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Original Article

Design and Development of 3D Printed Omnidirectional Patch Antenna for Mobile Communication

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***Abstract** - This research aims to present a specially created 3D-printed omnidirectional patch antenna suitable for mobile communication in rural as well as urban areas under specific bandwidth. It operates effectively at central frequencies of 38GHz and 54GHz, offering respective bandwidths of 1.94GHz and 2GHz. The proposed 3D-printed omnidirectional patch antenna's three sections-front, rear, and top-combine to form a distinctive and useful antenna construction. Six mm is the length, 6.25 mm is the breadth, and 0.578 mm is the thickness of this entire antenna. As new wireless communication technologies are developed, antennas will need to have outstanding characteristics, including minimal losses, wide bandwidth, and high gain. Layer by layer, Creations are assembled together by 3D printing using an additive technique that makes it possible to produce antennas with three-dimensional shapes more quickly, cheaply, and adaptable. As a means for better 3D patch antenna strength, a novel concept for a 3D-printed microstrip patch antenna is presented in this study. When building an antenna, FR4 is utilized as its substrate, and copper silk filament is used to create a patch. The proposed antenna design undergoes rigorous simulation using HFSS software for performance validation, and then the antenna is tested with the help of a vector analyzer.*

***Keywords** - Additive manufacturing, Flexible, 3D printed antenna, 5G.*

1. Introduction

The surge in wireless and radio communication network advancements has heightened the demand for antenna designs featuring enhanced attributes. These include dimensions related to the antenna, data velocity, obtain effectiveness of power, bandwidth, and traffic volume. In solution to this requirement, several antenna designs have emerged, aiming to strike a balance between factors such as design efficiency, high gain, minimal power loss, compact size, extensive bandwidth, radiation efficiency exceeding 70%, affordability, and achieving high data rates [1-9]. This demand is driven by the distinctive characteristics of 5G technology, characterized by its high data rates, wide bandwidth, and remarkable capacity.

The 3D printed omnidirectional microstrip patch antenna offers significant advantages over conventional antennas, including enhanced design flexibility, rapid prototyping, and the ability to create complex geometries that are difficult to achieve with traditional manufacturing methods. These benefits result in more efficient and customizable antennas tailored to specific applications. Unlike conventional antennas, 3D printed versions can be easily adapted and optimized for diverse environmental conditions, paving the way for advanced and versatile communication solutions.

The foundation of the Fifth Generation (5G) technology is rooted in millimeter wave radio frequencies, which harness the previously untapped spectrum using bands around 3 and 300 GHz; in compliance with 5G requirements, millimeter wave technology effectively utilizes the spectrum, particularly within the 20-90GHz band, specifically earmarked for 5G applications [2]. The selection of frequencies at 28GHz, 38GHz, and 72GHz, each accompanied by respective 300 MHz, 1 GHz, along 2 GHz, are three frequencies available, serve the purpose of 5G antenna design, primarily owing to their suitability for low-latency and high-data-rate systems [3]. The omnidirectional array antenna scheme involves arranging multiple antennas in a configuration that provides uniform radiation coverage in all directions. This setup ensures consistent signal strength and connectivity regardless of the receiver's position relative to the antenna. By combining the signals from individual antennas, the array can achieve enhanced performance, improved signal reliability, and better overall coverage, making it ideal for applications requiring seamless communication in 360 degrees.

Numerous substrate materials are available, with FR4 epoxy emerging as the preferred choice for millimeter-wave applications. Its optimal characteristics, characterized by minimal dispersion and low dielectric loss, render it exceptionally well-suited for Ultra-High Frequencies (UHF) [10, 11]. FR4 epoxy substrate exhibits advantageous traits such as minimal water absorption, low electric loss, and minimal moisture absorption, adaptable for many different kinds of purposes [10, 11].

In this research, we utilize a substrate featuring a ground layer on one side and a radiator patch on the opposite side, employing metal for both components. The choice of employing the M-line feeding technique is driven by the imperative in mobile communication to achieve getting a 12dB boost and use antenna arrays properly. Notably, the frequency found in the central resonant for this study is set at 38GHz, falling within the Ka-band spectrum, which spans from 27GHz to 40GHz [11]. Microstrip patch antennas are a favorable choice for various surfaces thanks to their compact and lightweight design, cost-effectiveness, ease of construction, and small footprint. Employing antenna arrays enhances both gain and efficiency [12].

On occasion, 3D printing, or three-dimensional printing, is used to refer to the technique of additive manufacturing that emerges as a technology capable of meeting these requirements by facilitating swift and straightforward prototyping. In essence, 3D printing involves the incremental building of a tangible item based on a digital representation [5], as illustrated in Figure 1.

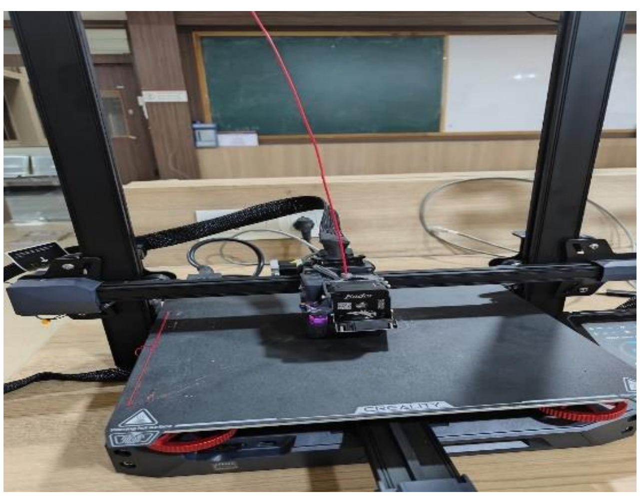


Fig. 1 3D printer

One benefit of this technique is its capacity to produce structures with varying degrees of intricacy, a wide range of shapes, significant flexibility, and at a relatively lowest possible manufacturing prices, Compared with additional traditional methods [5]. Considerable attention has been directed towards three-dimensional printing in the advancement of RF devices, particularly in the context of antenna elements [6].

This study assesses the construction of antennas using investigating several facets of printing in three-dimensional technology of recent structures designed for different frequencies. The antennas are manufactured using various materials and diverse techniques. The article delves into the primary benefits of 3D printing, exploring them extensively while also addressing the difficulties in implementing this kind of technology in the manufacture of radio frequency devices.

1.1. Main Contribution

- The patch antenna is designed in the HFSS software.
- The patch antenna is then manufactured with the help of a 3D printer.
- The 3D printed patch antenna is then tested on the vector analyzer.

1.2. Organization of the Paper

The paper is structured into five sections, with the current section aimed at providing context for the undertaken work and emphasizing its significance within the realm of radio frequency systems. Section II furnishes the method of 3-D printing innovation and its method of generating the patch antenna. Section III specifies the generation of 3D printing using a 3D printing device, making a patch dipole. Section IV outlines the results of experimental testing of a planned antenna with the vector analyzer. Section V demonstrates what comes out from a patch antenna technique using the S11 set, VSWR and the gain parameters.

2. Method

The first step in creating a 3D printed patch antenna is to design it with specialized antenna design software, such as HFSS software, to ensure exact measurements and requirements. For best results, choose a conductive filament, such as silk copper filament, when choosing a material for printing. To ensure excellent accuracy and resolution, layer the material in accordance with the antenna design using a 3D printer. To attain the necessary antenna characteristics, pay attention to printing parameters like the height of layers and infill density. Post-processing after printing could entail adjusting the proportions and smoothing the surface for best results. In order to incorporate the antenna into the system that is planned for testing and deployment, attach the required connections and components to it last.

2.1. Design Process

This article's proposed antenna is created utilizing a patch construction and includes certain physical measures to enhance its low band working frequency and growing bandwidth while maintaining a lower volume than previously published designs.

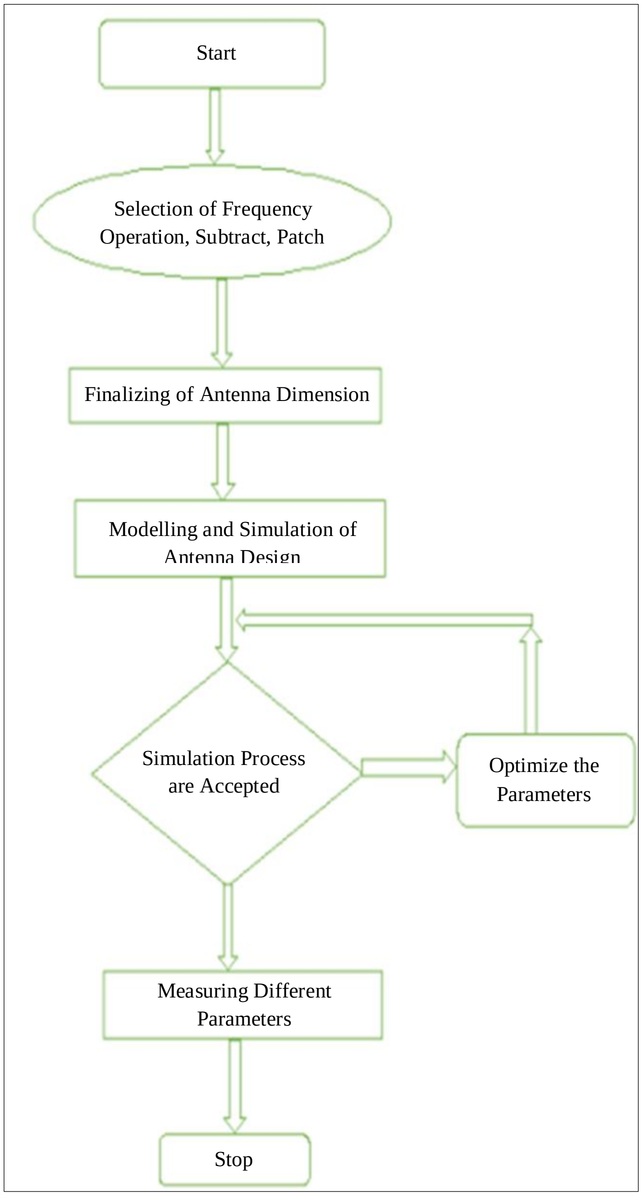


Fig. 2 Flowchart of the antenna design process

Figure 2 shows the antenna design process flow determined by operating frequency, antenna substrate material, and patch choice. The picture illustrates the steps involved in designing an antenna that depends on substrate, frequency, and patch choice.

Choosing a frequency band is the initial stage of the technique. Next, Dielectric permittivity, thickness, Loss coefficient, and substrate material cost are used to select the best one. The desired resonant frequency and radiation pattern control the size and form of the patch. Ultimately, before building and testing, the antenna design is simulated and improved using electromagnetic simulation software.

Table 1. Design guidelines for antenna parameters

Antenna Characteristics	Attributes	Measurement in millimeters
L_s	Substrate Length	6
W_s	Substrate Width	6.25
H	Substrate Height	0.78
L_p	Patch Length	2
W_p	Patch Width	2
M_t	Patch Height	0.035
W_f	Feed line width	0.2
L_f	Feed line Length	2.15
W_g	Ground Width	6.25
L_g	Ground Length	6

2.2. Designing a 5G Antenna

Figure 3 illustrates the substrate dimensions (Ls×Ws). Utilizing microstrip technology, a patch antenna. The substrate, composed of FR4 epoxy material, measuring 0.78 mm in height and having an electrical dielectric constant of 3.8, has a loss tangent of 0.02.

The substrate dimensions measure 6 millimeters by 6.25 millimeters. The microstrip patch antenna that is being examined utilizes M-line feeding, with the feed having a width (Wf) measuring 0.2 millimeters and a length (Lf) of 2.15 millimeters. The radiating patch's (Lp×Wp) specified dimensions are two millimeters by two millimeters.

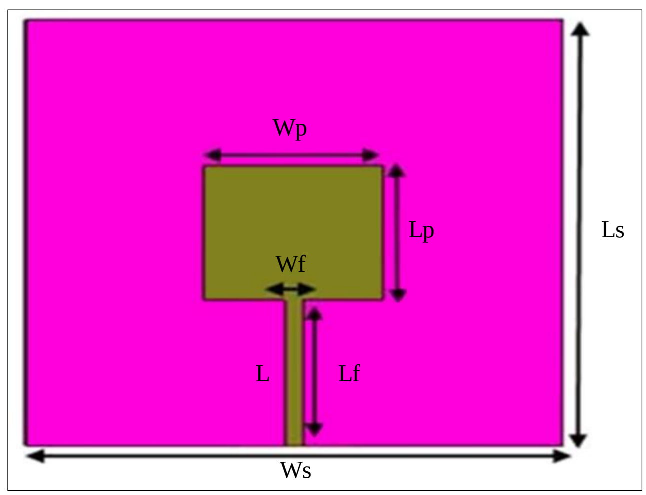


Fig. 3 Geometry of the antenna for the envisioned microstrip feed

The dimensions of the suggested antenna are calculated using recognized equations for microstrip patch antennas, as shown below.

Here are some key equations [13] and parameters used when creating microstrip patch antennas:

1. Resonant Frequency (f0): The resonant frequency of the microstrip patch antenna can be determined by applying the subsequent formula:

   $f_0=c/2\sqrt{\varepsilon_r}\sqrt{L/(L+2W)}$

2. Effective Dielectric Constant (ε_{eff}):

   $\varepsilon_{eff}= (\varepsilon_r +1)/2 + (\varepsilon_r -1)/2\ (1+ 12h/W)^{-1/2}$

3. Patch Length (L) for Resonant Frequency: To achieve the desired resonant frequency, you can rearrange the resonant frequency equation to solve for *L*:

   $L=c/2\sqrt{\varepsilon_r f_0}\sqrt{L/(L+2W)}$

4. Patch Width (W) for Resonant Frequency: Similarly, we can solve for *W* to achieve the desired resonant frequency:

   $W=c/2\sqrt{\varepsilon_r f_0}\sqrt{L/(L+2W)} - L$

5. Radiation Pattern and Directivity: The radiation pattern and the microstrip patch antenna's directivity can be determined using the following equations [14]:
   - Directivity (D) = $4\pi/\Omega$
   - Radiation Pattern = $\cos n(\theta)$, where n depends on the type of patch antenna (e.g., n=1 for a simple patch).

6. Input Impedance (Zin): The input impedance of the microstrip patch antenna can be calculated using the following formula:

   $Zin=Rr+jXr$ Where:

   a. *Rr* is the real part of the input impedance.
   b. *Xr* is the imaginary part of the input impedance.

7. Microstrip Line Width (Wm): To feed the microstrip patch antenna with a transmission line, we need to calculate the width of the microstrip line, which can be found using various methods like the transmission line theory

   - Patch width

   $$w= c/f_0\sqrt{2/s_r+1} \quad (1)$$

   - Patch length

   $$L=L_{eff}- 2\triangle L \quad (2)$$

   Where L_{eff} can be calculated by formula as stated below,

$$L_{eff}= c/2f_0\sqrt{S_{reff}} \quad (3)$$

ϵ_r =Dielectric constant of the substrate

$$S_{reff}= S_r+1/2 + S_r-1/2 \times \sqrt{1+(12h/w)}) \quad (4)$$

$$\triangle L= 0.412 \times h \times [(S_{reff}+ 0.3) (w/h +0.26)] / [(S_{reff}+ 0.253) (w/h +0.8)] \quad (5)$$

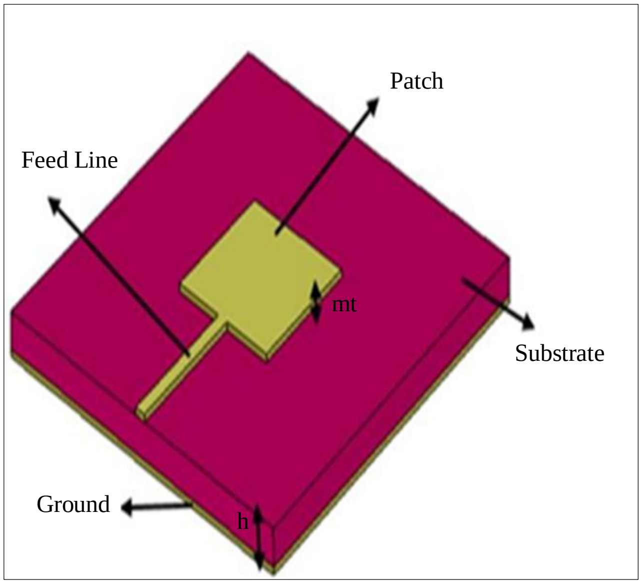


Fig. 4 Model in three dimensions of the suggested microstrip-feed antenna

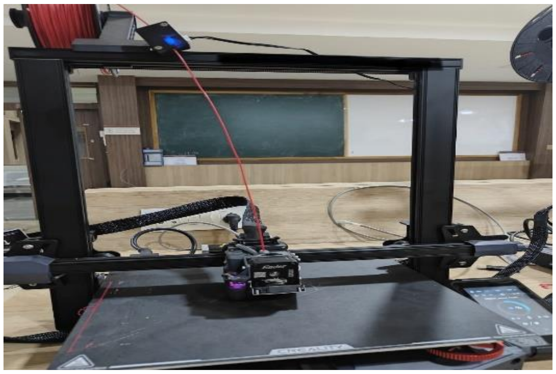
3. 3D Printed Antenna

Creating a 3D printed antenna involves utilizing a top-tier 3D printer and high-quality copper metal filament, recognized for its excellent conductivity [18]. Creating an antenna with a 3D printer involves several steps. First, a detailed antenna model is designed using specialized 3D modelling software, i.e. the Tinkercad software.

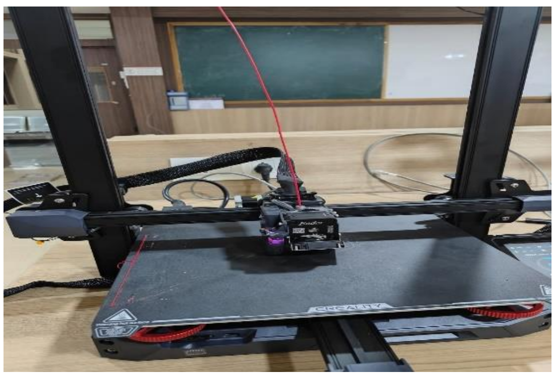
A high-quality 3D printer is then selected, and silk copper metal filament, renowned for its conductivity, is chosen. The copper filament is loaded into the printer, and meticulous calibration of settings such as temperature and layer thickness is performed to ensure precision [17].

The 3D printer then executes the printing process with the help of G-Code, which is to be extracted from the software, then layering the copper filament to construct the antenna and intricate structure. The additive manufacturing approach allows for customization and minimizes material wastage.

Figure 5 shows the (a) Full view of the used 3D printer, (b) An enlarged picture of a 3D printer, (c) Antenna's front aspect as planned, and (d) recommended the antenna's back side.



(a)



(b)

(c)

(d)

Fig. 5(a) Full view of the used 3D printer, (b) An enlarged picture of a 3D printer, (c) Antenna's front aspect as planned, and (d) recommended the antenna's back side.

4. Experimental Results

Specifications shown in Table 1 were taken into account when building the intended antenna. The patch antenna's manufactured prototype is displayed in the corresponding figures. The antenna's construction uses a FR4 substrate [14]. The copper foil was used to connect the antenna's three sections-the front, back, and top-at their borders. It should be noted that the performance parameters of the antenna may undergo some slight modifications as a result of this joining operation [15]. A Printed Circuit Board (PCB) is utilized as the ground plane to mount the entire assembly. This made it possible for the antenna to be successfully integrated into a mobile communication system [16]. In general, the integration of copper foil and a FR4 substrate to connect the different antenna components.

4.1. Antenna Testing Experimental Setup

The Figure 6 illustrates the testing of an antenna using a network analyzer. A tool purpose-built for assessing the performance of antennas is called a network analyzer [21]. Coaxial cables are used to send and receive signals between the network analyzer and the antenna.

Fig. 6 Displays a spectrum analyzer being used to examine a 3D-printed microstrip patch antenna

5. Results and Discussion

The graph presented in Figure 7 illustrates a slight deviation between the simulated and measured findings for the s11 parameter. Manual assembly of an antenna may be responsible for this deviation. [17]. The slight differences can be ascribed to manufacturing issues that were not taken into consideration in the simulations, consisting of the usage of SMA connectors as well as the precision of the soldering procedure. Measured data was acquired using a network analyzer [18].

Loss of return was calculated and represented in Figure 7 (S11). The difference between simulation and real outcomes is displayed in this graph [19]. The measured results are somewhat skewed when compared to the simulated values.

The movement may have resulted from the antenna's manual construction. The variations between what is observed and what is measured and simulated outcomes are attributed to minor production errors [20-23].

As illustrated in Figure 8, the antenna's simulated VSWR was connected to the measured VSWR. Measured VSWR values were below 2 (corresponding to about −10 dB return loss) throughout 5G operational bands [24].

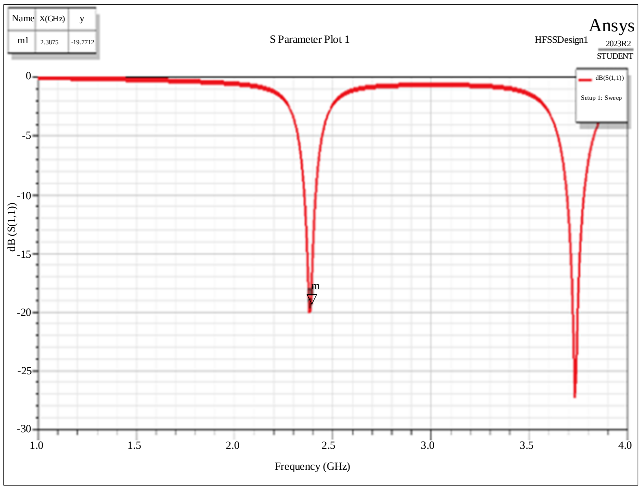


Fig. 7(a) Result of the simulated S11(DB) v/s Frequency (GHz)

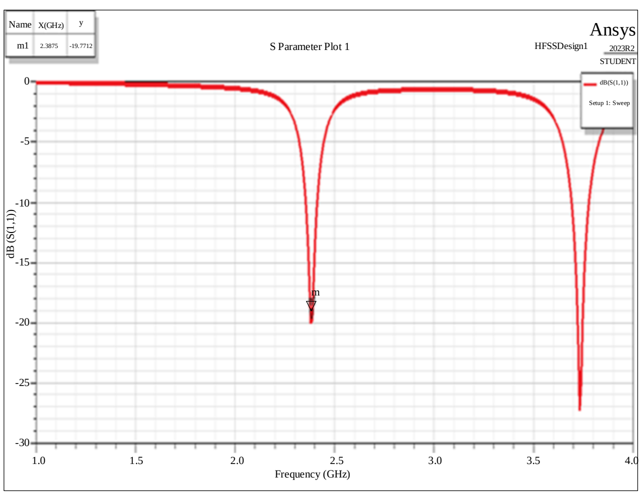


Fig. 7(b) Result of the measured S11(DB) v/s Frequency (GHz)

Figure 8 shows the measured and modeled VSWR The disparity between simulated and real outcomes is seen in this graph; the simulated findings are rather skewed in comparison to the measured results [25]. The manual fabrication of the antenna might have been the cause of the movement; additional components that were left out of the simulations and could have added to apparent slight alterations consist of SMA connections, welding, grounding, and patch on the substrate as an industrial forbearance [26].

Figure 9 attained maximum gain at all frequencies and at theta angles of 0°, 60°, and 90°. The graphic shows the antenna's maximum realized gain over frequencies for three different Radiating at 0°, 60°, and 90° angles. This is modeled realized gain result, which demonstrates how the value of gain increases with frequency [27]. The graph highlighted in red shows the realized gain of theta 0°. The graph with the blue marker indicates the realized gain of theta 60°. The graph with the green marker indicates the realized gain of Theta 90 [28]. The antenna has an optimal realized gain of roughly 7.8 dBi at a frequency of 3 GHz, and its most directed direction is broadside at 0° radiation angle. At a radiation angle of 60°, the antenna's maximum realized gain is approximately 5.

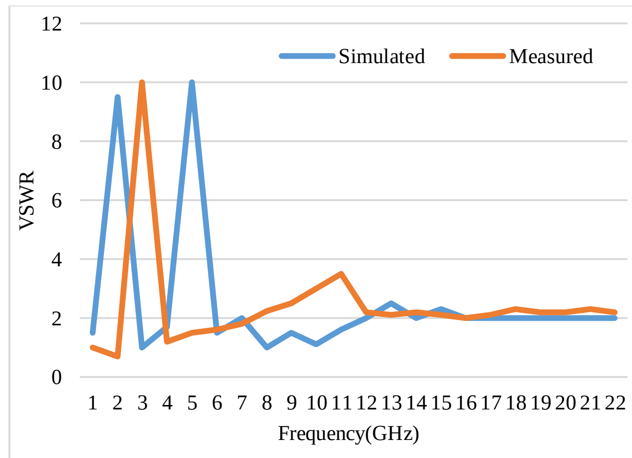


Fig. 8 VSWR (simulated & measured)

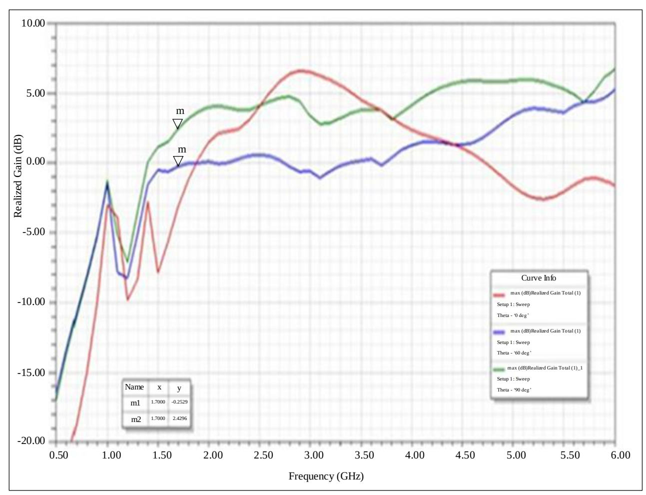


Fig. 9 Frequency Vs Gain graph

6. Conclusion

An omnidirectional microstrip patch antenna within a framework of 5G wireless transmission has been used in this work. Dual-band reception is made possible by the microstrip patch antenna, which is essential for 5G connectivity. The microstrip patch antenna covers frequencies of 38 GHz and 54 GHz.

Table 2. 5G Communication antenna

Antenna	Frequency of Resonance (GHz)	Return Loss in Decibels (dB)	Directivity in decibels isotropic (dBi)	Gain in Decibels (dB)	Frequency Bandwidth (GHz)	Efficiency Percentage (%)
5G Antenna	38	-15.5	7.2	6.9	1.94	93.5
	54	-12	8.2	7.4	2	82.7

The microstrip patch antenna, in contrast, produces gains of 7.4 dB at 54 GHz and 6.9 dB at 38 GHz. This antenna arrangement is a great option for 5G communication applications since it performs well regarding directivity, gain, bandwidth, and radiation efficiency, as shown in Table 2.

6.1. Future Scope

The use of 3-D printed omnidirectional antennae in antenna production is expected to rise dramatically in the future on a number of fronts. The ability to customize antennas to precise frequency ranges, applications, and spatial restrictions will increase dramatically. Design cycles will be revolutionized by rapid prototyping, allowing for faster iterations and a shorter time to market.

Once unfeasible or impracticable, complex geometries will become achievable, opening up new possibilities in terms of effectiveness and output. The development of new materials will lead to improvements in weight reduction, conductivity, and durability, which will improve antenna performance as a whole. With integrated components providing a variety of functions inside a single 3D printed structure, multi-functionality will flourish. As printing technology advances, 3D printed antennas will become more widely available and cost-effective for a greater variety of applications. In order to meet the rising need for small antennas in wearables, unmanned systems, and Internet of Things devices, miniaturization will become the norm. Supply chains will be streamlined, and on-demand production capabilities will decrease inventory costs.

Sustainability will increase as 3D printing reduces energy and material waste and complies with environmentally friendly manufacturing techniques. 3D printed antennas have the potential to completely transform the antenna manufacturing environment as industry adoption picks up speed, spurring efficiency and innovation in a variety of industries.

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