between 1 and 6 GHz, while the third band, sometimes called a high band, operates between 24 and 52 GHz. Here, however, we'll make use of a different unlicensed band, from 57 to 65 GHz, that's commonly referred to as V-band. Millimeter waves occupy a specific frequency range in the electromagnetic spectrum that goes from 3000 MHz to 300000 MHz and has bandwidth between 1 cm and 0.1 cm [15], [16], [17], [18]. Some call this spectrum the extremely high frequency (EHF) region. With reduced competition for bandwidth, mobile and wireless communications in the mm Wave spectrum can provide increased throughput and support for future expansion. It's helpful to use the mm-Wave band because it has a wide bandwidth for sending large amounts of data quickly, small wavelengths that allow for a lot of antennas, a wideband spread spectrum that lowers multipath fading, a strongly directed antenna, and minimal power transfer due to high antenna gain [19], [20]. However, millimeter waves have problems like signal loss and problems with transmission [15], [21], [22].

Fortunately, the millimeter wave band's short wavelengths make it possible to build a lot of antennas with high directed gain and beamforming capabilities [15]. The high spatial gain provided by beamforming antenna systems compensates for the band's inherent lousiness at millimeter wavelengths. Beamforming is intriguing because of the short wavelengths' facilitation of array design for use in portable devices. As 5G networks are being built and released for purchase around the world [23], [24], [25], multiple enhanced antenna array designs are being used. Among these are beamforming arrays, massive MIMO arrays, microstrip arrays [26], [27], [28], [29], [30], [31]. The antenna configurations of base and mobile stations in millimeter wave communications networks are influenced by the stochastic movement patterns of mobile devices, the propagation characteristics of signals in both indoor and outdoor urban environments, and the mobility patterns of users [29], [32]. For this reason, both the mobile and base stations should have phased arrays for electronic beam shaping in order to keep a good quality link [15], [33], [34]

1.3 Inspiration

Data traffic in wireless communications has grown over the years because of things like the IoT, mobile cloud computing, UHD videos, and interactions between vehicles [35], [36]. Recent studies show that the amount of data that can be sent wirelessly will likely grow 1000 times [35], [37]. For the proper functioning of these applications, it is imperative that wireless networks possess the capability to offer services like speedy data transfer, little delay, huge bandwidths, and huge-capacity channels. A lot of 5G networks use microstrip patch array antennas to make up for misplacement in the millimeters wave [38]. They do this at offering high gain and beam manipulation capability. One of the benefits of phased arrays is that they can electronically move beams in the direction you want them to go. They can also provide high antenna gain with fewer side lobes, the ability to shape beams, and microstrip antenna [39]. However, phased array antennas have some problems called the mutual coupling between emitting parts. This makes the array less useful overall. A lot of work has been done over the years to reduce the mutual coupling effect that comes with phased array antennas. Researchers have come up with several common ways to reduce mutual coupling. Some of researchers find the way to the utilization of electromagnetic band gap structures [40], [41]. However, some of the researcher working on defective ground structures to reduce the mutual coupling [42], [43]. Furthermore, some of the researcher implement metamaterials to overcome the mutual coupling in Antenna Array [44], [45], [46].

The utilization of antenna arrays is implemented as the emitting component in this thesis. The selection of microstrip patch antennas as opposed to alternative millimeter-wave choices is driven by a range of benefits, such as cost-effectiveness, lightweight characteristics, ease of feeding, and compact dimensions [47]. Antenna Arrays that incorporate microstrip patch antennas as radiating elements have increased coupling as a result of the interactions between these patches, namely due to space and surface wave phenomena. An additional aspect of a microstrip antenna's radiation pattern is that it is calculated by multiplying the electric field produced by an emitting element of antenna at the antenna's origin by array component. The array component is a mathematical term, which characterizes the arrangement of an elements of the antenna within an array antenna, and the relative importance of those elements. This is a special capability of each individual antenna array.

1.4 Problem Statement

The wireless communication sector has seen rapid progress in the implementation of 5G networks, providing exceptional connection and disruptive possibilities. As global focus turns to the upcoming advancements in 6G wireless technology, it is becoming more apparent that the expected benefits of 5G have not been fully achieved. Recent scholarly research and publications have shown problems and limits that hinder the optimal operation of 5G technology and its smooth transition from previous wireless technology generations, despite efforts to promote its use. The current literature shows a lack of detailed evaluation and enhancement of 60GHz antennas, especially in terms of optimizing their design for 5G applications. This gap mostly involves the absence of emphasis on compact antenna designs that can efficiently boost bandwidth, magnify gain, and improve directivity. This lack is important since the 60GHz spectrum provides a cost-efficient option compared to the expensive and less available 28GHz bandwidth often employed in 5G applications. Therefore, it is crucial to focus on creating small and effective 60GHz antennas designed to fulfil the requirements of 5G communication. Moreover, this gap is a major obstacle to effectively implementing 5G networks in the millimeter-wave (mmWave) range, which restricts the full utilization of their capabilities and slows down their general acceptance. Here are some important themes of concern within this research gap:

- Solution for Antennas that are limited.
- Solutions That Are Reasonably Priced.
- Problems Facing the Environment, especially at 60GHz mm Wave.
- Integration and Downsizing of Components at 60GHz mm Wave.

It is essential to fill these research gaps to fully utilize the unused capabilities of 5G communication devices that operate in the 60GHz range. We are now researching suboptimal antenna designs in 5G networks, specifically focusing on the 60GHz frequency spectrum. We intend to narrow the divide between theoretical potential and practical execution by examining this spectrum within the framework of 5G communication systems.

The study we conducted uses the CST Studio Suite Software to analyze the cost and design efficiency of three alternative substrate materials. We are focusing on improving specialized antenna designs for 5G networks to provide practical solutions that boost existing 5G capabilities and pave the way for future advancements, such as the transition to 6G at mmWave frequencies.

Our main goal is to optimize antenna size, achieve perfect impedance matching, enhance antenna gain, and improve important characteristics necessary to address expected issues in 5G wireless communication. We strive to enhance wireless communication technologies to support the integration of 5G networks and foster future developments.

1.5 Aim and Objectives

Addressing the limitation of 5G wireless systems: - The main goal is to create and enhance a 60GHz antenna for efficient performance in 5G networks. An antenna configuration needs to be developed to efficiently overcome the specific challenges presented by the 60GHz frequency spectrum. These challenges are to reduce the impact of oxygen absorption and deal with the restricted signal propagation range linked to this frequency. The antenna design primarily aims to increase signal intensity (Gain), optimize radiation pattern efficiency, and ensure precise impedance matching. The collaborative activities described seek to significantly improve the optimal performance of 5G networks operating in the 60GHz frequency range.

Optimized design of an Antenna: - The study's secondary purpose is to highlight the limitations present in 5G systems that hinder their ability to effectively fulfil the theoretical promises and practical performance expectations. By tackling issues including lack of coverage in certain places, signal penetration difficulties, and interference complexity. The primary goal is to provide effective solutions that can enhance the reliability and stability of emerging 5G wireless technology. This objective aligns with the overarching aim of laying a strong groundwork for the seamless adoption of upcoming wireless communication technologies, such as the anticipated 6G.

Impact on the Network's Capacity: - The objective is to study how an improved antenna design impacts the total capacity of the 5G wireless network. This objective focuses on evaluating how enhanced antenna performance affects data rates, network capacity, and user satisfaction. This analysis aims to demonstrate the importance of the proposed antenna improvements in meeting the data needs of 5G applications by quantifying the increase in capacity.

2 Background

This chapter examines the fundamental theory behind antenna arrays, investigating their many configurations and the complex networks that supply them. The main focus is to explain the operating principles that govern phased array antennas, providing detailed insights into how they work. We explore advanced techniques to reduce mutual coupling in arrays, which is essential for enhancing performance. We provide the essential antenna parameters for evaluating the effectiveness of phased array antennas and explore their practical consequences. Furthermore, we broaden our discussion to incorporate relevant insights obtained from the outcomes of our thorough antenna design, illuminating the effectiveness and practicality of the suggested configurations.

2.1 Antenna Array Overview

The term "antenna array" can describe a framework wherein numerous antenna components are organized in a specific electrical or structural arrangement. The primary objective of this system is to attain a directional radiation pattern [48]. The antenna elements can incorporate a diverse range of antenna types, such as microstrip antennas.

Antenna arrays can be implemented on a compact scale or across a significant expanse, encompassing applications in embedded devices as well as large-scale deployments like the Square Kilometer Array (SKA). When examining an individual antenna element in isolation, the radiation pattern it typically exhibits is marked by limited amplification and limited directivity [48]. To optimize the efficiency of a solitary antenna, one viable approach involves increasing its physical dimensions, hence leading to the generation of more concentrated radiation beams and a subsequent amplification in gain.

To manipulate the entire radiation distribution of an antenna array consisting of homogeneous antenna components, various factors can be modified:

- The antenna array's geometrical configuration.
- The patterns of each unique antenna.
- The spatial gap of antenna elements to one another.
- The amplitude of excitation.
- The phase of excitation.

The determination of the combined antenna element's radiation pattern involves the multiplication of the electric field of an individual element situated at the reference point by a coefficient referred to as the "array factor".

2.1.1 Array of Linear Antennas

In terms of geometry, this is the most basic arrangement for an antenna array. With uniform spacing between them, the antenna elements form a straight line [49], as shown in a Figure 2.1. There are two types of linear antenna arrays: uniform arrays and non-uniform arrays. In a uniform linear array antenna, each element has the same amount of current, the same distance between them, and a phase shift that gets bigger over time. With a non-uniform linear array, the antenna elements are not all spaced out the same way, and they are all given signals with different phases and amplitudes [48].

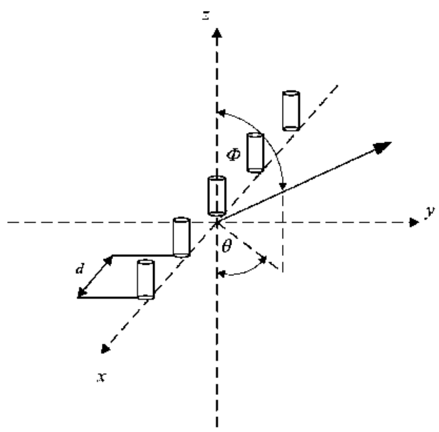

Figure 2.1: Diagram illustrating the array of linear antennas [50]

2.1.2 Array of Planar Antennas

Antenna components or independent antennas are systematically aligned inside a single layer in a planar array design as shown in Figure 2.2. The distinguishing characteristic of this geometric configuration is its exceptional capacity to provide beam steering in two separate planes, namely the azimuth and elevation planes. The ability to direct beams in these planes is a notable benefit, as it influences the radiation pattern of planar arrays by reducing side lobe levels [49]. The utilization of planar arrays allows for the creation of extensive arrays, which leads to a rise in terms of their complexity and their cost.

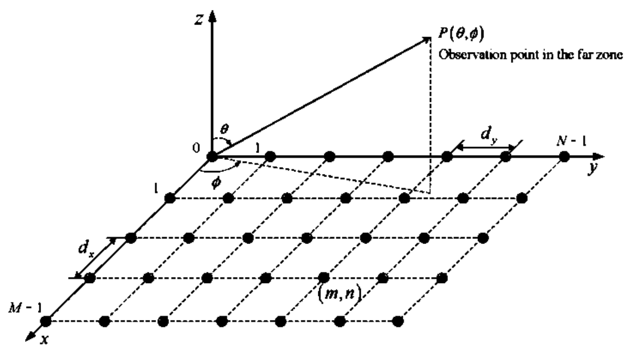

Figure 2.2: Diagram illustrating the array of planar antennas [51]

2.1.3 Array of Circular Antennas

The elements of this antenna array are configured in a circular arrangement as shown in Figure 2.3. It produces omnidirectional (in all directions) beams with uniformly spaced antenna elements that have similar phase and amplitude characteristics [52].

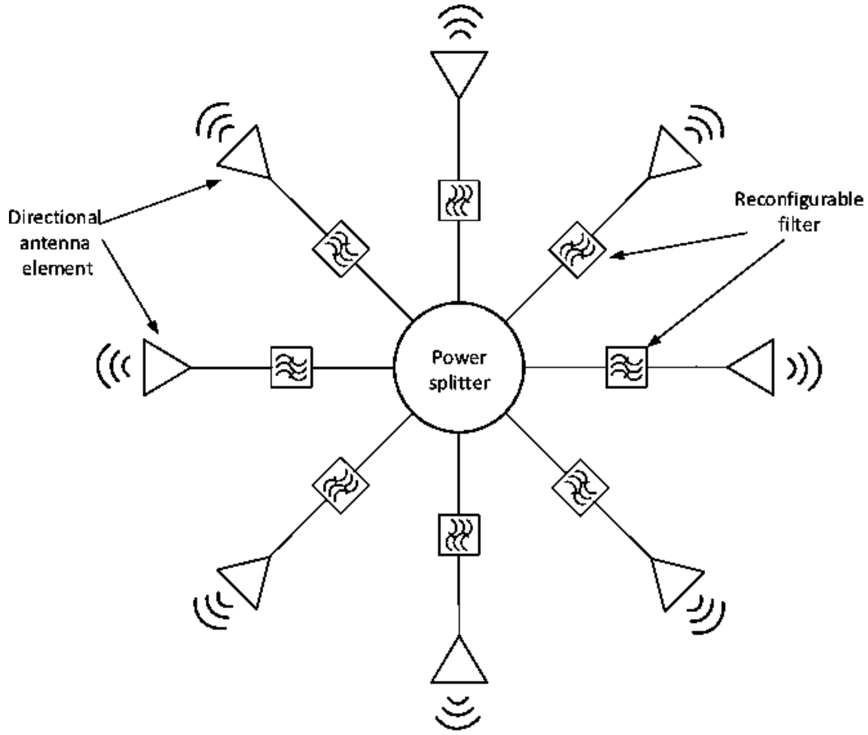

Figure 2.3: Diagram illustrating the array of circular antennas [52]

2.2 Networks of Feed for Antennas Array

In the design of an array, transmitting units can be fed by either a Sole transmission path (called "series feeding") or using several paths (called "corporate or parallel feeding").

2.2.1 Network for Series Feeds

Each antenna in this network of feeds receives its input from a single line. Each component is provided feed by the one previously them. Each modification that takes place in an antenna component significantly affects the operation of the other antenna components [49]. The benefits of this network of feed include its straightforward construction and assembly, as well as its ability to minimize losses of feed networks and maintain a minimum side lobe magnitude in the array. Arrays that employ frequency scanning for beam scanning or those with a fixed beam use this feed network, although its low bandwidth limits its usefulness in larger systems.

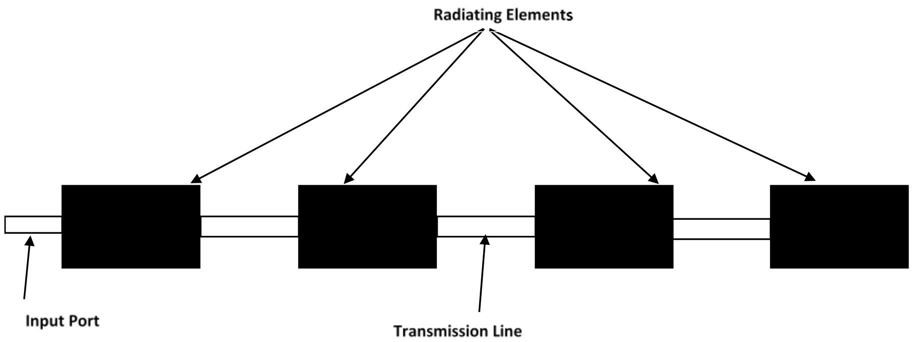

Figure 2.4: Diagram illustrating the network of series feeds.

2.2.2 Networks for Corporate Feeds

Multiple lines are employed in this feed network to supply the components of the antenna. The desired frequencies of the corporate feed network are accomplished through tapered lines or multi-section impedance transformers, with each line specifically designed to span a quarter wavelength [49] as shown in Figure 2.5. The benefits of this method include uniform power dispersion to all components of the antenna, the capability to support a broad frequency range, and the ability to scan the beam. The drawback of this approach is the significant feed losses caused by the presence of many lines.

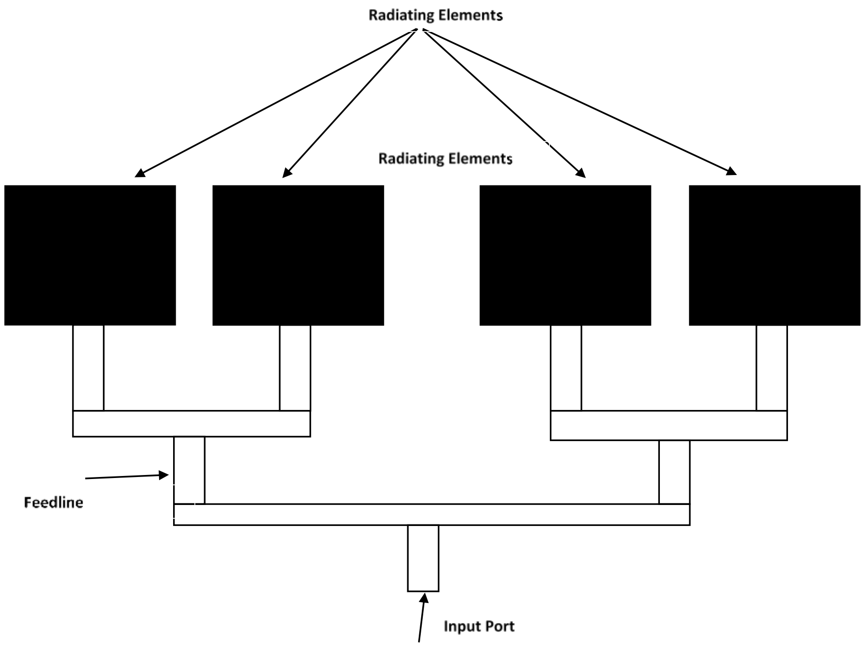

Figure 2.5: Diagram illustrating the network of corporate feeds.

2.3 Microstrip Patch Antenna

Phased array antennas utilize different types of antenna elements, such as dipole antennas, horn antennas, reflector antennas, and microstrip antennas. However, for this thesis, the chosen radiating component is the microstrip patch antenna. In 1953, the idea of microstrip patch antennas was initially proposed, and in 1955, the first patent for them was submitted. However, these antennas gained significant recognition in the 1970s because of the progress made in PCB technology. Subsequently, they have been widely used across a range of areas in cellular communication.

2.3.1 Microstrip Patch Antenna Fundamentals

A basic microstrip antenna consists of a substrate dielectric material, a patch as a radiating component, a ground surface, and a feedline for Input power [53], as depicted in Figure 2.6. In the depicted design illustrated in Figure 2.6, the radiating component of the antenna is engraved onto the substrate dielectric material and acts as a radiating element. Around the edges of this layer, electromagnetic energy breaks off and goes through the dielectric substrate. It is mirrored by the ground surface and then moves across the substrate before entering space. The design of a microstrip antenna involves the use of many dielectric substrates, each with an electric coefficient starting from 2.2 and ending at 12.

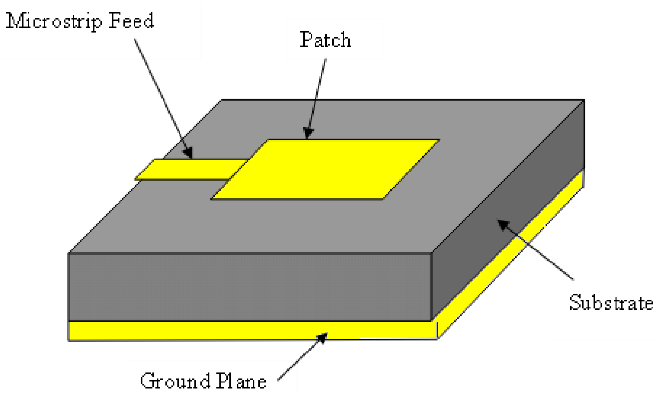

Figure 2.6: Structural design of microstrip patch antenna [54].

The radiating patch in practical applications is typically square, circular, or rectangular. However, rectangular, and circular forms are mostly utilized due to their benefits, including straightforward analysis, easy manufacture, and attractive electromagnetic radiation properties, distinctive attributes, or qualities [49].

2.3.2 Approaches to Microstrip Patch Antenna Feeding

The radiating patch can be excited through several methods, with the most widely employed techniques being microstrip feedline, feeding via coaxial probe, aperture coupling, and proximity coupling [53].

2.3.2.1 *Microstrip Feedline*

The focus of this approach is the linking of the radiating patch to a conductive strip.

Microstrip feedlines have the benefits of being easy to fabricate and having matching made simpler by adjusting the inset location. Nevertheless, this feeding strategy has the drawback of increasing unwanted radiation and unwanted radiation from the feed, consequently limiting the frequency range [55].

2.3.2.2 *Coaxial Probe Feeding*

This approach involves connecting the central core of the coaxial transmission line cable to the radiating patch, while the outside cable element is linked to the surface area of an antenna. The benefits of the feed via coaxial probe approach are simple fabrication, simple impedance matching, and minimal background noise. The approach has drawbacks in terms of its low bandwidth and difficulty in modeling it, particularly for thick substrates [55].

2.3.2.3 *Aperture Coupling*

The ground plane divides two distinct substrates in an aperture coupling feeding method. A microstrip feedline conveys energy to the radiating patch element through an aperture on the surface of the antenna, and it is located on the low dielectric material substrate, which is on the bottom half. A substrate with high permittivity often represents the bottom layer, whereas a thick substrate with low permittivity is characteristic of the top substrate. The bottom layer not only separates the substrates but also lowers the clarity of the polarization and the formation of unwanted radiation patterns. The feed mechanism part is fully optimized with this feeding plan [55].

2.3.2.4 *Proximity Coupling*

The feedline in a proximity coupling system is situated between two dielectric substrates. Proximity coupling provides a significantly higher bandwidth and less false spurious radiation than other mechanisms. Difficulty in fabrication is an issue with this approach because of the need for appropriate substrate layer alignment [55].

3 Design of Single Element Microstrip Patch Antenna

The many benefits of microstrip patch antennas over other types of antennas make them ideal for use as main radiating components in phased array antennas in a wide range of wireless applications. This section explores the detailed planning of a single rectangular patch antenna for use at 60 GHz. When designing a microstrip patch antenna, choosing the right dielectric substrate is crucial. A single rectangular patch antenna is thus designed in this chapter using three different dielectric substrates with different heights and dielectric constants. Using a quarter-wave transformer guarantees excellent impedance matching between the radiating patch and the transmission line. In addition, the results of the computer simulation technology (CST) Studio Suite software simulations of the proposed single patch antenna are presented in this chapter.

3.1 Design

Modern wireless communications have seen the advent of microstrip patch antennas, which are widely used for their many advantages. These features encompass their small size, affordability that allows for mass production, narrow profile, lightweight build, adaptability that supports multiple bands frequency operations, and capacity to accept both polarization techniques. Create a single rectangular patch antenna as the first step in building a phased antenna for 5G wireless applications. The dielectric material as a substrate, substrate height (C), and resonant frequency are some of the critical characteristics that must be defined in the first phase. You can't determine the antenna's dimensions, like the patch length and width, without these given data. In this section, we use three different dielectric substrates with different heights and dielectric constants to build a single rectangular patch antenna.

1) Using Rogger RT5880 Material
2) TEFLON
3) LTCC A6M

3.1.1 Rogger RT5880

A microstrip patch antenna was designed to operate at 60 GHz utilizing Rogers RT5880 substrate material, which has a relative permittivity of 2.2 and a height of 0.254 mm, known for its favorable dielectric qualities. The choice of Rogers RT5880 was crucial because of its low loss tangent and high dielectric constant, which are ideal for millimeter-wave applications like 5G communication networks. Table 3.1 details the calculated values necessary for designing a single-element patch antenna. The characteristics were calculated to guarantee the best performance in impedance matching, radiation efficiency, and directivity at the required operating frequency. The dimensions of the patch antenna were calculated by meticulous calculations and simulations, considering the substrate material qualities and the intended operating frequency.

The outcomes from the patch antenna created with Rogers RT5880 substrate material are quite encouraging and is represented below. The S11 value, reflecting the antenna's reflection coefficient, shows superb impedance matching with the feeding network. A graph of the S11 parameter illustrates the impedance bandwidth attained and confirms the efficiency of the design technique. The antenna's radiation characteristics, such as its 1D and 3D gain patterns, are revealed by a thorough examination. The 1D gain pattern shows the antenna's radiation strength in a certain plane, while the 3D gain pattern displays the antenna's radiation qualities in all directions. The gain patterns demonstrate the antenna's directivity and radiation efficiency, which are essential for assessing its performance in real-world situations. Various perspectives of the antenna model created with Rogers RT5880 are shown to provide a full understanding of its geometry and construction. The perspectives offer a thorough comprehension of the physical arrangement of the antenna, assisting in evaluating the feasibility of manufacture and eventual incorporation into larger antenna arrays or systems.

The combination of Rogers RT5880 substrate material, careful design considerations, and simulations has led to the creation of a high-performance microstrip patch antenna that operates at 60 GHz. The results demonstrate the effectiveness of the design approach and open the possibility for its use in antenna array designing and next millimeter-wave communication systems, such as 5G and beyond.

3.1.1.1 *Single element microstrip patch antenna design using Roggers RT5880.*

Table 3.1 represents the parameters and the calculated dimensions (mm) for the design patch antenna for single element using Roggers RT5880 material.

Table 3-1: Single Element Antenna Parameters using Rogger RT5880 material.

Parameters	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	1.976	Length of Patch	1.518
Weight of ground	3.5	Length of Ground	3.042
Weight of Substrate	3.5	Length of Substrate	3.042
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2.2	Material	Rogger RT 5880
Weight of Patch Cut	0.15	Height of Patch Cut	0.50
Weight of Ground Cut	0.90	Height of Ground Cut	0.41
Width of Feedline	0.80	Length of Feedline	0.76
Gain	5.94	Directivity	7.9
Reflection Coefficient	-52.593	Bandwidth	3251MHz
Input Impedance	47.898 ohm		

The below results show the of microstrip antenna for single element at 60GHz using Rogger RT5880 material as a substrate, Figure 3.1 shows the front side of designed antenna. Figure 3.2 displays the design antenna from behind and to the sides.

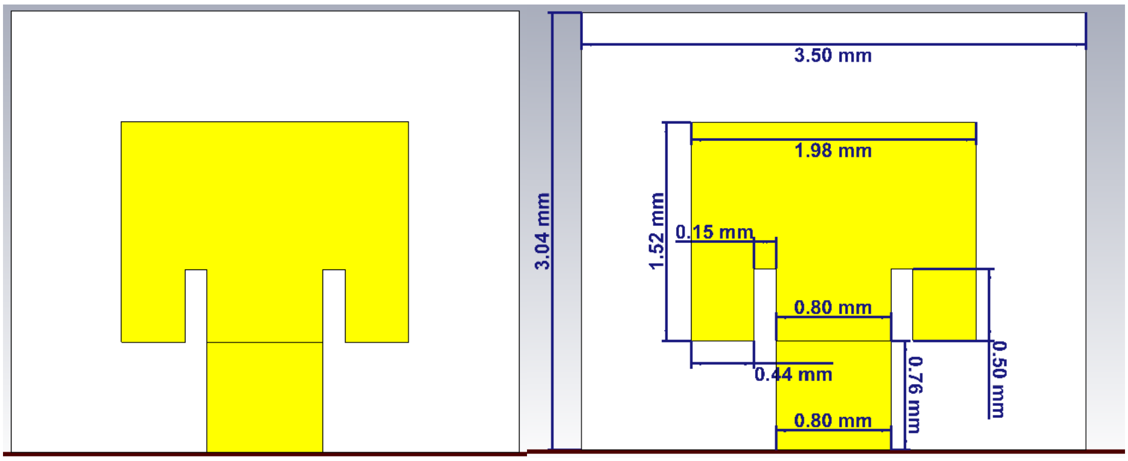

Figure 3.1: Front view of single element antenna using Rogger RT5880.

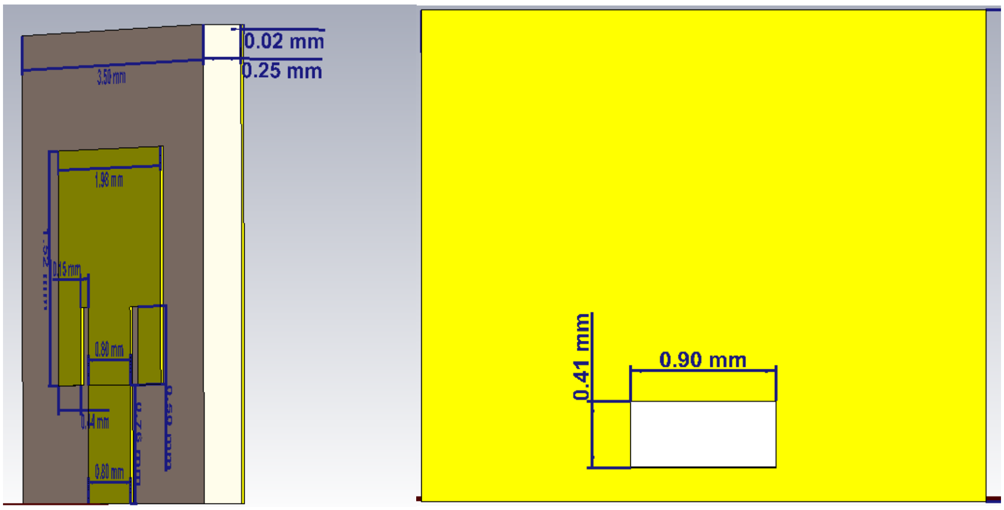

Figure 3.2: Side and back view of single element patch antenna using Rogger RT5880.

The graph below represents the bandwidth of the design microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 3251MHz.

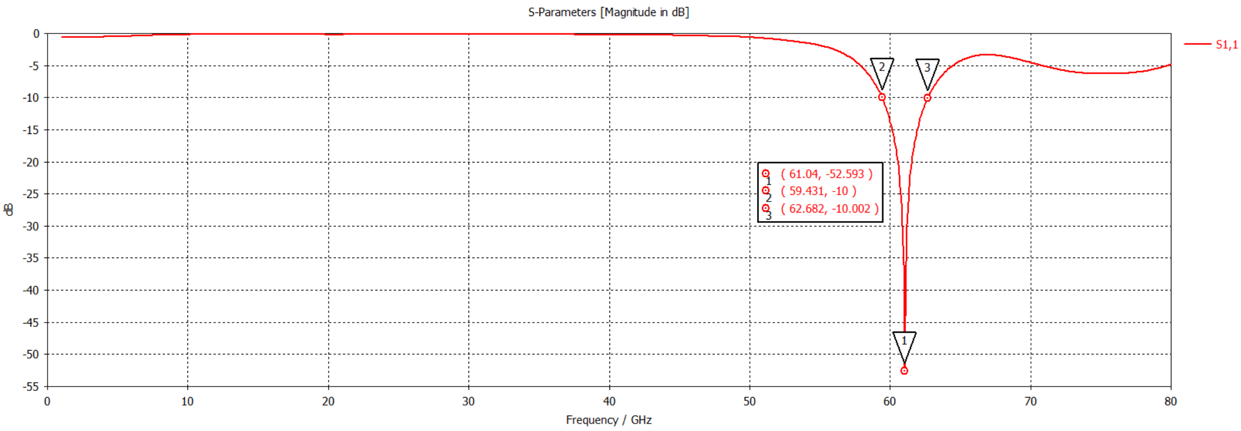

Figure 3.3: S parameter of single element patch antenna using Rogger RT5880.

The graph below represents the reference impedance of the design microstrip antenna for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is around 50 ohm (47.898 ohm)

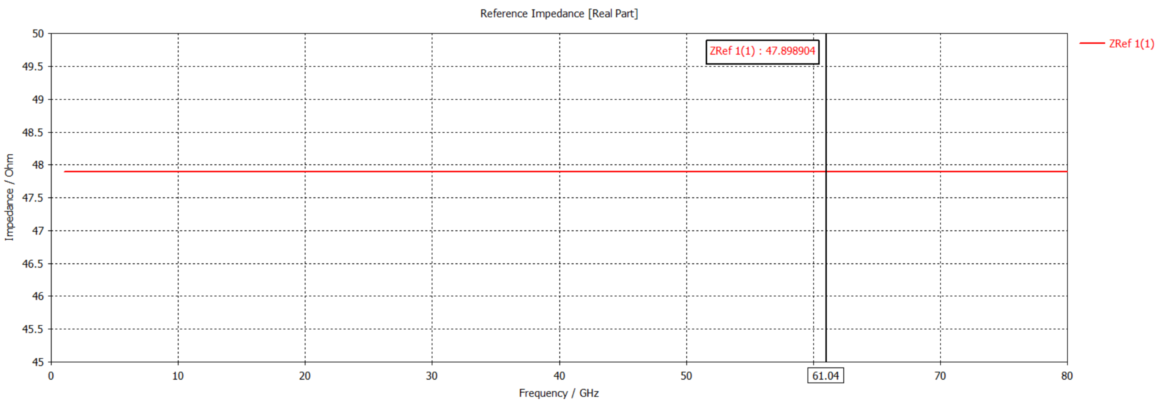

Figure 3.4: Input impedance of single element patch antenna using Rogger RT5880.

Figures 3.5 and 3.6 represent the Gain in polar and 3D form of the design patch antenna for 5G systems respectively.

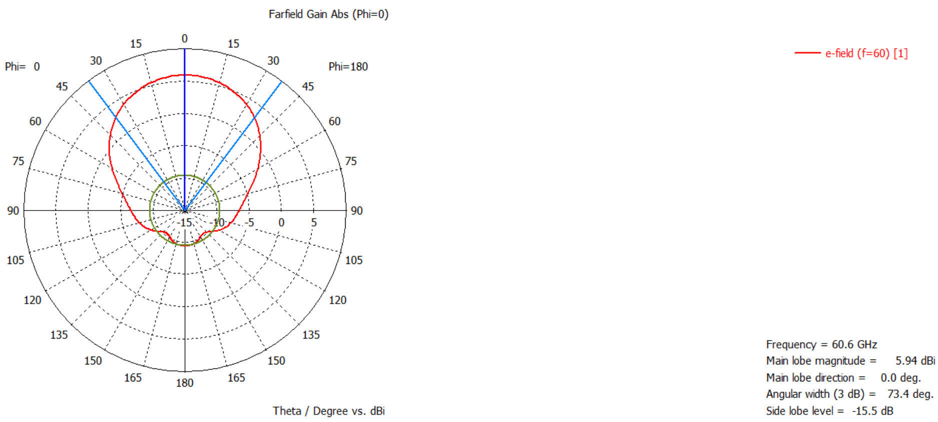

Figure 3.5: Gain of single element patch antenna in polar form using Rogger RT5880.

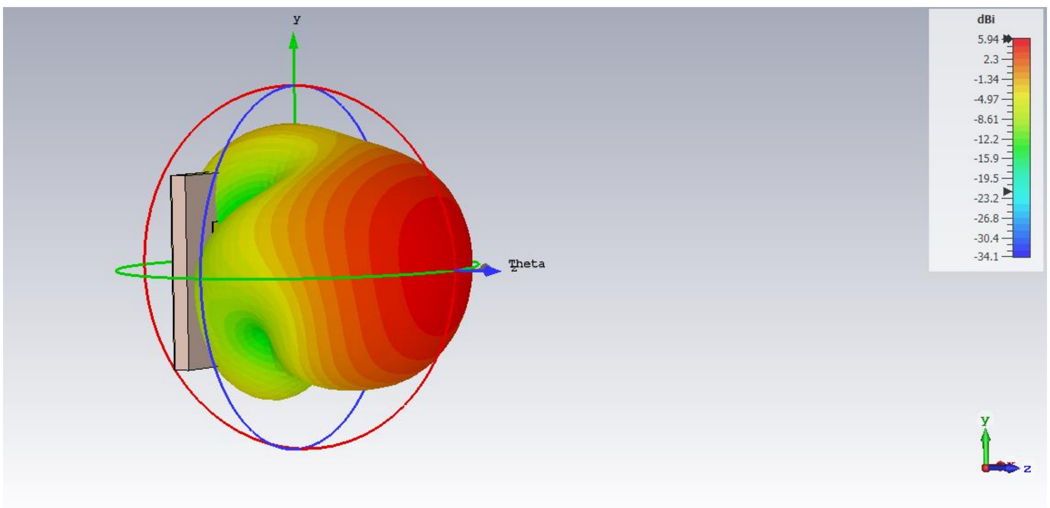

Figure 3.6: Gain of single element patch antenna in 3D form using Rogger RT5880.

3.1.2 Teflon

During this phase of the research, we focused on the detailed design process of a single element microstrip patch antenna operating at 60 GHz. We used TEFLON as the substrate material with a dielectric constant of 2 and a substrate height of 0.254 mm. The precise dimensions listed in Table 3.2 played a crucial role in optimizing antenna performance by considering impedance matching, radiation efficiency, and directivity at the specified frequency. By conducting thorough calculations and simulations, we have identified the design parameters required to achieve high-performance characteristics.

The outcomes of the microstrip antenna designed with TEFLON substrate material demonstrated promising results below. The S11 parameter graph showcased exceptional impedance matching, suggesting seamless integration with the feeding network. Simultaneously, a thorough examination of the antenna's radiation characteristics, encompassing 1D and 3D gain patterns, offered valuable insights into its directional radiation properties and efficiency. Furthermore, various perspectives of the antenna model provided a thorough analysis of its physical structure and geometry, aiding in comprehending fabrication feasibility and potential integration into larger antenna arrays or systems.

From a wider point of view, this project highlights the importance of careful design planning and simulations in creating high-performance microstrip antennas for millimeter-wave applications. Using TEFLON substrate material, with its beneficial dielectric properties, offers an effective solution for achieving optimal antenna performance at 60 GHz. This research significantly contributes to the continuous progress in wireless communication technology, leading to improved performance and reliability in high-frequency communication systems.

3.1.2.1 *Single element microstrip patch antenna design using Teflon.*

Table 3.2 represents the parameters and the calculated dimensions (mm) for the design single-element microstrip patch antenna using TEFLON material.

Table 3-2: Single Element Antenna Parameters using TEFLON material.

Parameters	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	2.20	Length of Patch	1.607
Weight of ground	3.724	Length of Ground	3.131
Weight of Substrate	3.724	Length of Substrate	3.131
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2	Material	TEFLON
Weight of Patch Cut	0.15	Height of Patch Cut	0.50
Weight of Ground Cut	0.90	Height of Ground Cut	0.41
Width of Feedline	0.802	Length of Feedline	0.76
Gain	6.29	Directivity	8.14
Reflection Coefficient	-22.048	Bandwidth	2668 MHz
Input Impedance	50.02 ohm		

The below results show the single element microstrip patch antenna at 60GHz using Teflon material as a substrate, Figure 3.7 shows the front side of designed antenna. Figure 3.8 displays the design antenna from behind and to the sides.

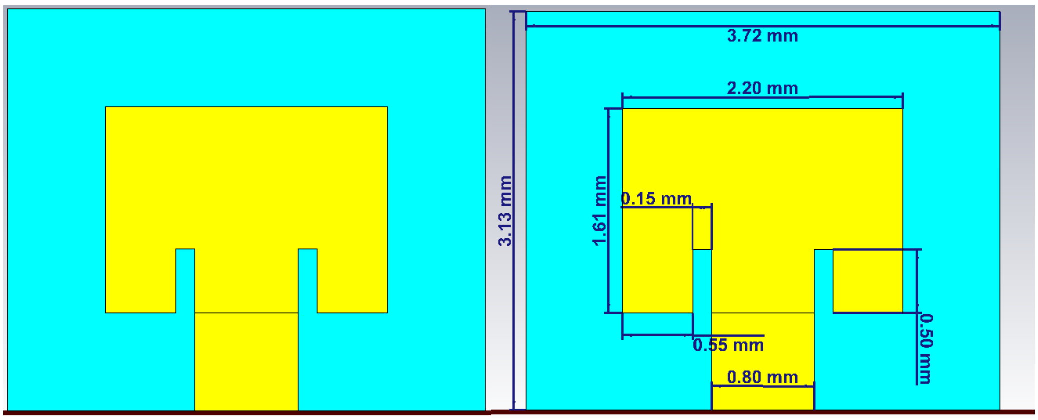

Figure 3.7: Front view of single element antenna using Teflon.

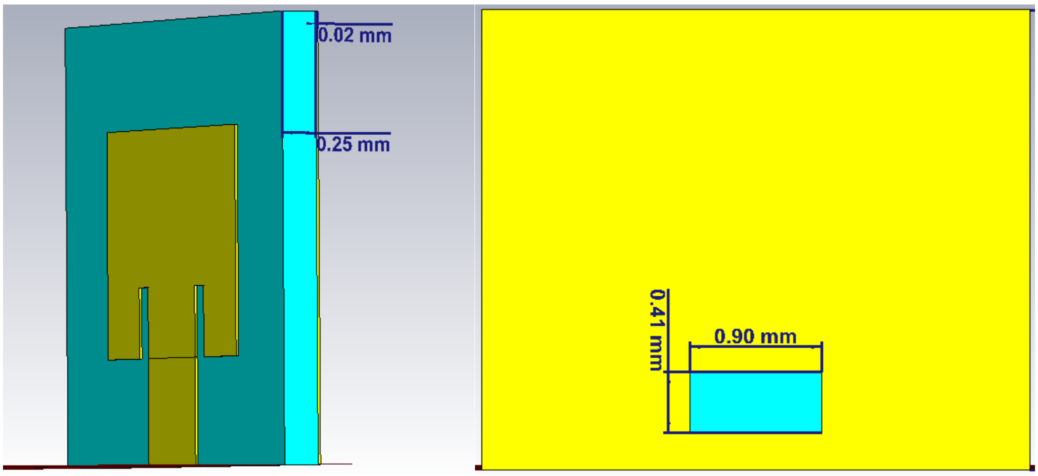

Figure 3.8: Side and back view of single element patch antenna using Teflon.

The graph below represents the bandwidth of microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 2668MHz.

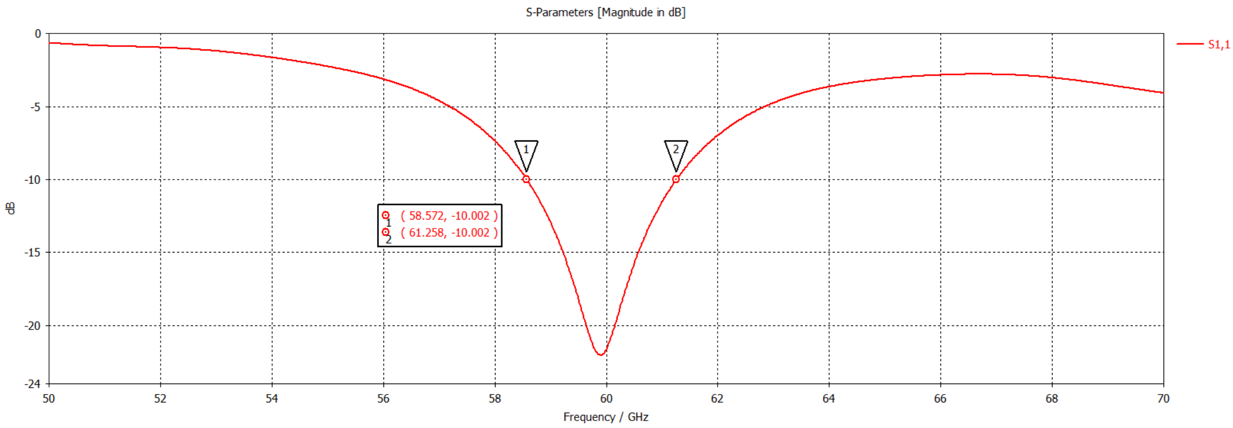

Figure 3.9: S parameter of single element patch antenna using Teflon.

The graph below represents the reference impedance of the design microstrip antenna for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is perfectly at 50 ohm.

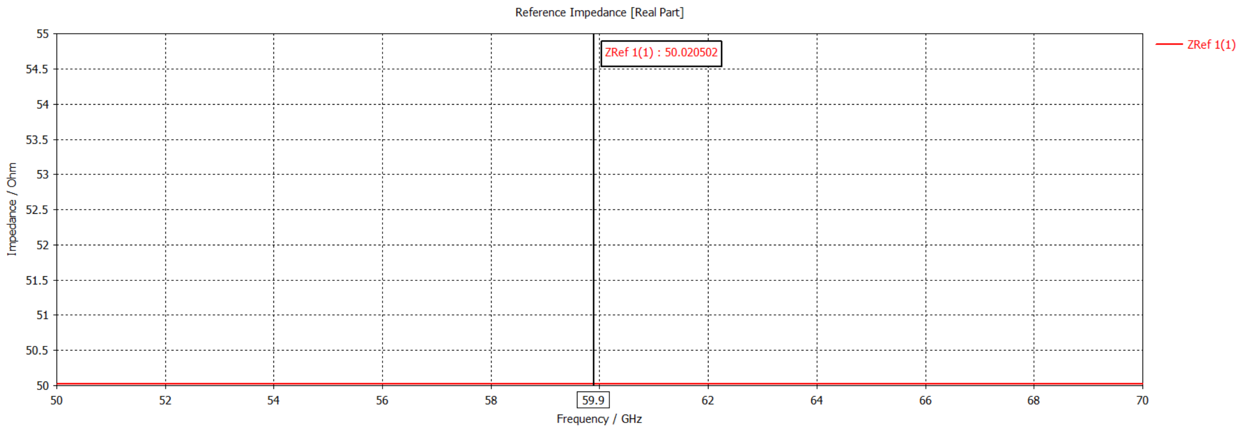

Figure 3.10: Input impedance of single element patch antenna using Teflon.

The figure 3.11 and 3.12 represent the Gain in polar and 3D form of single element of microstrip patch antenna for 5G systems respectively.

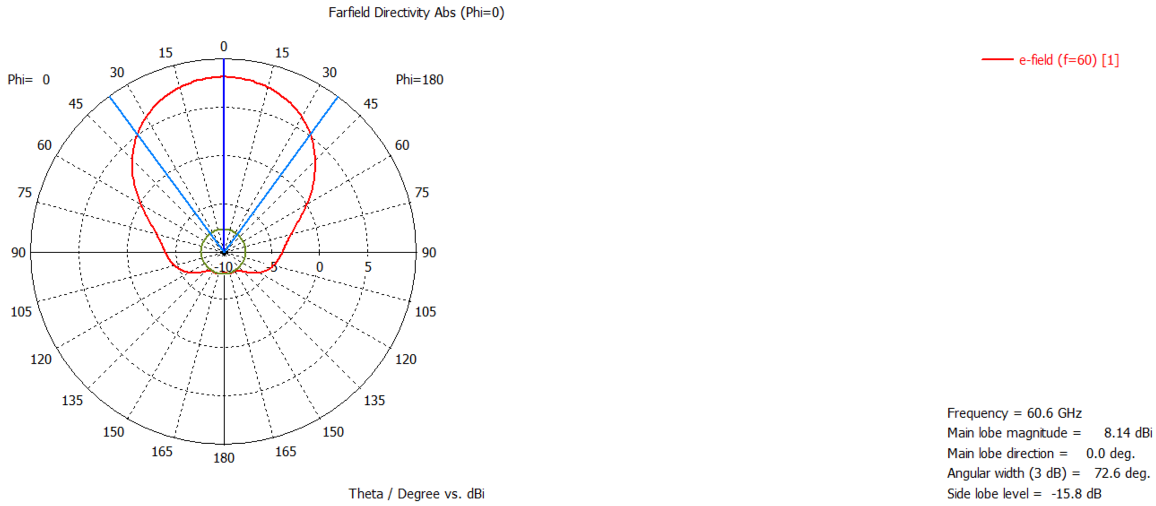

Figure 3.11: Gain of single element patch antenna in polar form using Teflon.

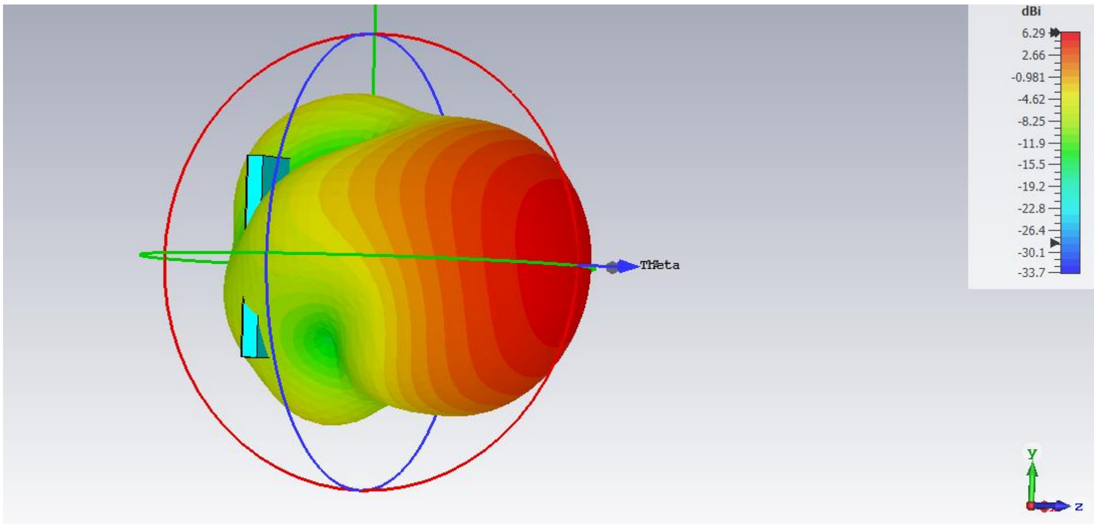

Figure 3.12: Gain of single element patch antenna in 3D form using Teflon.

3.1.3 LTCC A6M

This section delves into the design and analysis of a single-element microstrip patch antenna operating at 60 GHz, using LTCC A6M as the substrate material. By conducting detailed calculations and simulations, we identified the crucial parameters necessary for enhancing antenna performance. Table 3.3 displays these parameters, including impedance matching, radiation efficiency, and directivity. The results show impressive characteristics, with the S11 parameter graph demonstrating around 31 ohms reference impedance and a thorough analysis highlighting efficient radiation properties.

Moreover, the thorough analysis includes studying both 1D and 3D gain patterns, offering valuable insights into the antenna's directional radiation characteristics. Examining various perspectives of the antenna model provides a comprehensive insight into its geometry and structure, facilitating the evaluation of fabrication feasibility and potential incorporation into broader antenna arrays or systems.

This study significantly enhances antenna design methodologies, specifically in the field of high-frequency communication systems. Using LTCC A6M substrate material and careful design considerations, we improved our knowledge of effective microstrip patch antenna design. These findings not only enhance the field but also have important implications for the advancement of future wireless communication technologies.

3.1.3.1 *Single element microstrip patch antenna design using LTCC A6M*

Table 3.3 represents the parameters and the calculated dimensions (mm) for the design single-element microstrip patch antenna using LTCC A6M material.

Table 3-3: Single Element Antenna Parameters using LTCC A6M material.

Parameters	Demission’s (mm)	Parameters	Demission’s (mm)
Weight of Patch	2.19	Length of Patch	1.7
Weight of ground	3.714	Length of Ground	3.224
Weight of Substrate	3.714	Length of Substrate	3.224
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	5.9	Material	LTCC A6M

Weight of Patch Cut	0.15	Height of Patch Cut	0.50
Width of Feedline	0.770	Length of Feedline	0.76
Gain	3.78	Directivity	5.61
Reflection Coefficient	-25.155	Bandwidth	1743 MHz
Input Impedance	31.93 ohm		

The below results show the single element microstrip patch antenna at 60GHz using LTCC A6M material as a substrate, Figure 3.13 shows the front side of designed antenna. Figure 3.14 displays the design antenna from behind and to the sides.

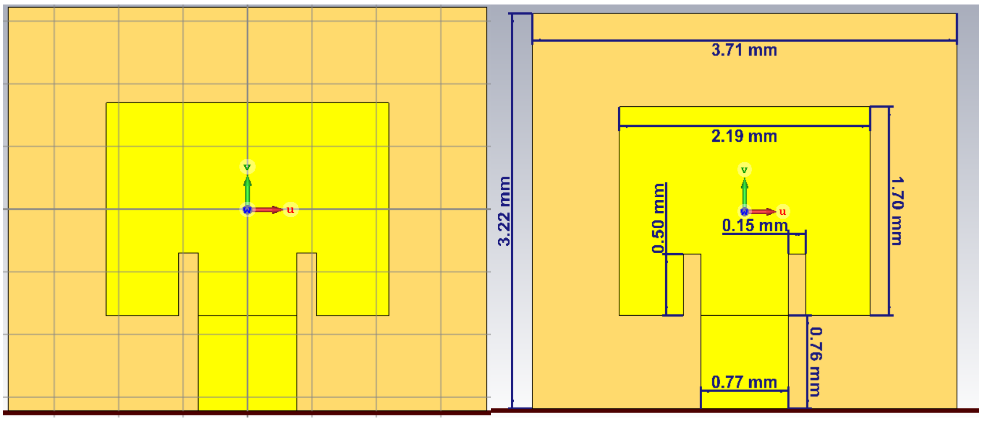

Figure 3.13: Front view of single element antenna using LTCC A6M.

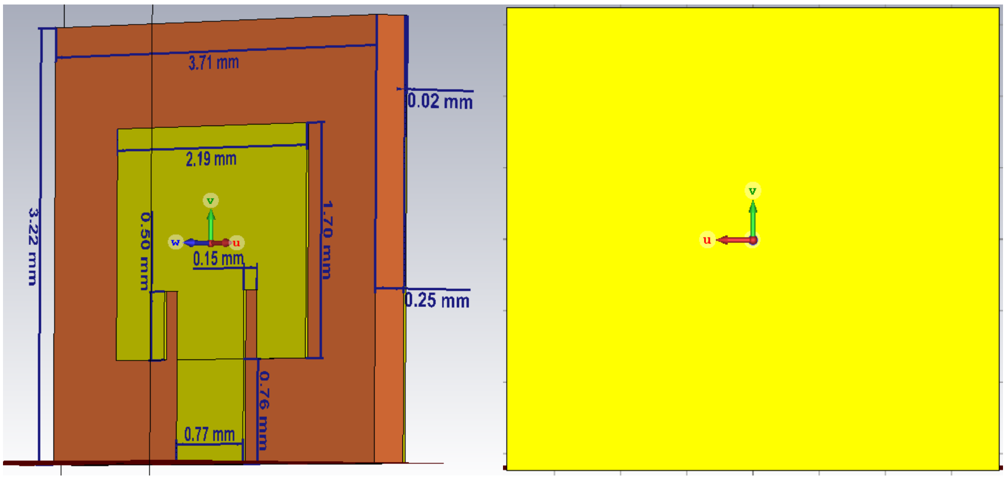

Figure 3.14: Side and back view of single element patch antenna using LTCC A6M.

The graph below represents the bandwidth of microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 1743MHz.

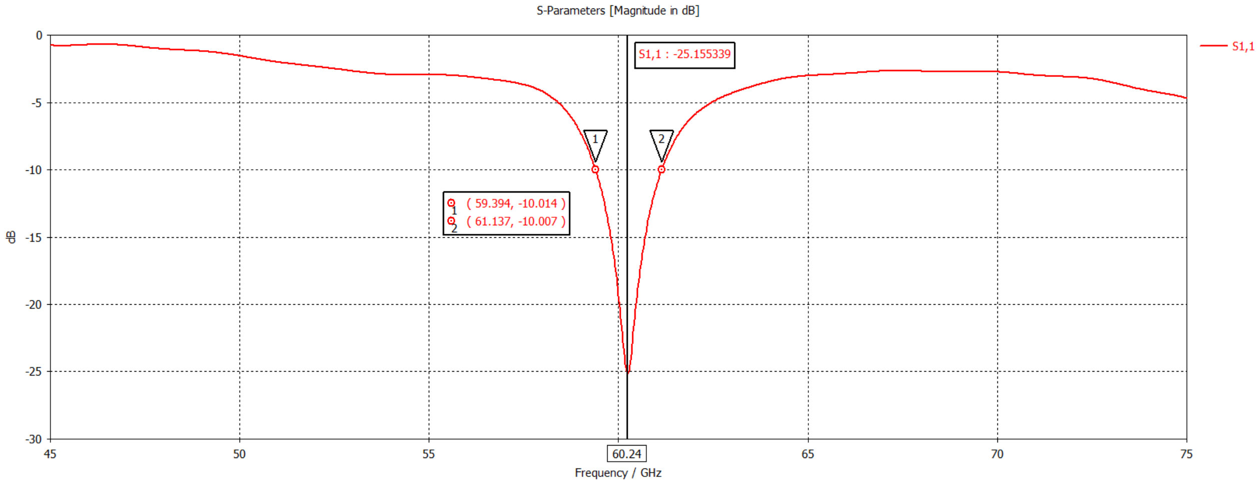

Figure 3.15: S parameter of single element patch antenna using LTCC A6M.

The graph below represents the reference impedance of the design microstrip antenna for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is 31.93 ohm.

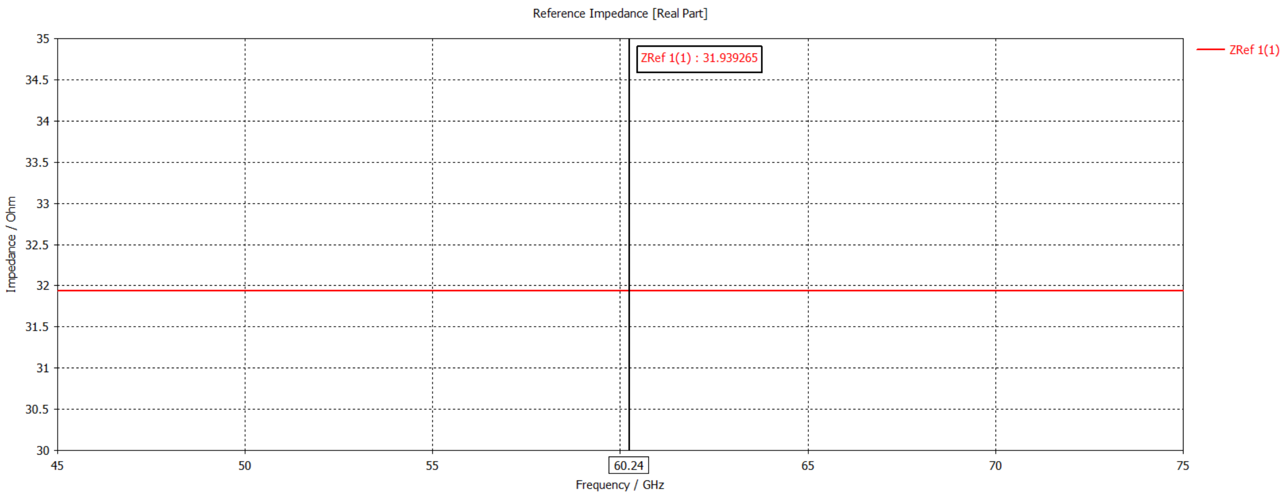

Figure 3.16: Input impedance of single element patch antenna using LTCC A6M.

The figure 3.17 and 3.18 represent the Gain in polar and 3D form of single element of microstrip patch antenna for 5G systems respectively.

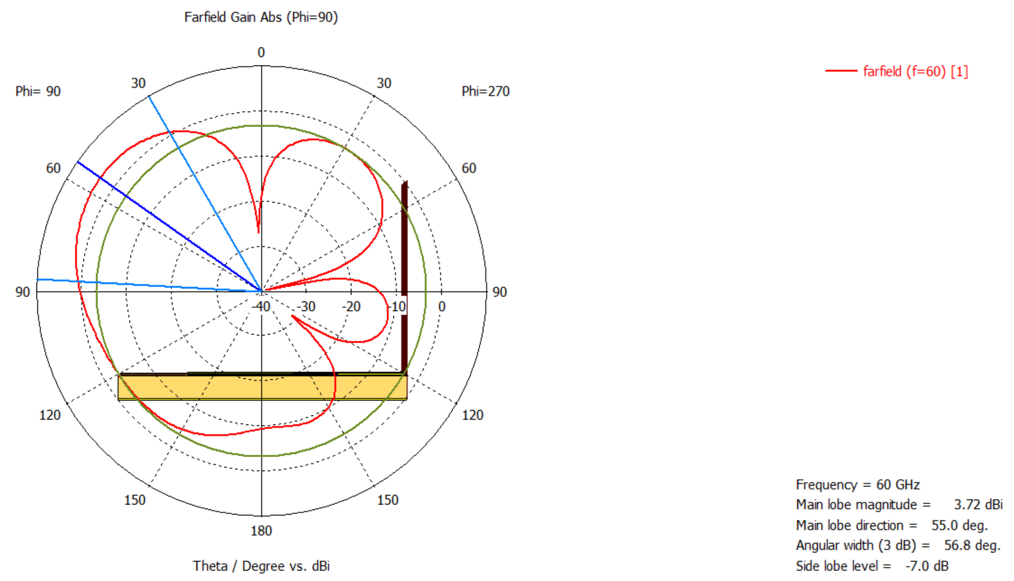

Figure 3.17: Gain of single element patch antenna in polar form using LTCC A6M.

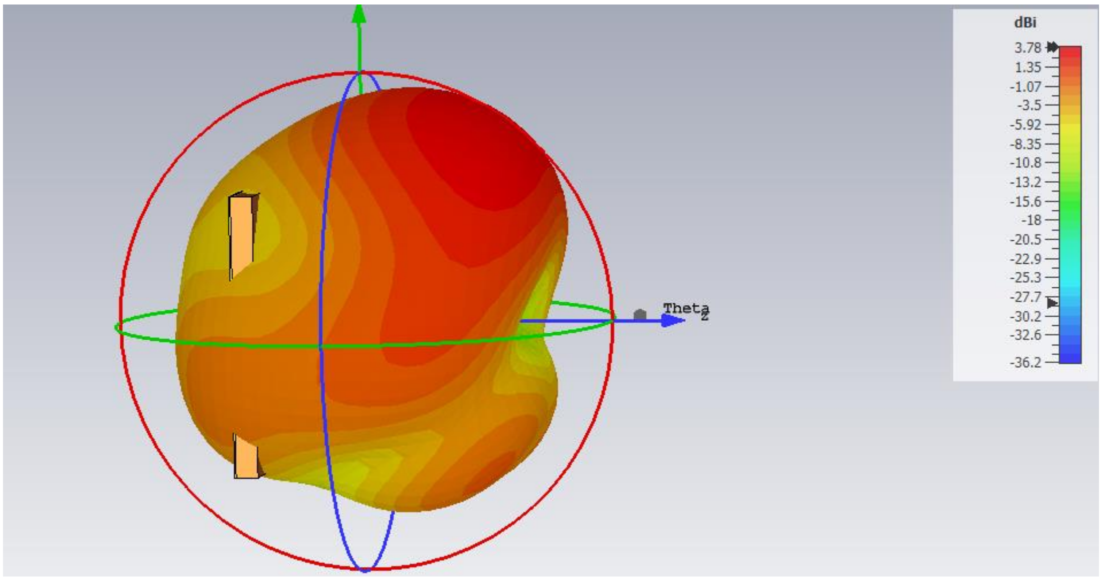

Figure 3.18: Gain of single element patch antenna in 3D form using LTCC A6M.

3.2 Conclusion

Comparing single-element patch antennas made from three different substrate materials highlights the importance of substrate choice in antenna design. Rogers RT5880 and Teflon substrates have specific strengths: Rogers excels in bandwidth and reflection coefficient, while Teflon has greater gain, directivity, and impedance matching at 60 GHz. In comparison, LTCC A6M substrate underperforms. The results offer important information for improving antenna designs for certain uses, highlighting the importance of analyzing substrate characteristics to reach desired performance standards.

4 Microstrip Patch Antenna Array

This thesis chapter delves into the detailed design and analysis of two and four-element antenna arrays operating at 60 GHz, moving beyond single-element patch antennas. Expanding on the foundation established in the prior chapter, which involved the detailed creation of single-element patch antennas using three different dielectric substrates with varying heights and dielectric constants, the focus now shifts to multi-element configurations. Utilizing the knowledge gained from the individual designs, the chapter aims to evaluate how antenna arrays perform with various substrate material compositions.

By using the CST Studio Suite software, thorough simulations and analyses are performed to assess the suggested antenna array configurations. By incorporating quarter-wave transformers, the antenna arrays' performance and efficiency are significantly improved due to the optimal impedance matching between the radiating patches and the transmission line. By carefully planning and continuously improving, the chapter seeks to explain how dielectric substrate properties affect the radiation characteristics, gain, and directivity of antenna arrays in different wireless applications.

This chapter provides valuable insights into the design and optimization of phased array antennas by systematically analyzing the performance of two and four-element antenna arrays using three different substrate materials listed below. Comparing different materials helps understand how they affect antenna performance, which can lead to improvements in design and better choices for specific applications.

- Rogger RT5880
- TEFLON
- LTCC A6M

4.1 Design

The next step in this research project is to develop microstrip patch antenna arrays with two and four elements, building upon the original single-element design. We use the knowledge acquired from designing single elements to carefully plan and execute combinations with several elements. We used three different dielectric substrates (Roggers RT5880, Teflon, and LTCC A6M) with varied heights and dielectric constants in this study, similar to the single-element design. We will assess the performance of the antenna arrays on various substrate materials through detailed simulations and analyses. We aim to optimize design parameters to ensure improved performance in 5G wireless communication scenarios by examining aspects such as impedance matching, radiation efficiency, and directivity. The creation of microstrip patch antenna arrays with two and four elements is a significant step forward in achieving a phased antenna system designed for 5G wireless applications. This work contributes to the advancement of wireless communication technologies and facilitates the integration of improved antenna systems into the 5G ecosystem.

4.1.1 Antenna Array using Rogger RT5880

4.1.1.1 *Two Elements Microstrip Patch Antenna Array using Rogger RT5880.*

Table 4.1 represents the parameters and the calculated dimensions (mm) for the design two-element microstrip patch antenna array using Rogger RT5880 material.

Table 4-1: Two Elements Antenna Array Parameters using Rogger RT5880 material.

Parameters (2)	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	1.20	Length of Patch	1.375
Weight of ground	5.60	Length of Ground	4.11
Weight of Substrate	5.60	Length of Substrate	4.11
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2.2	Material	Rogger RT 5880
Weight of Patch Cut	0.15	Height of Patch Cut	0.50
Weight of Ground Cut	1.20	Height of Ground Cut	0.4
Width of Feedline	0.228/0.452/0.785	Length of Feedline	0.76
Gain	7.64	Directivity	8.66
Reflection Coefficient	-28.77	Bandwidth	3222 MHz
Input Impedance	48.43 ohm		

The below results show the two elements microstrip patch antenna array at 60GHz using Rogger RT5880 material as a substrate, Figure 4.1 shows the front side of designed antenna. Figure 4.2 displays the design antenna from behind and to the sides.

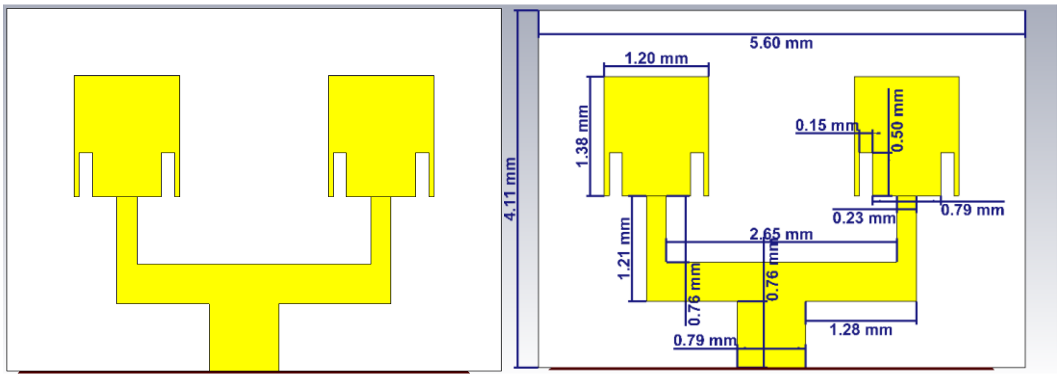

Figure 4.1: Front side view of two elements patch antenna array using Roggers RT5880.

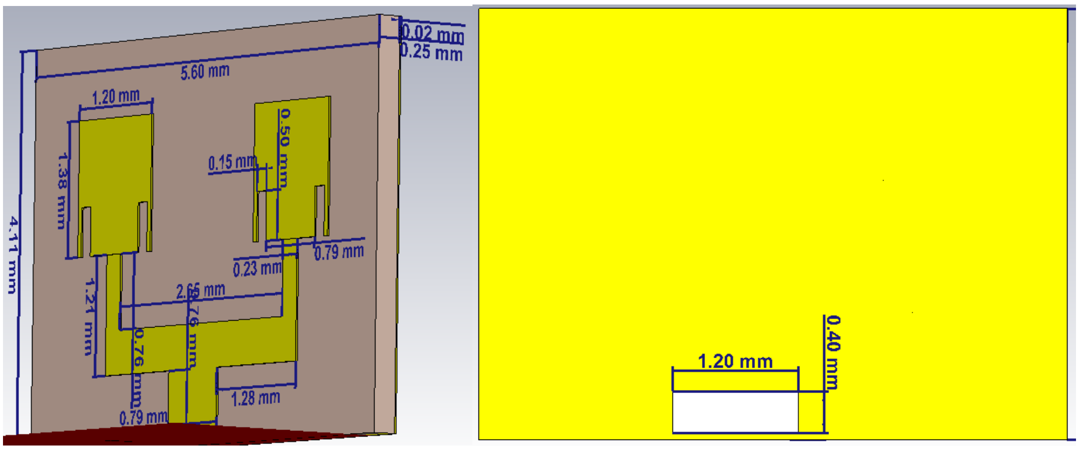

Figure 4.2: Side and back side view of two elements patch antenna array using Roggers RT5880.

The graph below represents the bandwidth of two elements microstrip antenna array for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 3222MHz.

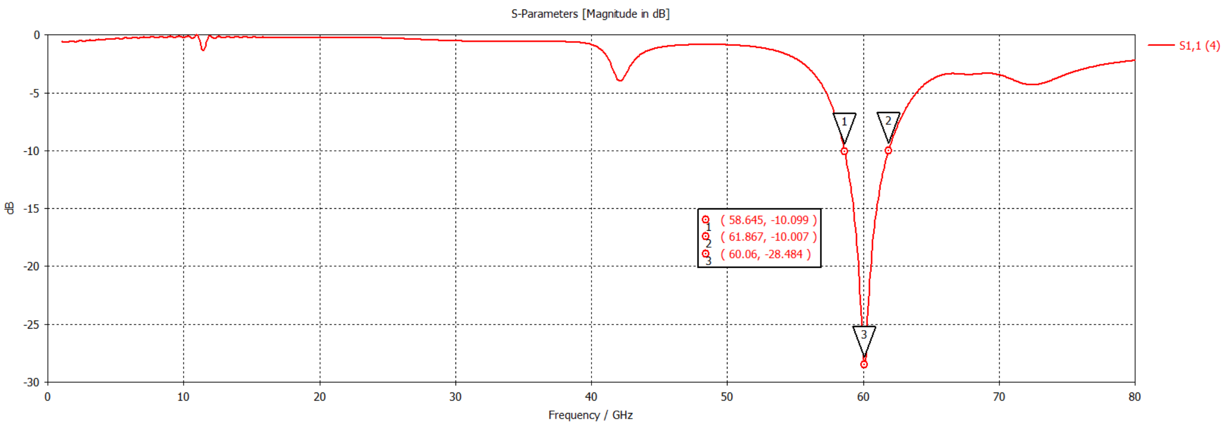

Figure 4.3: S parameter of two elements patch antenna array using Roggers RT5880.

The graph below represents the reference impedance of the two elements microstrip antenna array for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna array for single element is around 50 ohm (48.43 ohm).

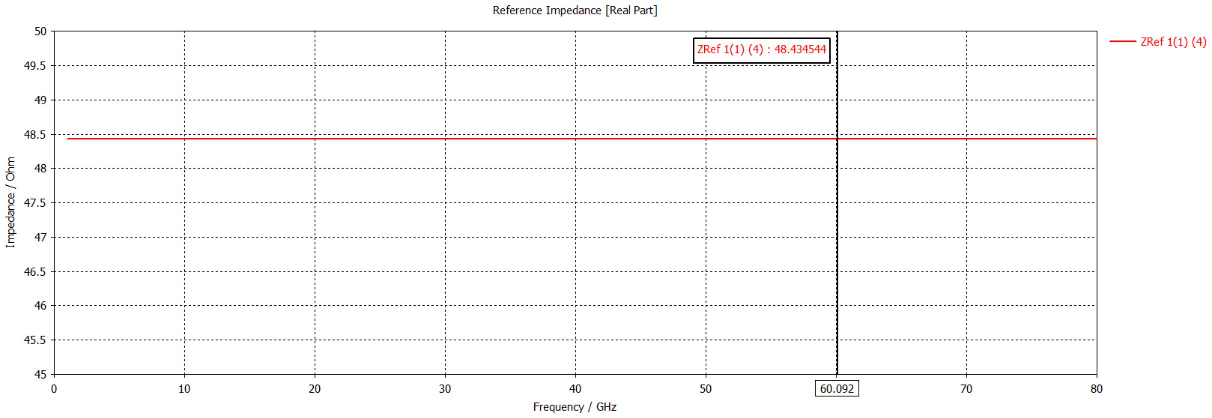

Figure 4.4: Input impedance of two elements patch antenna array using Roggers RT5880.

The figure 4.5 and 4.6 represent the Gain in polar and 3D form of two elements of microstrip patch antenna for 5G systems respectively.

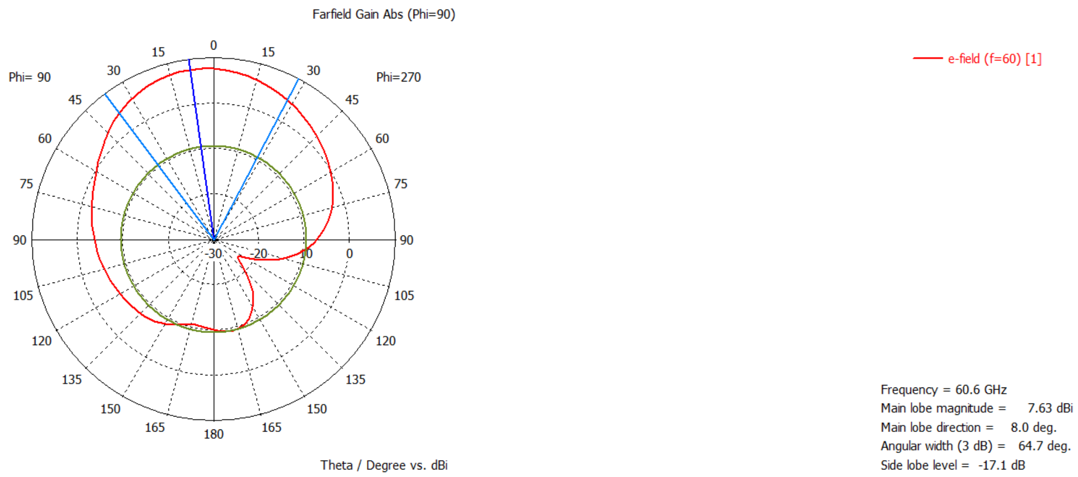

Figure 4.5: Gain of two elements patch antenna array in polar form using Roggers RT5880.

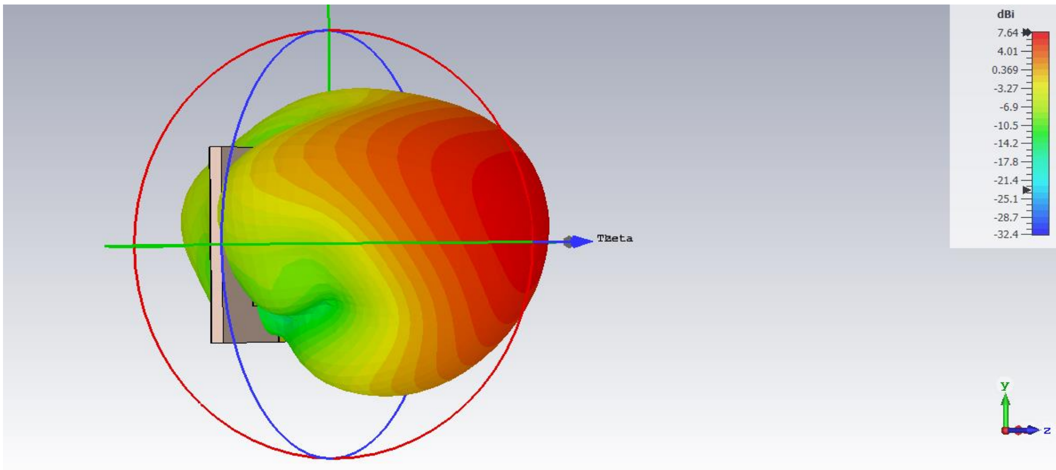

Figure 4.6: Gain of two elements patch antenna array in 3D form using Roggers RT5880.

4.1.1.2 *Four Elements Microstrip Patch Antenna Array using Roggers RT5880.*

Table 4.2 represents the parameters and the calculated dimensions (mm) for the design four-element microstrip patch antenna array using Rogger RT5880 material.

Table 4-2: Four Elements Antenna Array Parameters using Rogger RT5880 material.

Parameters (4)	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	1.37	Length of Patch	1.375
Weight of ground	12.04	Length of Ground	5.33
Weight of Substrate	12.04	Length of Substrate	5.33
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2.2	Material	Rogger RT 5880
Weight of Patch Cut	0.15	Height of Patch Cut	0.50
Weight of Ground Cut	1.50	Height of Ground Cut	1.25
Width of Feedline	0.228/0.452/0.785	Length of Feedline	0.76
Gain	10.5	Directivity	11.9
Reflection Coefficient	-42.315	Bandwidth	3970 MHz
Input Impedance	48.85 ohm		

The below results show the four elements microstrip patch antenna array at 60GHz using Rogger RT5880 material as a substrate, Figure 4.7 shows the front side of designed antenna. Figure 4.8 displays the design antenna from behind and to the sides.

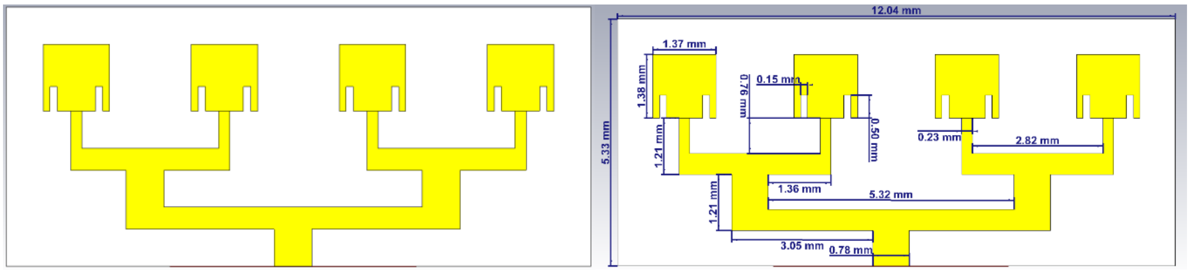

Figure 4.7: Front view of four elements patch antenna array using Roggers RT5880.

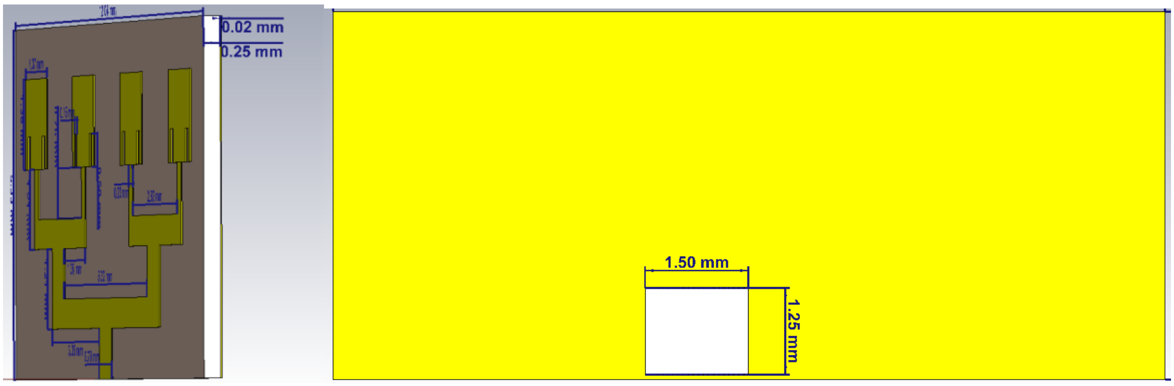

Figure 4.8: Side and back view of four elements patch antenna array using Roggers RT5880.

The graph below represents the bandwidth of four elements microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 3970MHz.

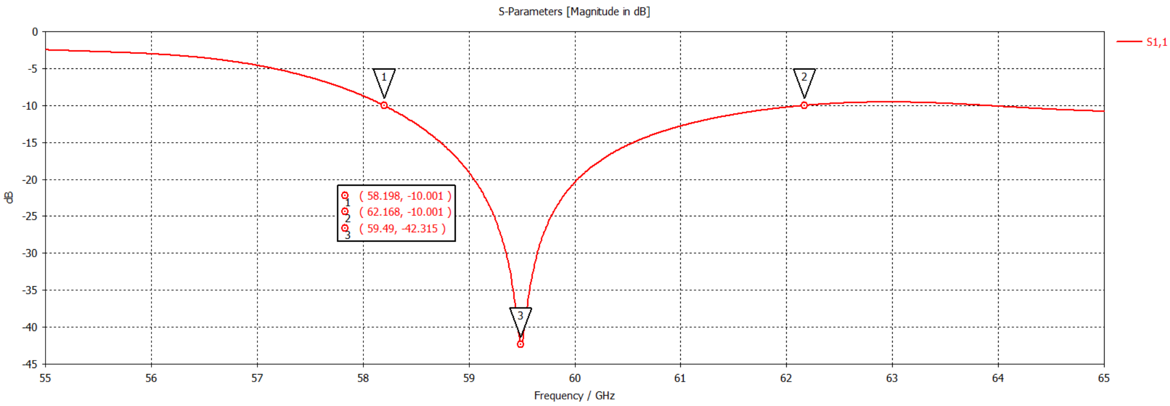

Figure 4.9: S parameter of four elements patch antenna array using Roggers RT5880.

The graph below represents the reference impedance of the design microstrip antenna for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is around 50 ohm (48.85 ohm).

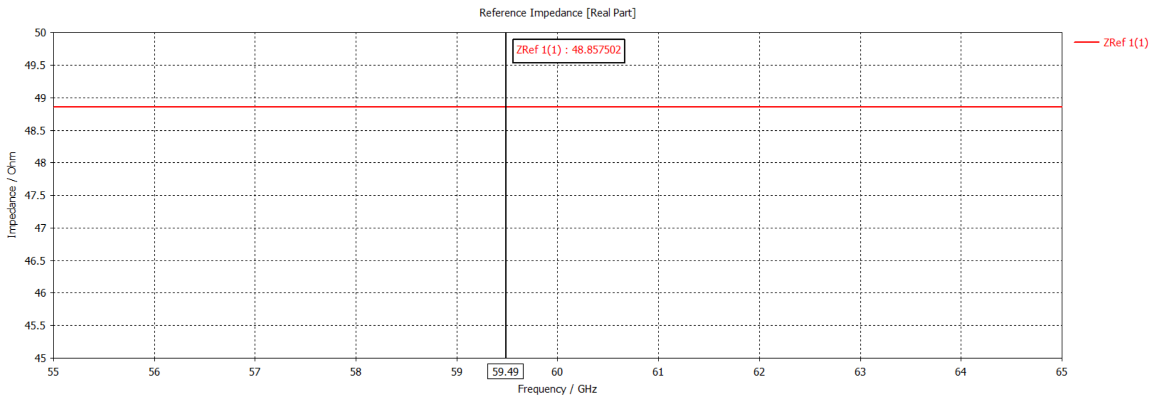

Figure 4.10: Input impedance of four elements patch antenna array using Roggers RT5880.

The figure 4.11 and 4.12 represent the Gain in polar and 3D form of four elements of microstrip patch antenna for 5G systems respectively.

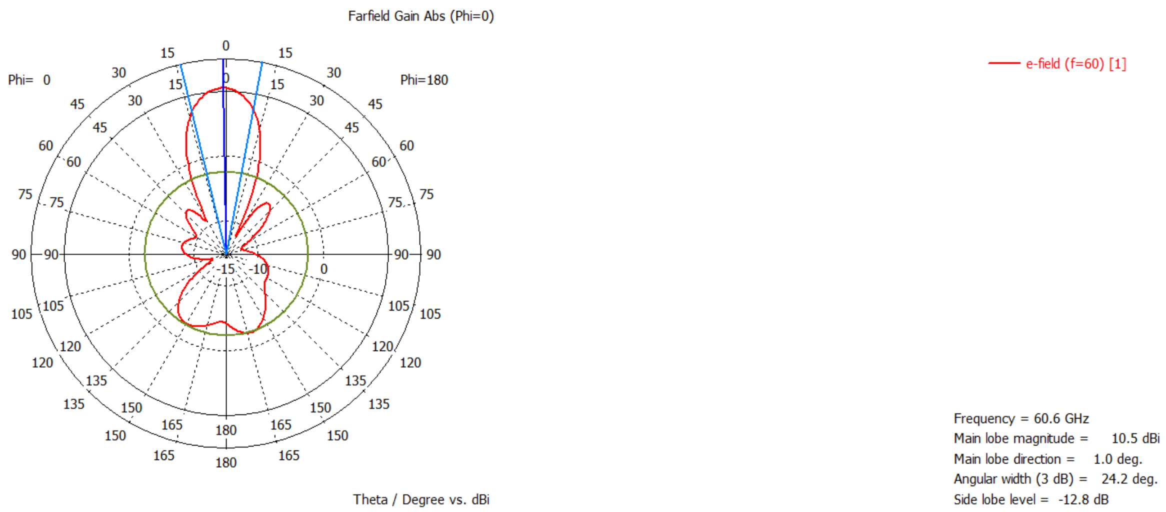

Figure 4.11: Gain of four elements patch antenna array in polar form using Roggers RT5880.

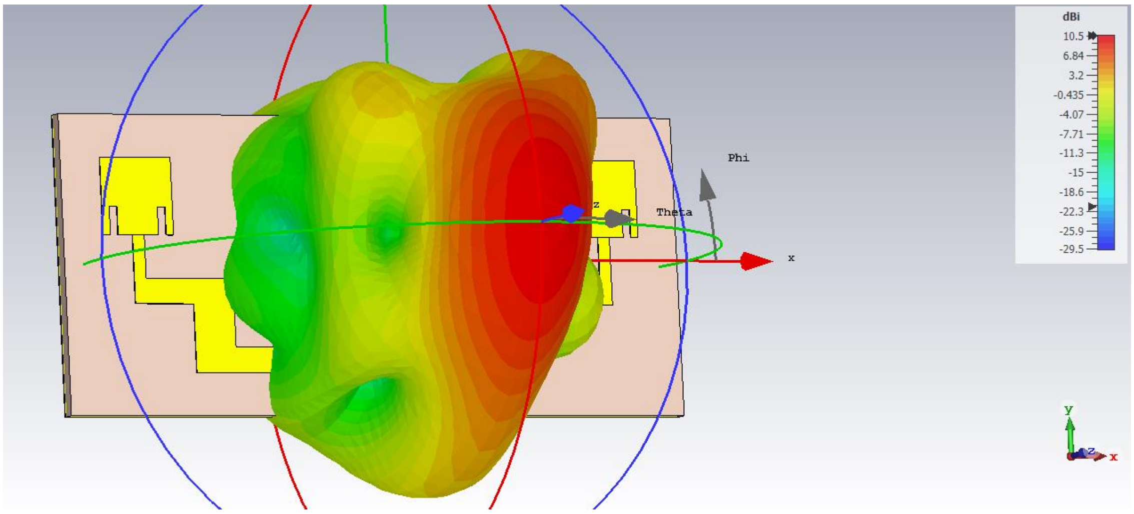

Figure 4.12: Gain of four elements patch antenna array in 3D form using Roggers RT5880.

4.1.2 Antenna Array using Teflon.

4.1.2.1 Two-elements microstrip patch antenna array using Teflon.

Table 4.3 represents the parameters and the calculated dimensions (mm) for the design two-element microstrip patch antenna array using TEFLON material.

Table 4-3: Two Elements Antenna Array Parameters using TEFLON material.

Parameters (2)	Demission’s (mm)	Parameters	Demission’s (mm)
Weight of Patch	1.97	Length of Patch	1.93
Weight of ground	7.23	Length of Ground	4.70
Weight of Substrate	7.23	Length of Substrate	4.70
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2	Material	TEFLON
Weight of Ground Cut	1	Height of Ground Cut	0.45
Width of Feedline	0.248/0.484/0.802	Length of Feedline	0.76
Gain	8.1	Directivity	9.49
Reflection Coefficient	-33.27	Bandwidth	2227 MHz
Input Impedance	49.47 ohm		

The below results show the two elements microstrip patch antenna array at 60GHz using Teflon material as a substrate, Figure 4.13 shows the front side of designed antenna. Figure 4.14 displays the design antenna from behind and to the sides.

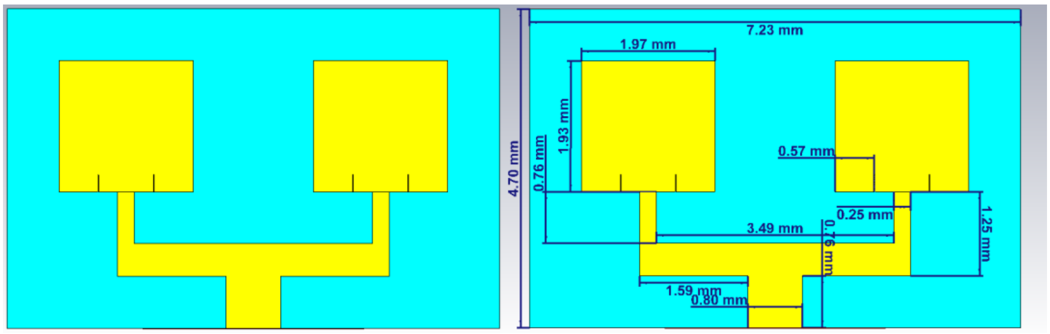

Figure 4.13: Front view of two elements patch antenna array using Teflon.

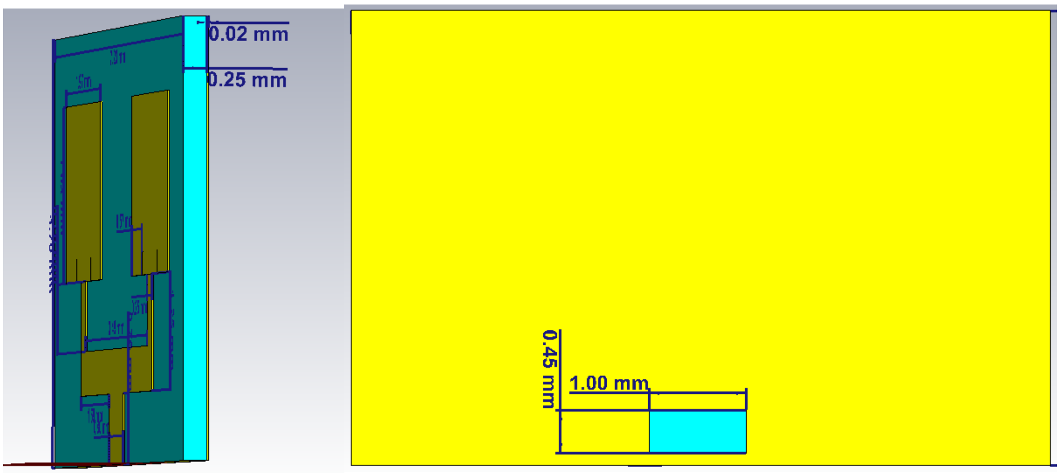

Figure 4.14: Side and back side view of two elements patch antenna array using Teflon.

The graph below represents the bandwidth of two elements of microstrip antenna array for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 2727MHz.

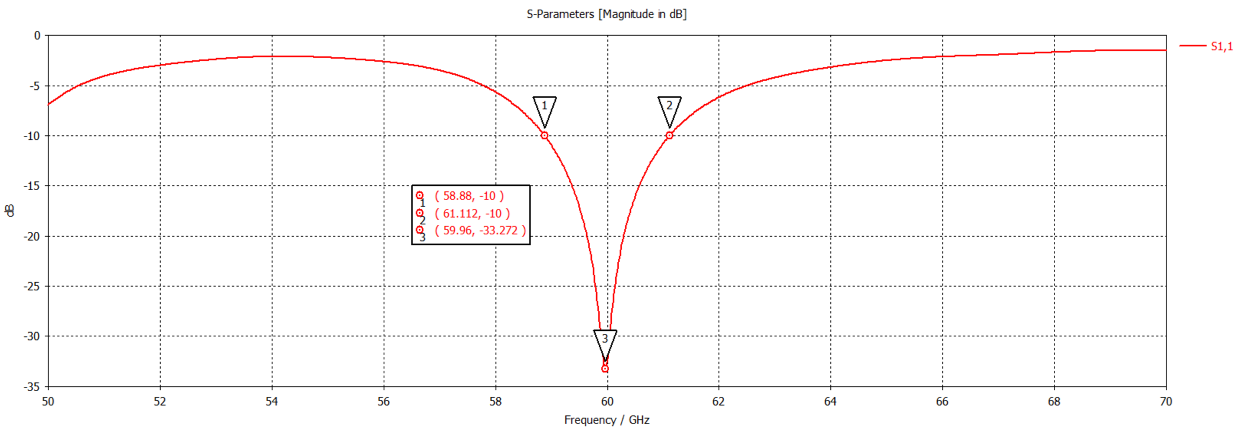

Figure 4.15: S parameter of two elements patch antenna array using Teflon.

The graph below represents the reference impedance of the design microstrip antenna array for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for two elements is around 50 ohm (49.47 ohm).

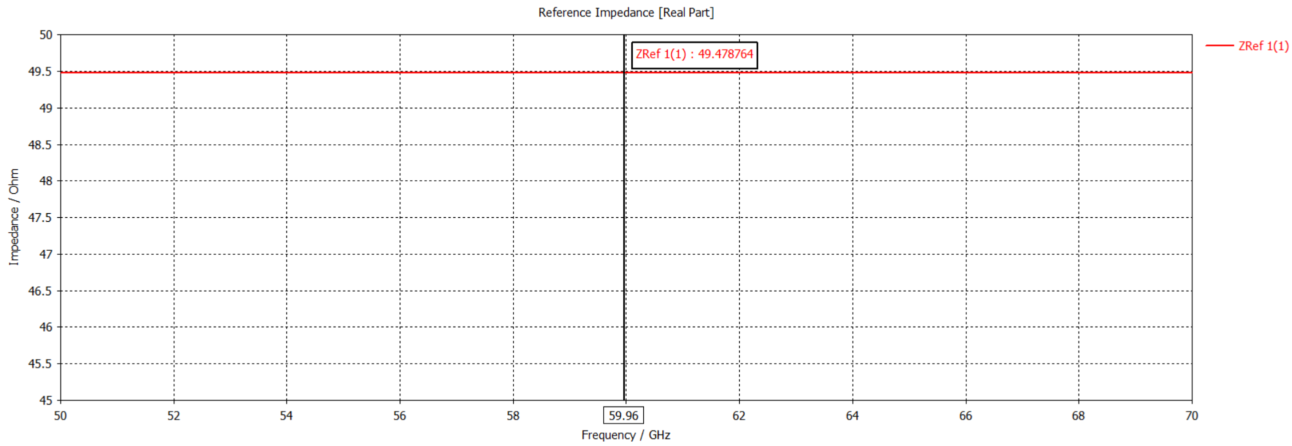

Figure 4.16: Input impedance of two elements patch antenna array using Teflon.

The figure 4.17 and 4.18 represent the Gain in polar and 3D form of two elements of microstrip antenna for 5G systems respectively.

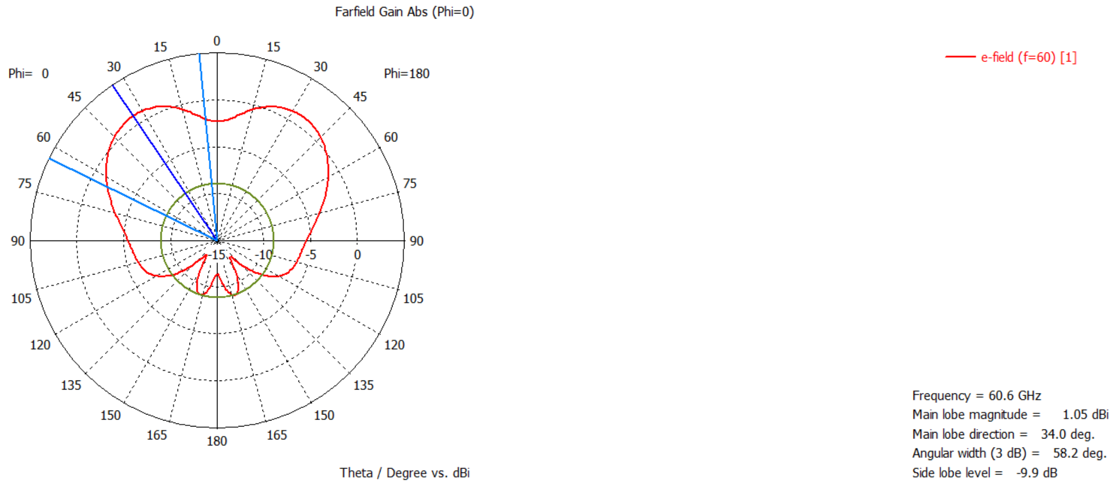

Figure 4.17: Gain of two elements patch antenna array in polar form using Teflon.

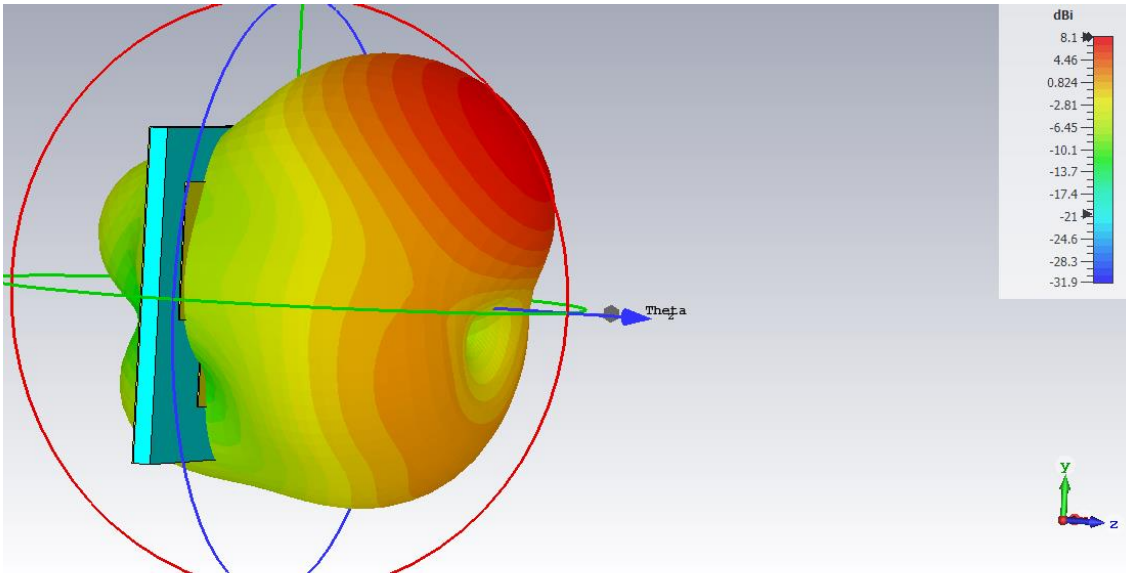

Figure 4.18: Gain of two elements patch antenna array in 3D form using Teflon.

4.1.2.2 *Four-element microstrip patch antenna array using Teflon.*

Table 4.4 represents the parameters and the calculated dimensions (mm) for the design four-element microstrip patch antenna array using TEFLON material.

Table 4-4: Four Elements Antenna Array Parameters using TEFLON material.

Parameters (4)	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	1.575	Length of Patch	1.8
Weight of ground	13.13	Length of Ground	5.82

Weight of Substrate	13.13	Length of Substrate	5.82
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	2	Material	TEFLON
Weight of Ground Cut	1.35	Height of Ground Cut	0.50
Width of Feedline	0.248/0.484/0.802	Length of Feedline	0.76
Gain	9.91	Directivity	11.1
Reflection Coefficient	-33.27	Bandwidth	1094 MHz
Input Impedance	50 ohms		

The below results show the four elements microstrip patch antenna array at 60GHz using Teflon material as a substrate, Figure 4.19 shows the front side of designed antenna. Figure 4.20 displays the design antenna from behind and to the sides.

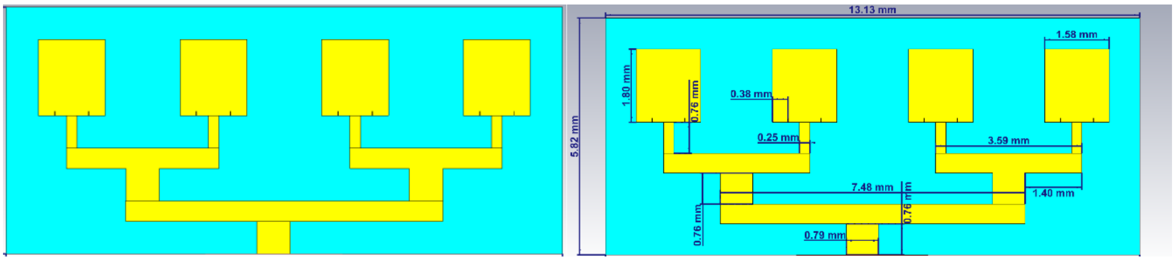

Figure 4.19: Front side view of four elements patch antenna array using Teflon.

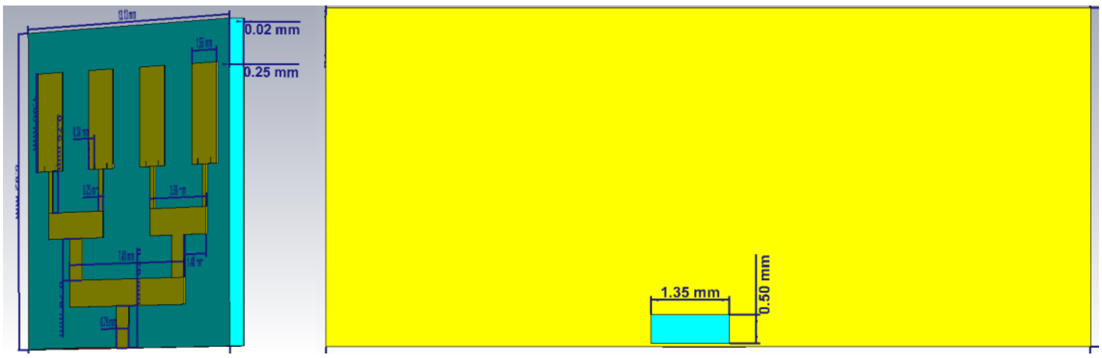

Figure 4.20: Side and back side view of four elements patch antenna array using Teflon.

The graph below represents the bandwidth of four elements microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 1094MHz.

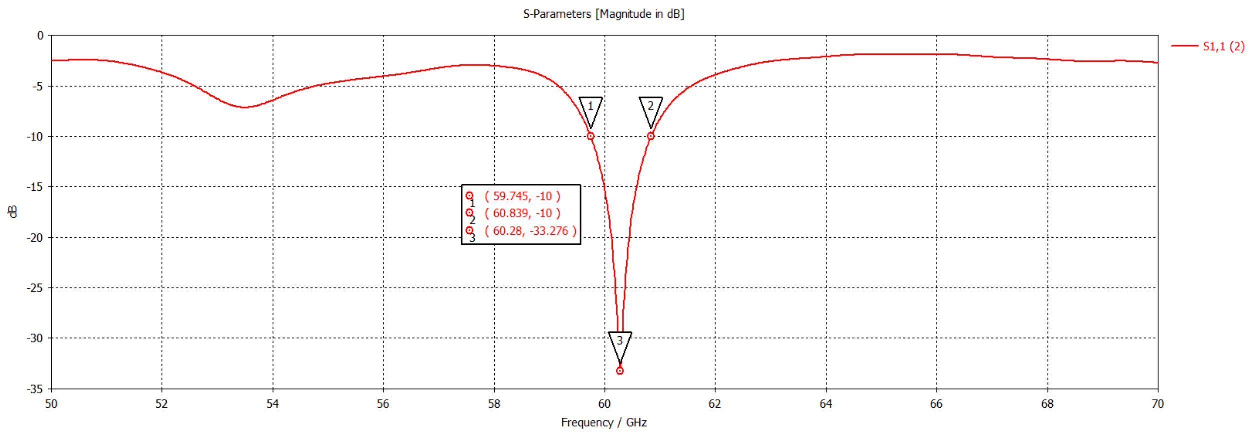

Figure 4.21: S parameter of four elements patch antenna array using Teflon.

The graph below represents the reference impedance of the design of four elements microstrip antenna array for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is 50 ohms.

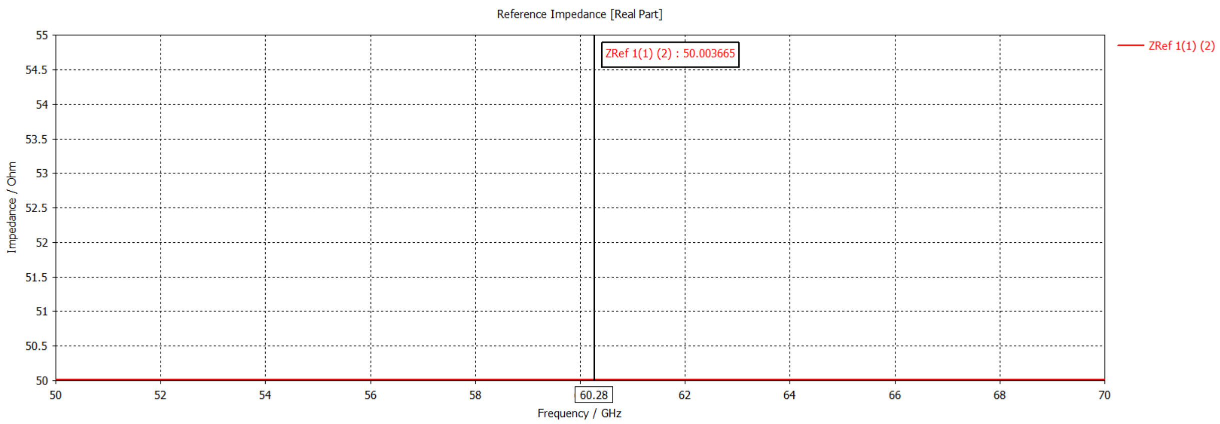

Figure 4.22: Input impedance of four elements patch antenna array using Teflon.

Figures 4.23 and 4.24 represent the Gain in polar and 3D form of four elements of microstrip antenna array for 5G systems respectively.

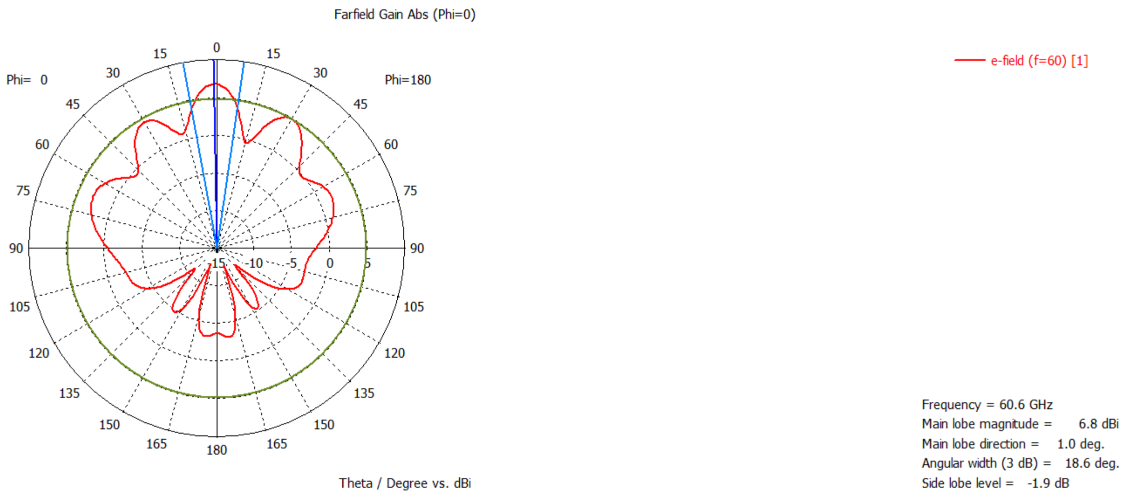

Figure 4.23: Gain of four elements patch antenna array in polar form using Teflon.

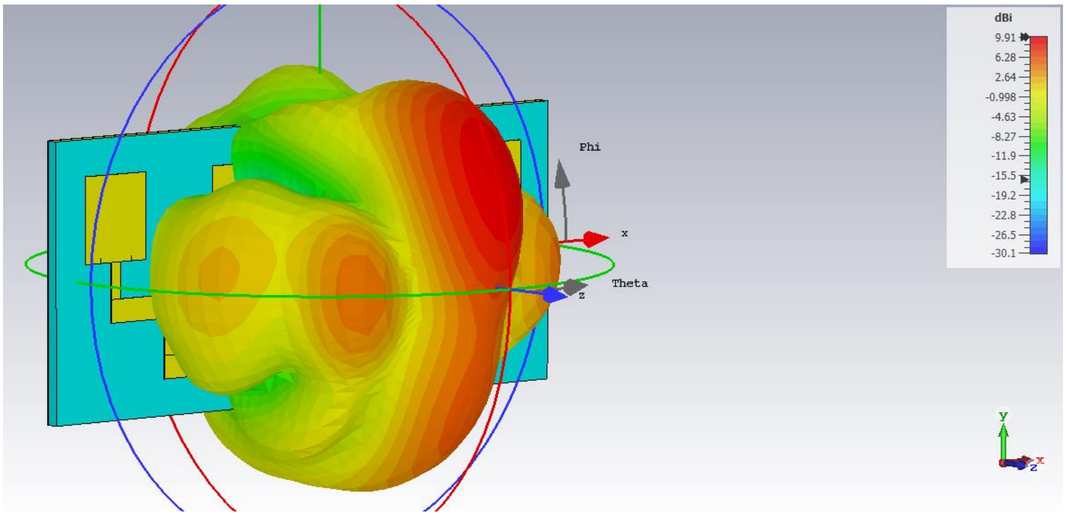

Figure 4.24: Gain of four element patch antenna array in 3D form using Teflon.

4.1.3 Antenna Array using LTCC A6M

4.1.3.1 *Two-elements microstrip patch antenna array using LTCC A6M.*

Table 4.5 represents the parameters and the calculated dimensions (mm) for the design two-element microstrip patch antenna array using LTCC A6M material.

Table 4-5: Two Elements Antenna Array Parameters using LTCC A6M material.

Parameters (2)	Demission's (mm)	Parameters	Demission's (mm)
Weight of Patch	2.19	Length of Patch	1.75
Weight of ground	6.93	Length of Ground	4.22

Weight of Substrate	6.93	Length of Substrate	4.22
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	5.9	Material	LTCC A6M
Width of Feedline	0.075/0.19/0.38	Length of Feedline	0.76
Gain	8.24	Directivity	8.86
Reflection Coefficient	-14.76	Bandwidth	2529 MHz
Input Impedance	50.02 ohm		

The below results show the two elements microstrip patch antenna array at 60GHz using LTCC A6M material as a substrate, Figure 4.25 shows the front side of designed antenna. Figure 4.26 displays the design antenna from behind and to the sides.

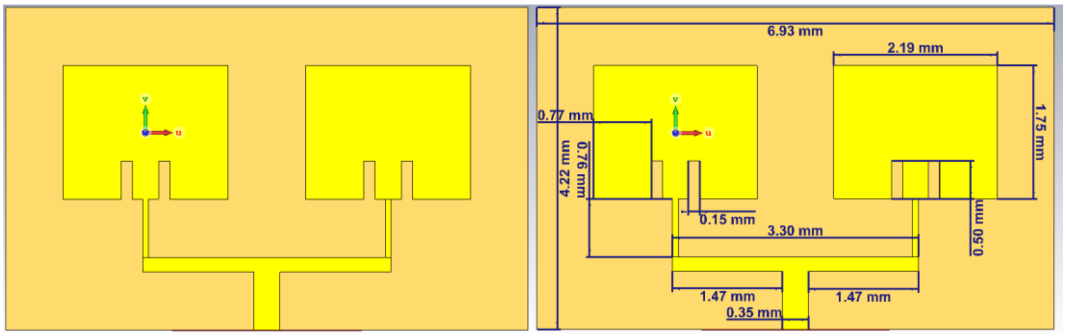

Figure 4.25: Front side view of two elements patch antenna array using LTCC A6M.

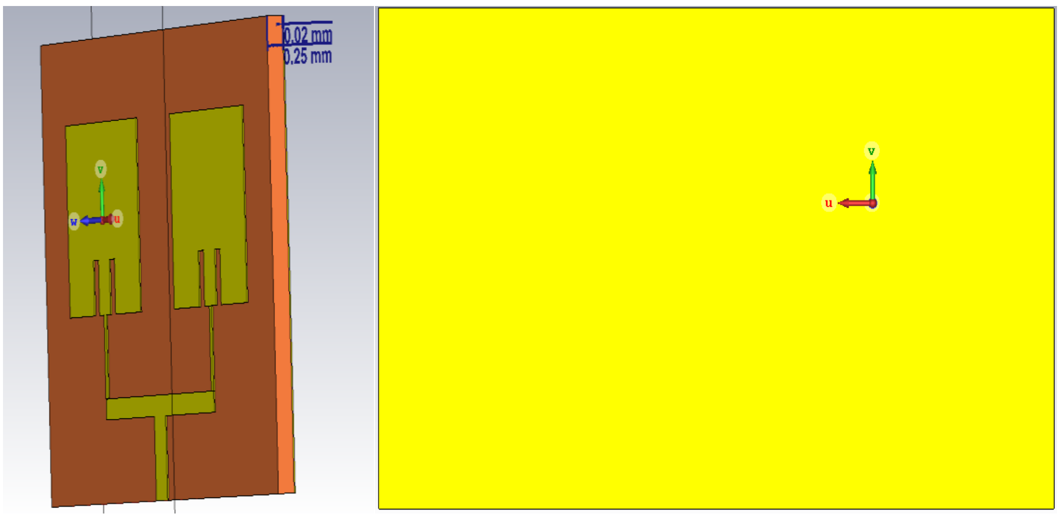

Figure 4.26: Side and back side view of two elements patch antenna array using LTCC A6M.

The graph below represents the bandwidth of two elements of microstrip antenna array for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 2529MHz.

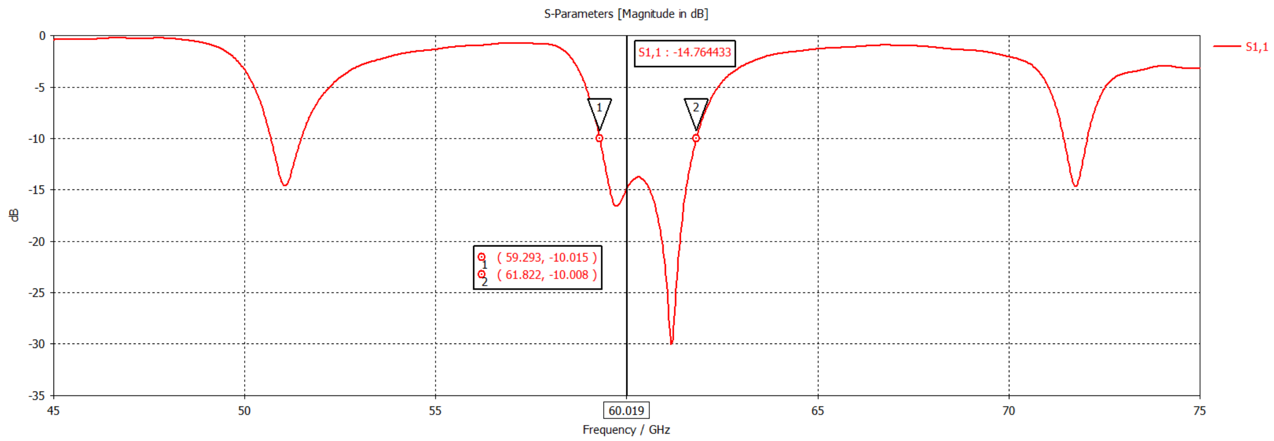

Figure 4.27: S parameters of two elements patch antenna array using LTCC A6M.

The graph below represents the reference impedance of the design microstrip antenna array for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for two elements is 50 ohms.

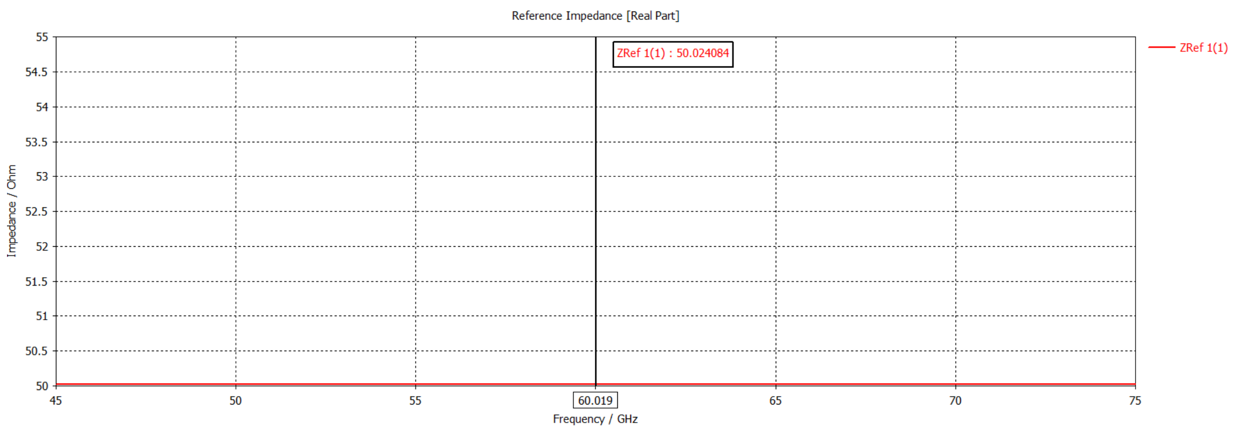

Figure 4.28: Input Impedance of two elements patch antenna array using LTCC A6M.

The figures 4.29 and 4.30 represent the Gain in polar and 3D form of two elements of microstrip antenna for 5G systems respectively.

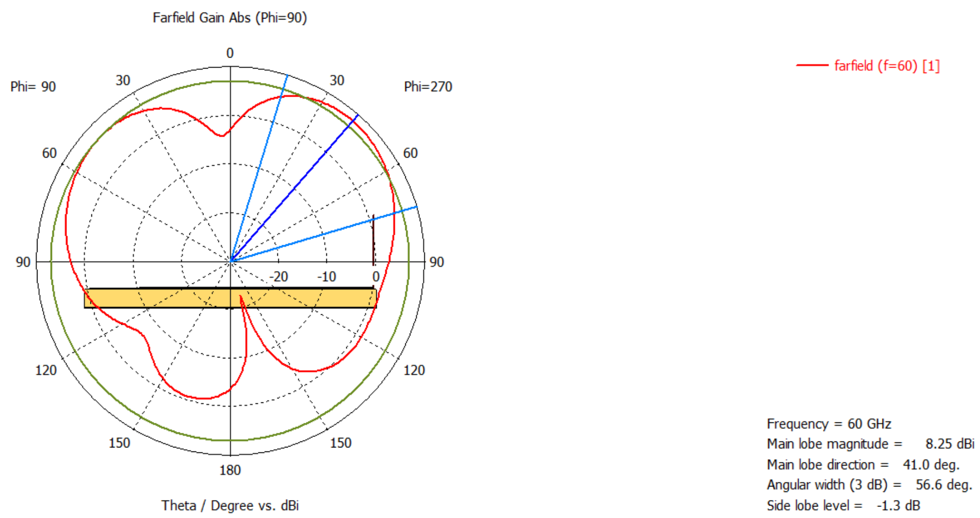

Figure 4.29: Gain of two elements patch antenna array in polar form using LTCC A6M.

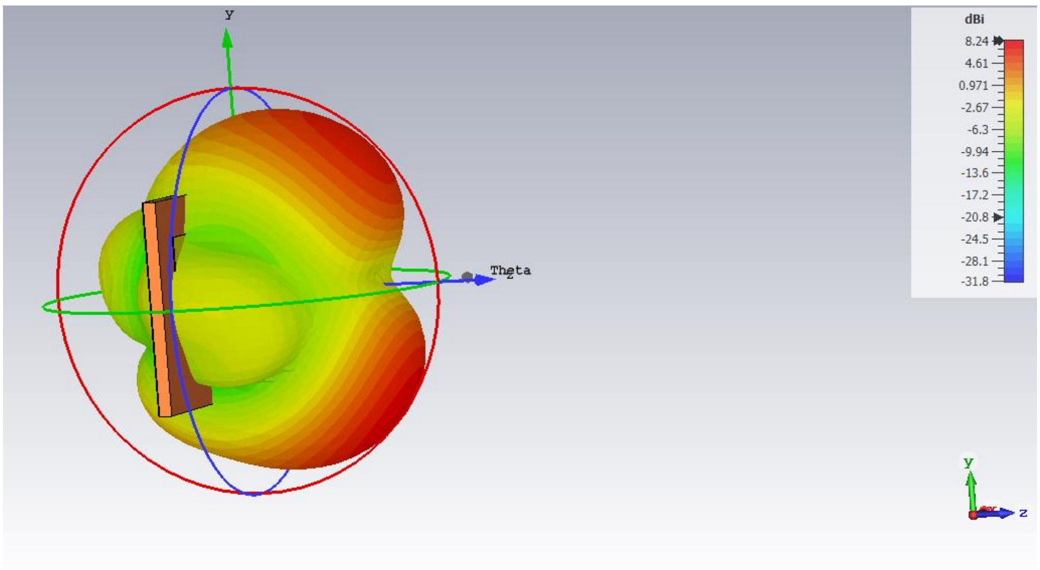

Figure 4.30: Gain of two elements patch antenna array in 3D form using LTCC A6M.

4.1.3.2 *Four-element microstrip patch antenna array using LTCC A6M.*

Table 4.6 represents the parameters and the calculated dimensions (mm) for the design four-element microstrip patch antenna array using LTCC A6M material.

Table 4-6: Four Elements Antenna Array Parameters using LTCC A6M material.

Parameters (4)	Demission's (mm)	Parameters	Demission's (mm)

Weight of Patch	2.273	Length of Patch	2.45
Weight of ground	13.71	Length of Ground	5.87
Weight of Substrate	13.71	Length of Substrate	5.87
Height of Copper cladding	0.018	Height of Substrate material	0.254
Dielectric constant	5.9	Material	LTCC A6M
Width of Feedline	0.075/0.19/0.38	Length of Feedline	0.76
Gain	8.35	Directivity	9.51
Reflection Coefficient	-26.65	Bandwidth	767 MHz
Input Impedance	47.91 ohms		

The below results show the four elements microstrip patch antenna array at 60GHz using LTCC A6M material as a substrate, Figure 4.31 shows the front side of designed antenna. Figure 4.32 displays the design antenna from behind and to the sides.

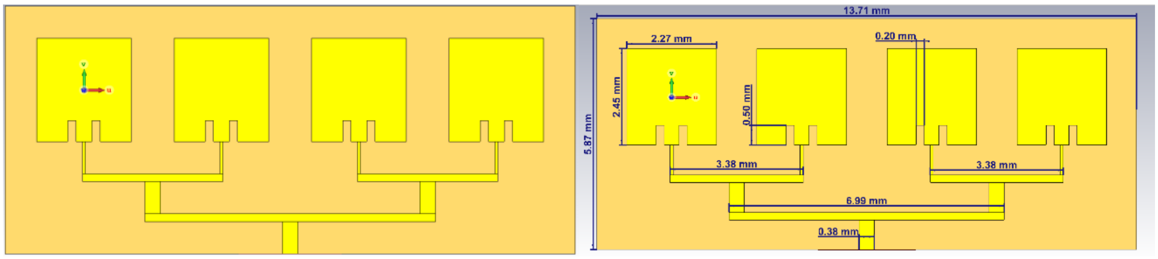

Figure 4.31: Front side view of four elements patch antenna array using LTCC A6M.

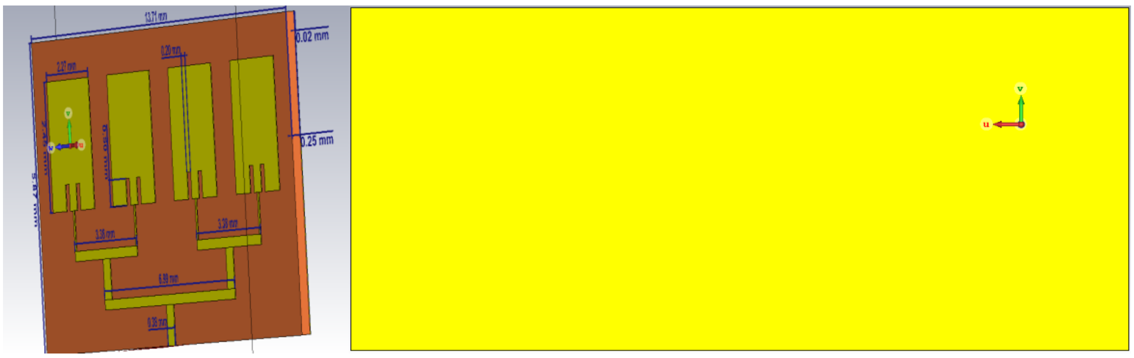

Figure 4.32: Side and back view of four elements patch antenna array using LTCC A6M.

The graph below represents the bandwidth of four elements microstrip antenna for 5G systems. In the graph, we can observe that the S11 parameters or Reflection Coefficient is lower than -10 dB, with a total bandwidth of 767 MHz.

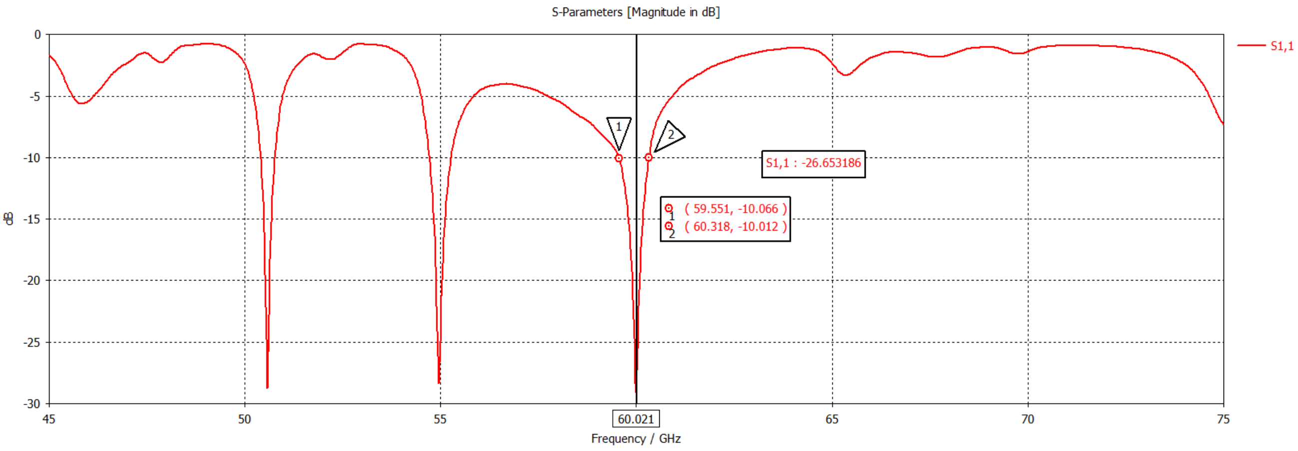

Figure 4.33: S parameter of four elements patch antenna array using LTCC A6M.

The graph below represents the reference impedance of the design of four elements microstrip antenna array for 5G wireless communication systems at the feedline. In the graph, we can observe reference impedance of the designed microstrip antenna for single element is around 50 ohms (47.91).

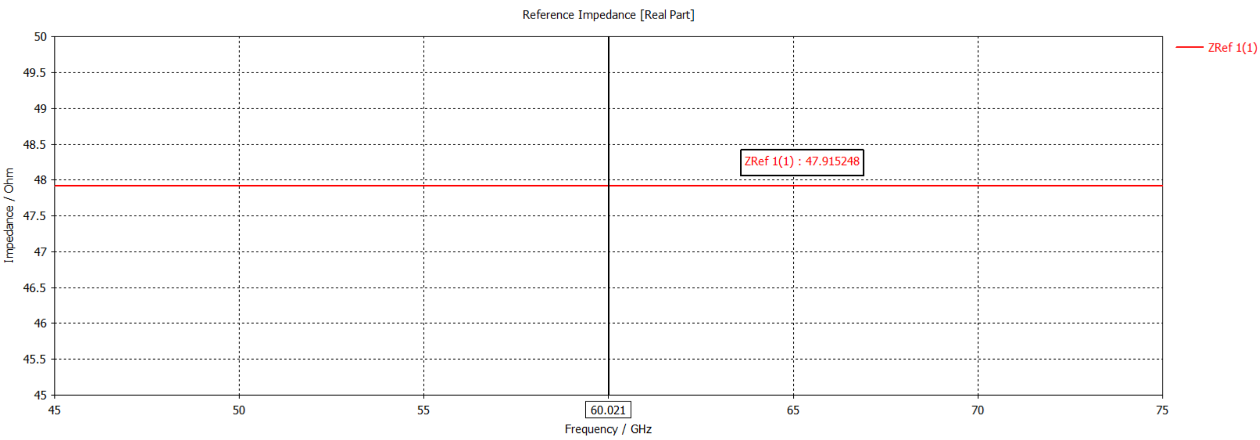

Figure 4.34: Input impedance of four elements patch antenna array using LTCC A6M.

The figures 4.35 and 4.36 represent the Gain in polar and 3D form of four elements of microstrip antenna array for 5G systems respectively.

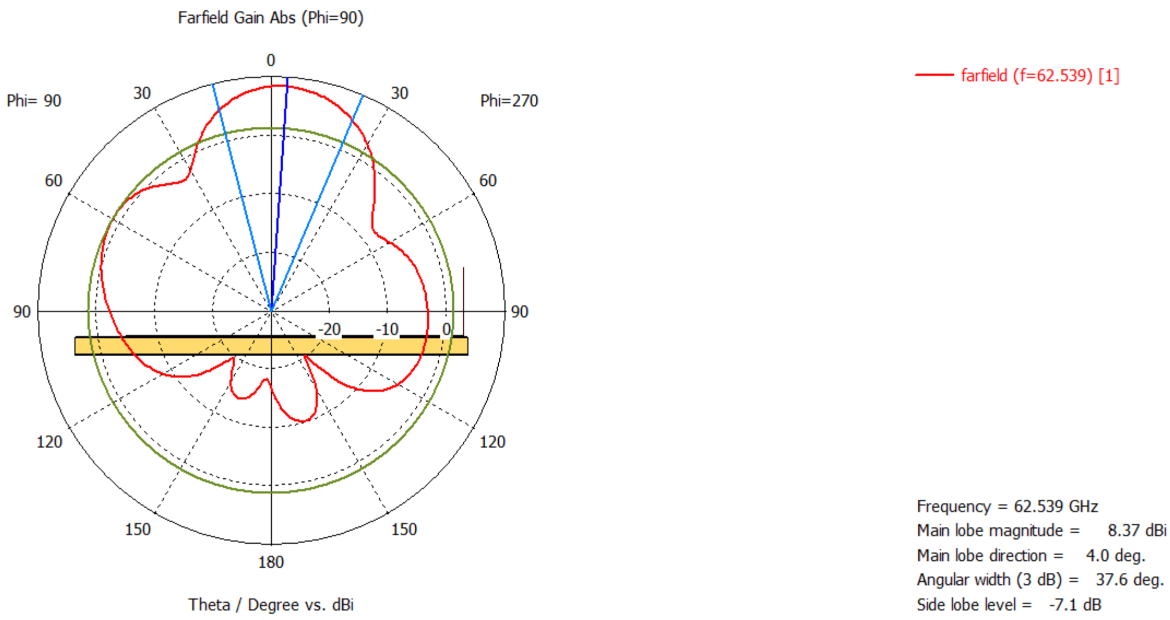

Figure 4.35: Gain of four elements patch antenna array in polar form using LTCC A6M.

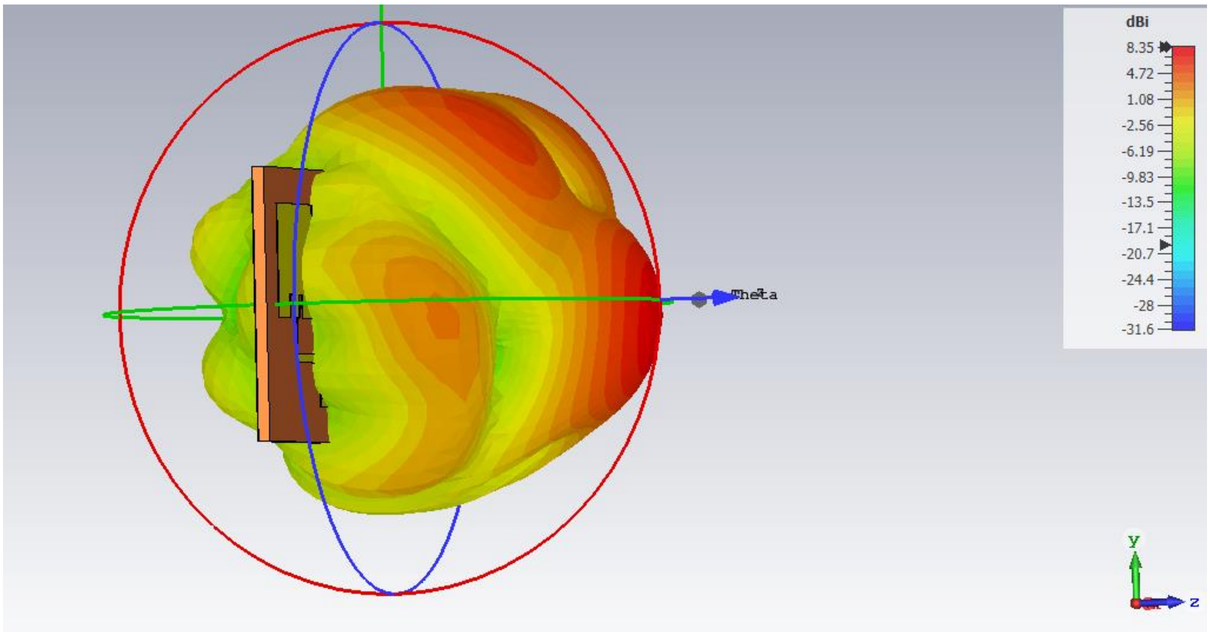

Figure 4.36: Gain of four elements patch antenna array in 3D form using LTCC A6M.

5 Comparison and Analysis

5.1 Discussion and Analysis of Single Element Patch Antenna.

An investigation was conducted on a single-element patch antenna utilizing three distinct substrate materials: Roggers RT5880, Teflon, and LTCC A6M with dielectric constants of 2.2, 2, and 5.9, respectively. The study provided valuable insights into the performance of each material. After the design phase, antennas made with Roggers RT5880 and Teflon substrates showed better performance than those made using LTCC A6M. An analysis of the findings in Table 5.1 reveals the unique characteristics of performance of each substrate material.

Table 5-1: Comparison between design of single element antenna results.

Name (Single Element)	**Roggers RT5880**	**Teflon Unit (mm)**	**LTCC A6M**
	Unit (mm)	***Unit (mm)***	***Unit (mm)***
Width of Patch	1.976	2.2	2.19
Length of Patch	1.518	1.607	1.7
Width of Ground / Substrate.	3.5 / 3.5	3.724 / 3.742	3.714 / 3.714
Length of Ground / Substrate.	3.042 / 3.042	3.131 / 3.131	3.224 / 3.224
Height Substrate	0.254	0.254	0.254
Height Cladding	0.018	0.018	0.018
Width of Feed	0.8	0.802	0.770
Gain	5.94	6.29	3.78
Directivity	7.9	8.14	5.61
Reflection Coefficient	-52.593 at 61.04GHz F	-22.048 at 59.9GHz F	-25.155 at 60.24 GHz F
Bandwidth	3251Mhz	2686 MHz	1743 MHz
Reference Impedance	47.898 Ohm	50.02 Ohm	31.93 Ohm
Dielectric Const.	2.2	2	5.9

Rogers RT5880 exhibited a broader bandwidth and lower reflection coefficient compared to Teflon substrates, suggesting superior impedance matching with the feeding network. Teflon showed superior gain, directivity, and provided enhanced VSWR (Voltage Standing Wave Ratio), as well as improved impedance matching, particularly at the 60 GHz operating frequency. The results indicate that Roggers RT5880 has high bandwidth and low reflection coefficient, while Teflon has better performance in gain, directivity, and impedance matching at the appropriate frequency.

The LTCC A6M substrate showed inferior performance in comparison to other substrates across different measurements. The antenna using LTCC A6M substrate did not perform as well as those using Rogers RT5880 and Teflon substrates, despite its higher dielectric constant. Substrate losses and impedance mismatch can affect antenna performance, emphasizing the significance of selecting the right substrate.

Comparing single-element patch antennas made from three different substrate materials highlights the importance of substrate choice in antenna design. Rogers RT5880 and Teflon substrates have specific strengths: Rogers excels in bandwidth and reflection coefficient, while Teflon has greater gain, directivity, and impedance matching at 60 GHz. In comparison, LTCC A6M substrate underperforms. The results offer important information for improving antenna designs for certain uses, highlighting the importance of analyzing substrate characteristics to reach desired performance standards.

5.2 Discussion and Analysis of Two Elements Array of Patch Antenna.

An analysis was carried out on a two-element patch antenna array using three different substrate materials: Roggers RT5880, Teflon, and LTCC A6M, having dielectric constants of 2.2, 2, and 5.9, respectively. The study offered useful insights into their comparative performances. Upon successful completion of the array design process, it was observed that all three materials exhibited improved performance compared to their individual-element counterparts. An extensive examination of the results highlights the distinct characteristics offered by each substrate material.

Roggers RT5880 demonstrated notable advantages in terms of bandwidth and size reduction when compared to other materials. Despite its small size, it had a wider bandwidth compared to the other substrates. Teflon exhibited enhanced gain, directivity, reflection coefficient, and impedance matching in comparison to Rogers RT5880. These traits are ideal for applications requiring high-performance antennas.

Table 5-2: Comparison between design of two elements antenna array results.

Name (Two Elements)	**Roggers RT5880**	**Teflon Unit (mm)**	**LTCC A6M**
	Unit (mm)	***Unit (mm)***	***Unit (mm)***
Width of Patch	1.2	1.97	2.19
Length of Patch	1.375	1.93	1.75
Width of Ground / Substrate.	5.60 / 5.60	7.23 / 7.23	6.93 / 6.93
Length of Ground / Substrate.	4.11 / 4.11	4.70 / 4.70	4.22 / 4.22
Height Substrate	0.254	0.254	0.254
Height Cladding	0.018	0.018	0.018
Width of Feed	0.228/0.452/0.785	0.248/0.484/0.802	0.075/0.19/0.38
Gain	7.64	8.1	8.24
Directivity	8.66	9.49	8.86
Reflection Coefficient	-28.77 at 60.092 GHz F	-33.27 at 60.1 GHz F	-14.76 at 60.019 GHz F
Bandwidth	3222Mhz	2227 MHz	2529 MHz
Reference Impedance	48.43 Ohm	49.47 Ohm	50.02 Ohm
Dielectric Const.	2.2	2	5.9

The LTCC A6M showed outstanding performance in terms of gain, directivity, and impedance matching, particularly at 50 ohms. This substrate material offered significant advantages, particularly in applications requiring precise impedance matching. However, its bandwidth and size performance may be limited.

Comparing two-element patch antenna arrays using three different substrate materials emphasizes the importance of substrate selection in array design. Rogers RT5880 showed outstanding bandwidth and small dimensions, Teflon offered strong gain, directivity, and superb reflection coefficient, and LTCC A6M ensured precise impedance matching at 50 ohms. The findings provide valuable insights for improving array designs for specific purposes, emphasizing the need to comprehensively assess substrate properties to fulfil particular performance standards in antenna arrays.

5.3 Discussion and Analysis of Four Elements Array of Patch Antenna.

An analysis was conducted on four-element patch antenna arrays using Rogers RT5880, Teflon, and LTCC A6M substrates with dielectric constants of 2.2, 2, and 5.9, respectively, to get valuable insights into their performance. Roggers RT5880 outperformed Teflon and LTCC A6M in both design and analysis, demonstrating superior qualities. An in-depth analysis of the findings emphasizes the unique benefits provided by Roggers RT5880 as a substrate material for high-frequency applications.

Table 5-3: Comparison between design of four elements antenna array results.

Name (Four Elements)	**Roggers RT5880**	**Teflon Unit (mm)**	**LTCC A6M**
	Unit (mm)	***Unit (mm)***	***Unit (mm)***
Width of Patch	1.37	1.575	2.273
Length of Patch	1.375	1.8	2.45
Width of Ground / Substrate.	12 / 12	13 / 13	13.71 / 13.71
Length of Ground / Substrate.	5.33 / 5.33	5.82 /5.82	5.87 / 5.87
Height Substrate	0.254	0.254	0.254
Height Cladding	0.018	0.018	0.018
Width of Feed	0.228/0.452/0.785	0.248/0.484/0.802	0.075/0.19/0.38
Gain	11.1	9.91	8.35
Directivity	12.2	11.1	9.51
Reflection Coefficient	-42.315 at 59.49 GHz F	-33.27 at 60.28 GHz F	-26.65 at 60.021 GHz F
Bandwidth	3970 MHz	1094 MHz	767 MHz
Reference Impedance	48.85 Ohm	50 Ohm	47.91 Ohm
Dielectric Const.	2.2	2	5.9

The Roggers RT5880 exhibited remarkable performance parameters such as high gain, directivity, wide bandwidth, and favorable VSWR. It showed better impedance matching and a smaller size compared to both Teflon and LTCC A6M substrates. Roggers RT5880 is the ideal substrate material for single-layer patch antennas in 5G communication systems at 60

GHz due to its attractive qualities.

However, Teflon and LTCC A6M showed good performance but did not compare to the overall benefits provided by Roggers RT5880. Teflon exhibited superior gain, directivity, reflection coefficients, and impedance matching in comparison to LTCC A6M. Their performance was inferior when compared to the extensive capabilities of Roggers RT5880.

6 Conclusion

This master thesis has focused on 5G wireless communication, specifically examining the problems and opportunities of the 60GHz frequency spectrum. We extensively analyze the usage of this spectrum, to address several challenges to implement 5G and to be ready for upcoming technologies like 6G. We have improved the performance of a microstrip patch array antenna for 5G applications. We first design and analyze it for some substrates, such as Rogger RT5880, Teflon and, LTCC A6M.

The project found significant performance differences between several substrate materials. The Rogger RT5880 was especially remarkable in directivity, gain, wide bandwidth, sympathetic matching network and low mass production units. This new information provides important guidance for the design of antennas and selection techniques for substrates which are essential to progress in wireless communication technology. Our research exploits untalented antenna designs, economically efficient solutions, ecological problems and miniaturization of components at 60 GHz millimeter wave bands: a gap in existing literature now filled. We bridge the gap between what could theoretically be achieved and what can practically be done by putting these technologies into use-a restoration of the development situation of 5G. We enhance the current status of 5G technology and establish a solid groundwork for future developments, such as the eventual shift to 6G.

The study provides useful practical ways to enhance 5G wireless communication performance by looking at crucial factors such as antenna size, impedance matching and antenna gain. What we did contributed toward discovering the hidden potentials of 5G devices in the 60GHz frequency range for the better efficient wireless network that can be more trusted and more powerful. However, it is not just that it helps to deal with existing difficulties in terms of 5G application, but it creates a way for further development for wireless communication. We revealed the best material of the substrate and size of a design of the developed antenna looking at today’s needs of wireless technologies that may result in developing further improved antennas specifically designed for modern wireless needs.

Reference

[1] A. Al-Salihy, M. A. Al-Madi, and S. Alomari, “A survey in mobile generations and their mobility management,” *European Journal of Scientific Research*, vol. 58, no. 1, pp. 88–102, Aug. 2011, Accessed: Nov. 08, 2023. [Online]. Available: https://www.researchgate.net/publication/289923942

[2] T. Mshvidobadze, “Evolution mobile wireless communication and LTE networks,” *2012 6th International Conference on Application of Information and Communication Technologies, AICT 2012 - Proceedings*, 2012, doi: 10.1109/ICAICT.2012.6398495.

[3] D. J. Goodman, “Second generation wireless information networks,” *IEEE Trans Veh Technol*, vol. 40, no. 2, pp. 366–374, 1991, doi: 10.1109/25.289417.

[4] S. Ohmori, Y. Yamao, and N. Nakajima, “The Future generations of mobile communications based on broadband access technologies,” *IEEE Communications Magazine*, vol. 38, no. 12, pp. 134–142, 2000, doi: 10.1109/35.888267.

[5] J. L. Burbank, Julia. Andrusenko, J. S. Everett, and W. T. M. Kasch, “Second-Generation (2G) Cellular Communications,” in *Wireless Networking: Understanding Internetworking Challenges*, Wiley-IEEE Press, 2013, pp. 250–365.

[6] N. Chandran and M. C. Valenti, “Three Generations of Cellular Wireless Systems,” *IEEE Potentials*, vol. 20, no. 1, pp. 32–35, 2001, doi: 10.1109/45.913210.

[7] S. Behrad, E. Bertin, and N. Crespi, “Securing authentication for mobile networks, a survey on 4G issues and 5G answers,” *21st Conference on Innovation in Clouds, Internet and Networks, ICIN 2018*, pp. 1–8, Jun. 2018, doi: 10.1109/ICIN.2018.8401619.

[8] J. A. Del Peral-Rosado, R. Raulefs, J. A. López-Salcedo, and G. Seco-Granados, “Survey of Cellular Mobile Radio Localization Methods: From 1G to 5G,” *IEEE Communications Surveys and Tutorials*, vol. 20, no. 2, pp. 1124–1148, Apr. 2018, doi: 10.1109/COMST.2017.2785181.

[9] B. Clerckx, A. Costanzo, A. Georgiadis, and N. Borges Carvalho, “Toward 1G Mobile Power Networks: RF, Signal, and System Designs to Make Smart Objects Autonomous,” *IEEE Microw Mag*, vol. 19, no. 6, pp. 69–82, Sep. 2018, doi: 10.1109/MMM.2018.2844018.

[10] Q. K. Ud Din Arshad, A. U. Kashif, and I. M. Quershi, “A Review on the Evolution of Cellular Technologies,” *16th International Bhurban Conference on Applied Sciences and Technology*, pp. 989–993, Mar. 2019, doi: 10.1109/IBCAST.2019.8667173.

[11] T. Alexander, W. Mazurczyk, A. Mishra, and A. Perotti, “Mobile Communications and Networks,” *IEEE Communications Magazine*, vol. 57, no. 1, p. 42, Jan. 2019, doi: 10.1109/MCOM.2019.8613272.

[12] A. M. Niknejad, S. Thyagarajan, E. Alon, Y. Wang, and C. Hull, “A circuit designer’s guide to 5G mm-wave,” *2015 IEEE Custom Integrated Circuits Conference*, pp. 1–8, Nov. 2015, doi:

10.1109/CICC.2015.7338410.

[13] L. Wan *et al.*, “4G/5G Spectrum Sharing: Efficient 5G Deployment to Serve Enhanced Mobile Broadband and Internet of Things Applications,” *IEEE Vehicular Technology Magazine*, vol. 13, no. 4, pp. 28–39, 2018, doi: 10.1109/MVT.2018.2865830.

[14] P. Gandotra and R. K. Jha, “Next generation cellular networks and green communication,” *2018 10th International Conference on Communication Systems and Networks, COMSNETS*, pp. 522–524, Mar. 2018, doi: 10.1109/COMSNETS.2018.8328261.

[15] S. Kutty and D. Sen, “Beamforming for Millimeter Wave Communications: An Inclusive Survey,” *IEEE Communications Surveys and Tutorials*, vol. 18, no. 2, pp. 949–973, Apr. 2016, doi: 10.1109/COMST.2015.2504600.

[16] R. T. Prabu, M. Benisha, V. T. Bai, and V. Yokesh, “Millimeter wave for 5G mobile communication application,” in *Proceeding of IEEE - 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics, IEEE - AEEICB 2016*, Institute of Electrical and Electronics Engineers Inc., Aug. 2016, pp. 236–240. doi: 10.1109/AEEICB.2016.7538280.

[17] F. Boccardi, R. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, “Five disruptive technology directions for 5G,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74–80, 2014, doi: 10.1109/MCOM.2014.6736746.

[18] T. E. Bogale and L. B. Le, “Massive MIMO and mmWave for 5G Wireless HetNet: Potential Benefits and Challenges,” *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 64–75, Mar. 2016, doi: 10.1109/MVT.2015.2496240.

[19] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, “Spatially sparse precoding in millimeter wave MIMO systems,” *IEEE Trans Wirel Commun*, vol. 13, no. 3, pp. 1499–1513, 2014, doi: 10.1109/TWC.2014.011714.130846.

[20] Q. C. Li, H. Niu, A. T. Papathanassiou, and G. Wu, “5G network capacity: Key elements and technologies,” *IEEE Vehicular Technology Magazine*, vol. 9, no. 1, pp. 71–78, 2014, doi: 10.1109/MVT.2013.2295070.

[21] I. Ndip, T. H. Le, O. Schwanitz, and K. D. Lang, “A comparative analysis of 5G mmWave antenna arrays on different substrate technolgies,” *MIKON 2018 - 22nd International Microwave and Radar Conference*, pp. 222–225, Jul. 2018, doi: 10.23919/MIKON.2018.8405183.

[22] R. R. Turjo, S. M. Real, and M. H. Sagor, “Phased Array Antenna with Key Shaped Elements for 60 GHz mmWave Communications,” *2019 International Workshop on Antenna Technology, iWAT*, pp. 178–181, Mar. 2019, doi: 10.1109/IWAT.2019.8730642.

[23] M. Shafi *et al.*, “5G: A tutorial overview of standards, trials, challenges, deployment, and practice,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1201–1221,

Jun. 2017, doi: 10.1109/JSAC.2017.2692307.

[24] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, “The road towards 6G: A comprehensive survey,” *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021, doi: 10.1109/OJCOMS.2021.3057679.

[25] M. Alsabah *et al.*, “6G Wireless Communications Networks: A Comprehensive Survey,” *IEEE Access*, vol. 9, pp. 148191–148243, 2021, doi: 10.1109/ACCESS.2021.3124812.

[26] J. Helander, K. Zhao, Z. Ying, and D. Sjöberg, “Performance Analysis of Millimeter-Wave Phased Array Antennas in Cellular Handsets,” *IEEE Antennas Wirel Propag Lett*, vol. 15, pp. 504–507, 2016, doi: 10.1109/LAWP.2015.2455040.

[27] A. Shaikh and M. J. Kaur, “Comprehensive Survey of Massive MIMO for 5G Communications,” *2019 Advances in Science and Engineering Technology International Conferences, ASET 2019*, pp. 1–5, May 2019, doi: 10.1109/ICASET.2019.8714426.

[28] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, “A survey of millimeter wave communications (mmWave) for 5G,” *Wireless Networks*, vol. 21, no. 8, pp. 2657–2676, Nov. 2015, doi: 10.1007/S11276-015-0942-Z.

[29] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, “Millimeter wave beamforming for wireless backhaul and access in small cell networks,” *IEEE Transactions on Communications*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013, doi: 10.1109/TCOMM.2013.090513.120848.

[30] S. Rajagopal, S. Abu-Surra, Z. Pi, and F. Khan, “Antenna array design for multi-Gbps mmWave mobile broadband communication,” *GLOBECOM - IEEE Global Telecommunications Conference*, pp. 1–6, 2011, doi: 10.1109/GLOCOM.2011.6133699.

[31] S. Han, C. L. I, Z. Xu, and C. Rowell, “Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G,” *IEEE Communications Magazine*, vol. 53, no. 1, pp. 186–194, Jan. 2015, doi: 10.1109/MCOM.2015.7010533.

[32] T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao, and J. I. Tamir, “Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor Urban cellular communications,” *IEEE Trans Antennas Propag*, vol. 61, no. 4, pp. 1850–1859, 2013, doi: 10.1109/TAP.2012.2235056.

[33] W. Roh *et al.*, “Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 106–113, 2014, doi: 10.1109/MCOM.2014.6736750.

[34] R. Valkonen, “Compact 28-GHz phased array antenna for 5G access,” *IEEE MTT-S International Microwave Symposium Digest*, pp. 1334–1337, Aug. 2018, doi: 10.1109/MWSYM.2018.8439223.

[35] X. Wang *et al.*, “Millimeter wave communication: A comprehensive survey,” *IEEE*

Communications Surveys and Tutorials, vol. 20, no. 3, pp. 1616–1653, 2018.

[36] X. Ge, R. Zi, X. Xiong, Q. Li, and L. Wang, "Millimeter Wave Communications with OAM-SM Scheme for Future Mobile Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2163–2177, Sep. 2017, doi: 10.1109/JSAC.2017.2720238.

[37] F. Khan and Z. Pi, "mmWave mobile broadband (MMB): Unleashing the 3-300GHz spectrum," in *2011 34th IEEE Sarnoff Symposium, SARNOFF 2011*, 2011, pp. 1–6. doi: 10.1109/SARNOF.2011.5876482.

[38] T. Anwar, A. Marzuki, and I. A. Ukaegbu, "Design of Wideband Microstrip Patch Antenna Array with Improved Feedline for 60GHz Wireless Applications," *2023 IEEE 17th International Conference on Application of Information and Communication Technologies (AICT)*, pp. 1–4, Oct. 2023, doi: 10.1109/AICT59525.2023.10313165.

[39] W. Hong *et al.*, "Limitations of phased arrays for 5G wireless communications," *2017 IEEE Antennas and Propagation Society International Symposium, Proceedings*, vol. 2017-January, pp. 1467–1468, Oct. 2017, doi: 10.1109/APUSNCURSINRSM.2017.8072776.

[40] H. S. Farahani, M. Veysi, M. Kamyab, and A. Tadjalli, "Mutual coupling reduction in patch antenna arrays using a UC-EBG superstrate," *IEEE Antennas Wirel Propag Lett*, vol. 9, pp. 57–59, 2010, doi: 10.1109/LAWP.2010.2042565.

[41] A. Y. I. Ashyap *et al.*, "An overview of electromagnetic band-gap integrated wearable antennas," *IEEE Access*, vol. 8, pp. 7641–7658, 2020, doi: 10.1109/ACCESS.2020.2963997.

[42] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, "Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends," *Int J Antennas Propag*, vol. 2017, pp. 1–22, 2017, doi: 10.1155/2017/2018527.

[43] L. H. Weng, Y. C. Guo, X. W. Shi, and X. Q. Chen, "An overview on defected ground structure," *Progress In Electromagnetics Research B*, vol. 7, pp. 173–189, 2008, doi: 10.2528/PIERB08031401.

[44] A. Kumar, A. Q. Ansari, B. K. Kanaujia, J. Kishor, and L. Matekovits, "A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 2: Metamaterials and Many More," *Radio Sci*, vol. 56, no. 3, p. e2020RS007222, Mar. 2021, doi: 10.1029/2020RS007222.

[45] V. M. Jayakrishnan and M. L. Liya, "A survey of electromagnetic waves based metamaterials and applications in various domains," in *Proceedings of the 3rd International Conference on Smart Systems and Inventive Technology, ICSSIT 2020*, Institute of Electrical and Electronics Engineers Inc., Aug. 2020, pp. 662–666. doi: 10.1109/ICSSIT48917.2020.9214163.

[46] A. Valipour, M. H. Kargozarfard, M. Rakhshi, A. Yaghootian, and H. M. Sedighi, "Metamaterials and their applications: An overview," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 236, no.

11, pp. 2171–2210, Mar. 2021, doi: 10.1177/1464420721995858.

[47] C. A. Balanis, *Antenna theory: analysis and design*, 4th ed., vol. 4. New Jersey: A JOHN WILEY & SONS, 2016.

[48] L. C. Godara, "Applications Of Antenna Arrays To Mobile Communications, Part I: Performance Improvement, Feasibility, And System Considerations," *Proceedings of the IEEE*, vol. 85, no. 7, pp. 1031–1060, 1997, doi: 10.1109/5.611108.

[49] R. C. Hansen, *Microwave Scanning Antennas Volume II: Array theory and practice*, 1st ed. New York and London: Academic Press, 1966.

[50] J. Haring, N. Majer, and R. Hronec, "DIRECTIONAL PATTERN ANALYSIS OF A LINEAR PHASED ANTENNA ARRAYS," *Advances in Electrical and Electronic Engineering*, vol. 7, pp. 74–77, 2008, Accessed: Mar. 12, 2024. [Online]. Available: https://www.researchgate.net/publication/267404996_DIRECTIONAL_PATTERN_ANALYSIS_OF_A_LINEAR_PHASED_ANTENNA_ARRAYS?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6Il9kaXJlY3QiLCJwYWdlIjoiX2RpcmVjdCJ9fQ

[51] Y. Wang *et al.*, "Sub-array level structural compensation method for radiating and scattering performance of array antennas," *IET Microwaves, Antennas and Propagation*, vol. 17, no. 12, pp. 940–954, Oct. 2023, doi: 10.1049/MIA2.12405.

[52] G. M. Asadullah, M. S. Islam, M. R. Islam, and N. H. M. Adnan, "Circular Equivalent Planar Array-A new approach," *2020 Joint 9th International Conference on Informatics, Electronics and Vision and 2020 4th International Conference on Imaging, Vision and Pattern Recognition, ICIEV and icIVPR 2020*, Aug. 2020, doi: 10.1109/ICIEVICIVPR48672.2020.9306595.

[53] R. B. Waterhouse, *Microstrip Patch Antennas: A Designer's Guide*. Springer US, 2003. doi: 10.1007/978-1-4757-3791-2.

[54] P. Palta, J. Singh, S. Goyal, R. Kakkar, and D. Khosla, "Microstrip Patch Antenna for X band Applications: Design & Analysis," *Journal of Xidian University*, vol. 14, no. 4, pp. 2506–2512, May 2020, doi: https://doi.org/10.37896/jxu14.4/276 2506.

[55] S. Srivastava, A. Khandelwal, and Dr. S. Sharma, "Microstrip Patch Antenna: A Survey," *IOSR Journal of Electrical and Electronics Engineering*, vol. 9, no. 4, pp. 07–13, 2014, doi: 10.9790/1676-09420713.