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Original Article

Design of 4X4 Microstrip Patch Array Antenna for 5G mmWave Applications

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Abstract *- Millimeter waves (mmW) are currently seen as a crucial component of the 5G spectrum. High frequencies yield increased bandwidth, enabling the operation of exceptionally higher data rates, minimal latency, and ultra-high capacity. The deployment of mmW frequency spectrums for 5G technologies necessitates efficient designs for antenna arrays and antennas, essential components of contemporary communication technologies. The benefits of Microstrip Patch Antennas (MPA) encompass compact dimensions, flexible surfaces, simple fabrication, and interoperability with technology for integrated circuits. Multiple experiments have been conducted in recent decades to improve the performance of this antenna, which has been utilized extensively in both industrial and commercial sectors. This research proposes designing and implementing a 4x4 MPA for 5G mmW applications. The novelty of this research includes the design and implementation of a 4x4 microstrip patch antenna optimized for 5G mmW applications with effective gain, directivity, bandwidth, and overall efficiency. The rapid advancement of 5G technology has significantly elevated the demand for increased data speeds, extensive bandwidth, and improved network capacity. The mmW frequency spectrum, specifically within the 24 GHz to 40 GHz range, presents a viable alternative owing to its capacity for wide bandwidths and high-speed data transmission. Nevertheless, issues such as higher path loss and reduced penetration necessitate advanced antenna designs to enhance performance in 5G networks. The proposed antenna is designed and simulated using the CST microwave studio tool and achieved 9.54 dB Gain, -26.71 dB S11, 10.13 dB directivity, 2.52 GHz bandwidth, 1.23 Voltage Standing Wave Ratio (VSWR), and 86.82% efficiency. The proposed antenna model demonstrates a balanced performance across key parameters, providing a strong combination of gain, directivity, bandwidth, and efficiency, making it competitive with existing models for 5G mmW applications.*

Keywords *- Microstrip Patch Antenna, 4x4 MPA, 5G mmW Application, Gain, Directivity, VSWR, Efficiency.*

1. Introduction

The rapid advancement of wireless transmission and mobile networking technologies has resulted in the proliferation of diverse wireless services and the growing popularity of smart devices, culminating in a major increase in data traffic within wireless networks.

To accommodate the substantial demands of data traffic, the mmW communication method, capable of utilizing vast unlicensed bandwidths over conventionally licensed microwave spectrums, has acquired significant interest in both the industry and research community and is acknowledged as the crucial technology in 5G wireless communication networks [1].

The 5G technology is anticipated to achieve 40 percent coverage of the population and 1.9 billion subscribers in 2024, or 20 percent of all cellular subscriptions. These statistics suggest it will be the most rapid worldwide deployment. Furthermore, data traffic generated by smartphones constitutes approximately 90 percent and is projected to attain 95 percent by the conclusion of 2024 [2].

As smartphone usage continues to expand, the global data traffic of mobile phones is projected to reach approximately 130 exabytes/month, quadrupling the figure from 2019, with 35 percent of this information sent via 5G networks [3]. The increasing need for data and substantial requirement of data traffic could be addressed by the increased range provided by the high range frequencies (24–40GHz) of 5G new radio technology [4].

The existing 4G technology provides carrier bandwidths of 5, 10, and 20MHz, while the 5G mid-ranges could deliver 50 and 100MHz, and the 5G high-range band could provide 400 to 800MHz. The broader bandwidth facilitates a reduced communication time gap, decreasing network latency.

Table 1. mmW antenna types

Type of Antenna	Advantages	Drawbacks
Reflector	Elevated gain and efficiency, compact dimensions, and fine radiation directivity.	Higher cost
Horn	Broad frequency range, compact side lobes, elevated power capacity, and uncomplicated design.	Lower gain
Lens	High directivity and broad frequency band.	High profile
On-chip Integrated	Elevated integration, exceptional reliability, compact design, reduced cost, and large-scale production.	Minimal resistivity, minimal metal conductivity, and high dielectric constant.
Microstrip	Minimal profile, economical, integration of microwave, lightweight, and conducive to mass production.	Limited power capacity, low radiation efficiency, and narrow bandwidth.

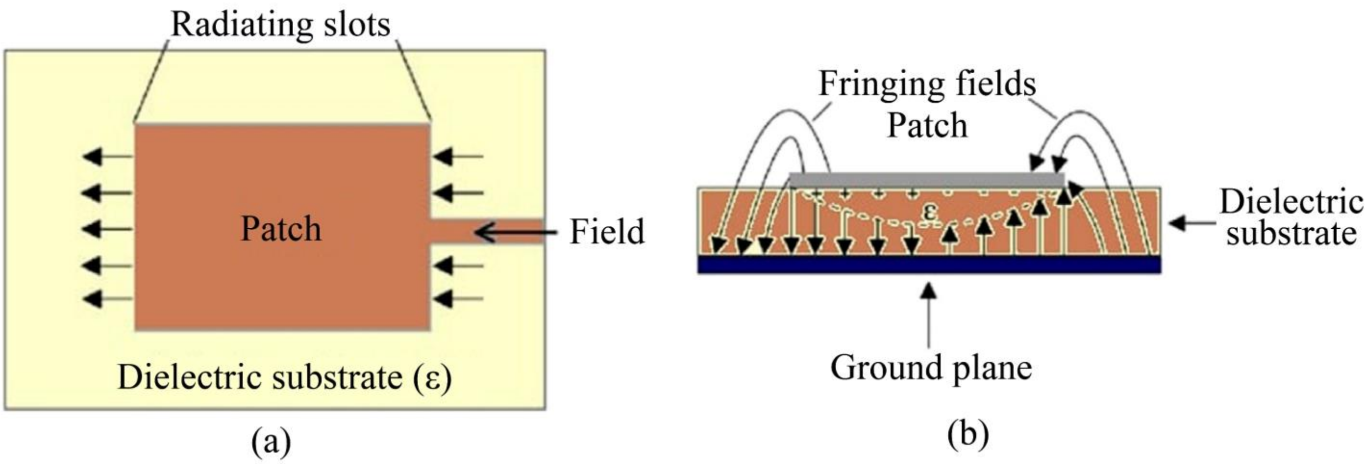

Fig. 1 Microstrip Patch Antenna (a) Top View; (b) Side View

Table 1 delineates the categories of antennas suitable for millimeter wave applications. Their corresponding advantages and drawbacks are presented in a table [3]. 5G signifies the subsequent evolution of wireless communication technology, providing enhanced speeds, reduced latency, and increased bandwidth relative to preceding generations like 4G and 3G. The principal characteristics of 5G encompass [5]:

- Peak data range of 10 Gbps for Uplink and peak data range of 20 Gbps for downlink.
- Latency diminished to as low as 1 ms at Ultra-Reliable Low Latency Communication (URLLC) settings.
- Ability to simultaneously connect additional devices by broadening the resources of radio spectrums from the sub-3GHz level utilized in 4G to 100GHz and over.
- Compact transmitters may be discreetly positioned on structures, vegetation, and various items [4].

The primary benefits of communication models functioning at mmW could be described as follows:

- Exceptionally broad bandwidths: in contrast to the frequency ranges ranging from 300 MHz to 3 GHz, mmW applications can use more extensive spectrum segments, resulting in enhanced data ranges.
- Antenna dimensions: the radiating component's physical size diminishes in proportion to the wavelengths, facilitating the combination of RF and antenna circuits to create compact devices.
- Electromagnetic energy focusing: Due to the diminished operating wavelength, extensive antenna arrays exceeding 100 elements can be incorporated into compact physical spaces, facilitating adaptive beamforming for generating linear beams with improved directivity attributes, which were crucial for enhancing service quality in practical operational contexts [5-6].

An MPA is typically utilized in contemporary wireless communication technologies, including satellite communications, mobile networks, Wireless Local Area Networks (WLAN), and Global Positioning Systems (GPS). MPA is crucial for attaining directed patterns of steerable radiations and facilitating beam steering in diverse communication models. It improves range and coverage by focused signal transmissions, increasing the 5G network's coverage [7].

MPAs are a category of printed antennas that function according to the fundamentals of microstrip lines of transmission. The design consists of a radiating element situated atop a dielectric substrate positioned within the radiating and ground patches, with a ground plane affixed to the other antenna side configurations, as seen in Figure 1 [6].

The mmW spectrum is the focal point for numerous advanced wireless applications because of its extensive bandwidth and minimal latency [8].

1.1. Research Gap & Problem Statement

Current antenna designs for 5G mmWave applications frequently do not attain a balance among high gain, broad bandwidth, and compact dimensions while also preserving efficiency and impedance matching throughout the 24-40 GHz frequency spectrum. Numerous models either demonstrate inadequate directivity or show inadequate S11 and VSWR values, hence constraining their efficacy for high-performance communication systems [9]. This study proposes a 4x4 microstrip patch array antenna that optimizes parameters to fulfill the demanding requirements of 5G networks. Traditional antenna designs often struggle to provide the necessary gain, bandwidth, directivity, and impedance matching required for reliable communication in 5G networks, especially within the mmW frequency range [10]. The proposed antenna model aims to overcome these limitations by optimizing key parameters such as VSWR, S11, gain, and efficiency to enhance overall performance [11-12]. With its compact structure and array configuration, this research offers a solution that achieves improved directivity and gain and maintains a broad operational bandwidth and higher efficiency, enabling it to be highly appropriate for next-generation 5G applications that demand stable, high-speed connectivity over long distances.

1.2. Research Objectives

The research focuses on designing a high-performance 4x4 MPA antenna for 5G mmW applications, addressing the challenges of achieving efficient signal transmission at high frequencies, specifically between 24-40 GHz. The objectives of the proposed antenna design include:

- To design a 4x4 MPA to achieve a high gain suitable for 5G mmW applications, ensuring focused beam direction and high directivity.
- To improve the total efficiency of the antenna, losses due to dielectric materials, conductor, and surface wave effects should be minimized to enhance overall performance.
- To minimize the VSWR at the operating frequency in the 5G mmW band, reducing reflection losses and maximizing power transfer.
- To conduct a comprehensive analysis of the antenna's 2D and 3D radiation patterns to validate the directional characteristics.
- To evaluate the proposed antenna design with gain (dB), S11 (db), Directivity (dB), Bandwidth (GHz), VSWR, and Efficiency (%)and compare the results with the current models for validation.

The rest of the sections in the paper are arranged as follows: Analysis of existing research works based on MPA designs for 5G mm applications. Design and development of the proposed 4x4 MPA model. Simulation results and a discussion of the proposed antenna model and its comparison with current models are presented in the Experimentation and Analysis section. Lastly, the conclusion and future directions of the work are presented.

2. Related Works

This literature review explores various designs and analyses of antenna structures. Table 2 concisely compares the models based on their approach, scenario, advantages, and drawbacks. A 2-band, 4-port Multi-Inputs–Multi-Outputs (MIMO) antenna was designed for a 28-38GHz mmW 5G application [13]. The study employed a design methodology to achieve 2-band functionality in the MIMO configuration with compact footprints. All the MIMO elements were constructed as elements of the elliptical and circular structures linked by the narrow strips and supplied with tapered feedlines. The model's maximum gains and overall efficiency were 4.15 dBi, 7.73 dBi and 80.13%, 85.44% for frequencies of 28 and 38GHz. To assess the comprehensive performance of the MIMO antennas, all its metrics were analyzed and found to be satisfactory.

An MPA was developed in [14] for a frequency of 28 GHz, aimed at 5G communications. The research created and simulated a rectangular MPA. The antenna functioned at a frequency of 28GHz, demonstrating the reflection coefficients of -24 dB, 2.2 dBi gain and 280 MHz bandwidth. The inset feed method was compatible with the 50 Ω line of transmission impedance. The antenna demonstrated the reflection coefficients of -24 dB, 1.24 VSWR, 51.6Ω input impedance, and 2.2 dBi gain at the operational frequency, characterized by a small design appropriate for 5G communication.

The work in [15] presented the designing, modeling, and simulations of a small MPA for 5G uses at 24.5 GHz. 24.5 GHz was a frequency utilized in the 5G band in frequency level 2, so-referred to as mmW. A parametric evaluation was conducted to optimize the dimensions by adjusting various factors. The experimental results yielded the antenna with the bandwidths of 2.05 GHz and the peak gains of 6.312 dBi throughout the operational bands. Moreover, steady radiation patterns were successfully achieved.

An MPA was developed in [16] to exhibit high bandwidth in the mmW spectrum, compact dimensions, stable radiation patterns, and comparatively elevated gain in the 28 GHz frequency band. The findings of this study demonstrated efficacy in broader bandwidth and enhanced gain for 5G applications. The study [17] discussed the circular elliptic antenna ring design attempted to minimize dimensions, reduce weights, lower fabrication costs, and achieve optimal performance in 2x2 and 4x4 patch antenna MIMO- Ultra-

Wide Band (UWB) configurations. The first design features two radiators, both oriented perpendicularly on one side. The second design comprises four radiators arranged perpendicularly to one another on a single side. The frequency of MIMO MPAs was 60 GHz, suitable for the mmW range utilized in 5G applications in the UWB range. The findings were simulated by analyzing the constructed antenna, revealing strong reliability in impedance and radiation properties.

An MPA functioning at 28 GHz for prospective 5G communication technology was examined and modelled in [18]. The antenna substrate employed for the model was Rogers RT/Duroid 5880. CST microwave studio software was utilized for antenna simulation because of its user-friendly interface. The simulation yielded the loss of return as -38.348 dB, an 8.198 dB gain, a 77% radiation efficiency, and a -18.3 dB level of side-lobe.

The research [19] designed a 5G antenna that resonates at 28 GHz. The 5G antenna patch features a rectangular ring measuring 8mm x 5mm. The rectangular ring measures 1mm on all sides. The antenna’s return loss measured was -24.79dB. The 5G antenna achieved an average gain of 7.9dBi, exhibited a unidirectional radiation pattern, and operated within a bandwidth range of 27.36 to 29.29GHz, with a frequency of 28.108GHz. The four-element array antennas demonstrated an average gain of 13.385 dBi, a bandwidth range of 27.29 to 29.14 GHz, and a center frequency of 28.024 GHz. A 1x4 5G array antenna was built, significantly enhancing the antenna’s gain. A Defective Ground Structure (DGS) was employed on the ground plane to enhance antenna performance.

An MPA powered by microstrip feeding for the Ka-band applications was presented in [20]. This research was developed for future applications in networks at 29.87 and 39.02GHz. The design utilized Rogers RT/Duroid 5880 (tm) substrate was employed. The radiation characteristics, including VSWR, S11, Gain, Radiation Patterns, Surface Current Distributions, and Radiation Efficiency, were analyzed.

A dual-band-printed antenna was designed in [21] for mm-wave frequencies 38 and 28 GHz. Two radiating elements were used to design the antenna. In the main patch, the first element was given as input through a microstrip line with inset feeds, and the next parasitic elements were capacitively coupled to it.

The antenna’s design characteristics were adjusted by full parametric research to provide high impedance matching at 38 GHz and 28 GHz. The MPA created a four-port efficient MIMO system. The one-element antenna model and MIMO were built and tested, demonstrating good impedances matching across the low and high bands of frequency that matched simulation results.

A single-port antenna array was designed in [22] for 5G applications to operate in the mmW frequency spectrum. The antenna exhibited a 2:1 VSWR, resonating at 28.0 GHz and encompassing the frequency range of 27.06–28.35 GHz. The designed model demonstrated over 93.0% radiational efficiency. At a resonance frequency of 28.0 GHz, the achieved gain was 16.07 dBi. A maximum of 0.4W of electricity was absorbed or emitted by the port from an input power of 0.5W. Merely 0.01W was dissipated by the dielectric substrates.

A 4x4 MPA array sub-module was designed in [23] for integration into a 5G wireless system for communication. The antenna was developed and refined to function at 85GHz, aligning with the midpoint. The developed patch antenna exhibited fair directivity attributes, featuring a primary lobe magnitude and an angular width suitable for integration into a system for wireless communication functioning within the high-frequency 5G spectrum.

A comprehensive 28GHz, 5G mmW 8x8 MPA on a multilayered substrate was designed in [24]. The 8x8 array is automatically steerable and simultaneously provides many beams at any random elevation and azimuth angles, with uniform or varied peak gains. A computational model was introduced to determine the weight necessary for generating numerous beams. The antenna generated several beams at various random angles, and the findings are presented. The multibeam computing approach was validated using measurements at 28GHz in the azimuth plane, accommodating both unequal and equal power beams with a range of side lobes exceeding 17dB.

The work [25] presented a mathematical modeling analysis of the 5G mmW spectrum, focusing on comparative assessments of radiation efficiency, gain, and input impedance. The method enhanced antenna efficiency by as much as twenty percent with an increase in the thickness of the substrate. Various antennas were modelled to enhance reflection coefficients effectively. An optimum substrate thickness for an antenna was required when exceeding 0.787 mm or falling below 0.127 mm.

The MPA arrays (8x8, 4x4, and 2x2) with a semi-elliptical slot patch and a ground etched layout were designed in [26] for 5G applications. The antenna’s radiator element was constructed with Roger’s substrate 5880, featuring a 2.2 dielectric constant and 0.34 mm thickness. The antennas were modelled to function at 28GHz within the local multipoint distribution service spectrums. The findings indicated that the total efficiency, bandwidth, gain, and return losses were effective.

A multiband MPA was designed in [27] for 5G mmW wireless technology. The antenna was developed using the genetic algorithm approach. The antenna design utilized a substrate called Rogers RT-Duroid 4003 as the dielectric material. The Conformist circular and rectangular patches were altered to achieve multiband functionality in the mmW bands of 25 to 32GHz and 40 to 60GHz. The recorded radiation efficiency and gain values attained 9.75dBi at 0.85% and 10.75 dBi at 0.84%.

Table 2. Critical analysis of reviewed research works

Ref	Approach	Application	Advantages	Disadvantages
[13]	Dual-band 4-port MIMO antenna	5G wearable applications	Dual-band functionality, compact design, good gain (4.15 dBi, 7.73 dBi), high efficiency (80.13%, 85.44%).	Complex structures and challenges in wearable device integration are faced.
[14]	Rectangular MPA with inset feed for 28 GHz	5G mobile communication	Good reflection coefficient (-24 dB), compact design, suitable for mobile applications.	Low gain (2.2 dBi).
[15]	Small MPA with parametric evaluation for 24.5 GHz	5G applications	High bandwidth (2.05 GHz), moderate gain (6.312 dBi), steady radiation pattern.	Gain is not competitive for mmW applications.
[16]	MPA on FR-4 substrate for 28 GHz	5G mmW applications	High bandwidth (14.674 GHz), excellent reflection coefficient (-40.14 dB), stable radiation pattern.	Moderate gain (5.29 dBi).
[17]	Circular elliptic antenna ring for MIMO-UWB configuration at 60 GHz	5G UWB applications	Reduced size, lower cost, good impedance, and radiation properties.	High frequency (60 GHz) limits integration into current 5G bands.
[18]	MPA on Rogers RT/Duroid 5880 for 28 GHz	5G communication technology	High gain (8.198 dB), good return loss (-38.348 dB).	Moderate efficiency (77%).
[19]	5G antenna with rectangular ring and DGS, resonating at 28 GHz	5G communication	High gain (13.385 dBi), broad bandwidth.	Complex design with DGS and manufacturing is difficult.
[20]	MPA for Ka-band	Next-gen networks at 29.87 GHz and 39.02 GHz	Broadband, low loss, high radiation efficiency.	High-frequency operation is limited to practical 5G applications.
[21]	Dual-band printed antenna for MIMO at 28/38 GHz	5G MIMO systems	High impedance matching, compact design.	Higher complexity due to dual-band structure.
[22]	Single-port array for mmW 28 GHz	5G applications	Very high gain (16.07 dBi), excellent efficiency (>93%).	High power requirements, potentially higher cost.
[23]	4x4 MPA at 85 GHz, modelled using CST	5G high-frequency wireless communication	High directivity (16 dBi), suitable for high-frequency integration.	Higher frequency (85 GHz) beyond mainstream 5G mmW spectrum.
[24]	8x8 phased array on multilayer substrate at 28 GHz with multiple beamforming	5G mmW with steerable beams	Independently steerable multiple beams, low side lobe levels.	Complexity in beamforming and array design.
[25]	Comparative analysis of 5G mmW antenna arrays and substrate thickness	5G mmW antenna arrays	Enhanced efficiency (up to 20%) by optimizing substrate thickness.	Dependency on specific substrate thickness for performance.
[26]	MPA with the semi-elliptical slotted patch at 28 GHz	5G broadband applications	Effective gain and return loss, multiband functionality.	Complex design with a slotted patch.
[27]	Multiband MPA using genetic algorithm for 25–32 GHz and 40–60 GHz	5G mmW wireless technology	High gain (9.75–10.75 dBi), multiband functionality.	Requires advanced optimization tools (HFSS, genetic algorithm).
[28]	mmW antenna with perturbed ground plane for 28 GHz	5G wireless technology	Very high efficiency (98%), wideband resonance, dual-beam capability.	Limited gain (3.3 dBi), design complexity due to the perturbed ground plane.

A small, low-cost, lightweight, and easily installable mmW antenna, including a perturbed ground plane, was designed in [28]. The antenna was constructed on a 0.254 mm ultra-thin Roger's substrate 5880. A single component comprising three square, rectangular loops and transmission lines was constructed with an overall measurement of 9x11 mm. The loop elements were stacked, and adding the square slots in the ground planes resulted in a wideband resonance response. The antenna has a gain above 3.3dBi, with radiation and 98% efficiency at 28GHz. The architecture facilitated spatial diversity and reduced interference effects among nearby channels by offering dual-beam capability among the specified frequency bands. The array gain was 10.1dBi, and the efficiency exceeded 92% at 28GHz.

3. Proposed Antenna Model & Design

3.1. Theoretical Fundamental of MPAs

An MPA is predominantly utilized to emit electromagnetic waves into space in wireless communications. The main four elements of an antenna with a microstrip patch are the ground, substrate, patch, and feed. It is available in multiple configurations, such as square, elliptical, circular, ring, and rectangular, with a dielectric constant on one end and a ground plane on the opposite end. MPAs are employed in diverse applications, including automobiles, logistics tracking, GPS, and microwave communications.

Figure 2 represents the two illustrations of the proposed antenna design. The first structure represents the geometrical parameters of the single element, and the second structure represents the 4x4 antenna design. Upon selecting 28GHz as the operational frequency, the components utilized for an antenna must be prioritized. The overall dimensions of the antenna, comprising 4 components, are 26.51mm in width and 20.37mm in length. The uniform distribution in this array is achieved by ensuring a uniform input impedance for every patch, resulting in identical amplitude values. The transmission lines linked to every patch possess the input impedances of 50Ω. This microstrip line is extensively utilized in microwave circuit fabrication due to its compatibility with photolithographic techniques and its facilitation of basic integration of both active and passive elements through surface mounting. The antenna comprises three levels. The ground constitutes the lowest level, the substrate is intermediate, and the patch antenna represents the uppermost level. The copper foil was usually employed to fabricate the metallic patches. The substrate component preserves the requisite separation within its patch and ground plane while supporting the radiating patches.

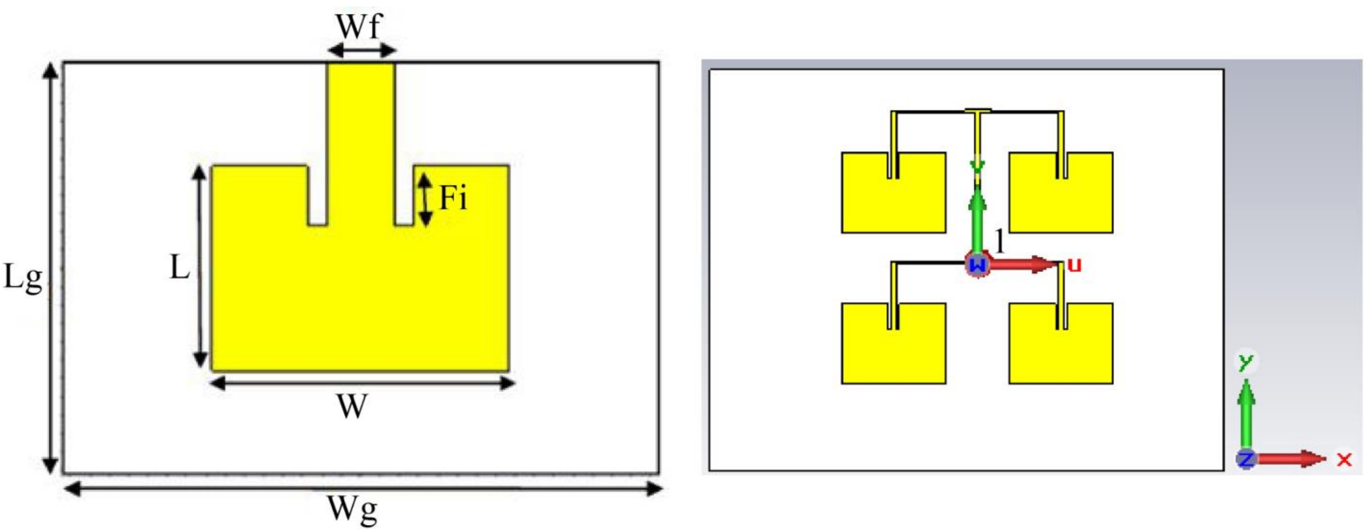

Fig. 2 Geometrical design of proposed antenna model

Table 3. Parameters of the antenna design

Parameter	Value
VSWR	1:2
Bandwidth	≥400 MHz
S11	<-10dB
Input Impedance	50*Ω*
Frequency	24 to 40 GHz
Copper Thickness	0.035 mm

The primary consideration for selecting substrates for industrial use is that they are costly. For array fundamentals functioning at lower microwave frequency (<15GHz), the dielectric honeycomb of a foam board can be used as the substrate. This can increase bandwidth while lowering losses, material costs, and the quality of the antenna. Copper serves as the patch and ground antenna, whereas Rogers RT5880 was utilized as the antenna's substrate. The design specifications are crucial in antenna design, as they significantly influence the antenna's overall performance. The antenna has been modelled as a small MPA resonating at 24 to 40GHz. The antenna should exhibit the reflection coefficients (S11) of below -10dB, a VSWR of ≤ 2dB at a 50 Ohm line impedance matching, and a bandwidth of ≥ 400 MHz, as indicated in Table 3 [20].

After selecting the dielectric substrate and utilizing the antenna geometrical formulas, the antenna parameters were estimated and developed. A parametric analysis was performed to assess the impact of the antenna's size on its performance and to identify the optimal dimensions. The parametric evaluation and antenna design were conducted using CST Microwave Studio (CST 2019) simulation software. Following the design and development of the antenna, the simulated outcomes for the S11, VSWR, gain, and radiation patterns were evaluated and discussed in both 2D and 3D perspectives. To assess the efficacy of the proposed antenna design, its performance has been compared with other recently discussed antenna models in the literature review.

3.2. Proposed Antenna Design

The MPA's design is developed upon three essential parameters: the resonant frequency f_r, the substrate thickness h, and the substrate's relative permittivity ε_r. Utilizing the reduced formulation of the transmission line model, a direct and pragmatic design methodology is considered for rectangular MPAs. Through the implementation of this technique, the resonant frequency ranges, the permittivity of the substrates to be utilized, and the thickness were delineated. Consequently, the parameters such as $\varepsilon_r = 2.2$, $f_r = 24\ GHz$, and $h = 0.7mm$ were designated. The initial step involves calculating the patch size based on the substrate's properties (thickness h and relative permittivity ε_r) and the resonance frequencies. The power source was generated via the microstrip lines. The Rogers 5880 substrate was selected due to its efficient price-to-quality ratio and its 2.2 permittivity, which was optimal. The selected attributes were as follows: Resonant frequency: $f_r = 24$ to 40GHz; substrate: Rogers RT/duroid 5880" with $\varepsilon_r = 2.2$.

Designing a rectangular MPA entails selecting the substrate material with thickness h, the required dielectric permittivity constant ε_r and resonant frequency f_r in Hz, from which the work ascertains the antenna dimension, namely the width of the antenna W. This could be computed through the subsequent equations [24].

To optimize the radiator, the width 'W' could be determined using Equation (1).

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Here, C was the light's velocity in a free space. The equation indicates that the antenna substrate's width has an inverse relationship with the resonant frequencies; however, the thickness of the optimal substrate could be established by evaluating various thickness values.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+12\frac{h}{W}}} \tag{2}$$

Equation (2) can be used to approximate the efficient dielectric constant ε_{eff} or the efficient relative permittivity. The equation represents a relationship between the material attribute $\frac{h}{W}$, where W denotes the strip's width, and h signifies the thickness of the substrate.

ΔL, incremental length produced by the fringing field can be ascertained from Equation (3); because of the fringing effects, the antenna patch was larger than its actual size. Therefore, ΔL could be expressed as follows:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{h}{W}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{h}{W}+0.8\right)} \tag{3}$$

The patch's effective length L_{eff} is calculated employing Equation (4), which illustrates its dependency on C (the speed of light in a free space), the effective dielectric constant ε_{eff}, and the resonance frequency f_r. Subsequently, the patch's real length L is obtained by employing Equation (5).

$$L_{eff} = \frac{C}{2f_r\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$L = L_{eff} - 2\Delta L \tag{5}$$

Z_{input} is the input impedance at the edge of the patch, critical for achieving optimal power transfer and minimizing reflections in the antenna system.

$$Z_{input} = 90\frac{\varepsilon_r^2}{\varepsilon_r-1}\left(\frac{L}{W}\right)^2 \tag{6}$$

L_{feed} is the depth needed for impedance matching within the coaxial feeder and the radiating patches, ensuring that the MPA resonates correctly at the target frequency.

$$L_{feed} = \frac{L}{\pi}cos^{-1}\left(\sqrt{\frac{Z_A(L_{feed})}{Z_{input}}}\right) \tag{7}$$

L_g and W_g were the length and width of the conductive ground plane, which influence factors like the antenna's radiation pattern, gain, and bandwidth.

$$L_g = L + 6h \quad (8)$$

$$W_g = W + 6h \quad (9)$$

The 4x4 MPA antenna for 5G mmW applications configuration aims to improve performance by augmenting directivity and gain. The antenna design consists of a 4x4 array of patches with intervals of d_l across the array's length L_{array} and d_w across its width W_{array}. To avoid the formation of grating lobes in radiation, it is crucial that the dimensions d_l and d_w remain under half of the wavelength at the resonance frequency. In the S-parameters, S11 was the input ports' voltage reflection coefficient, and S22 was the output ports' voltage reflection coefficient [25]. The design parameters of the proposed antenna are described in Table 4.

3.3. Parameters of Proposed Antenna Design

To achieve greater gain and directivity, arrays of patch elements could be employed together with the feed networks. Techniques for electrical energy distribution to all the patches encompass proximity coupling, aperture coupling, and microstrip line. The antenna was supplied from the base via a 50 Ω coaxial cable, with the feed line inputs for the patches selected at the radiating edges. Consequently, there was no discrepancy in the patch's inputs. The quarter wavelength transformer was employed to match the 100 Ω line to the 25 Ω equivalent resistances of two parallel 50 Ω lines.

Table 4. Parameters of the Proposed 4x4 MPA

Parameters	Values (mm)
L_g	5.4
W_g	7.6
L	3.05
W	4.4
L_{array}	20.37
W_{array}	26.51
h_{array}	0.81
d_w	3.07
d_l	4.33

4. Experimental Results and Simulations

4.1. Experiment Setup

This section highlights the simulation outcomes of the established 4x4 MPA, which includes a ground plane. The simulated findings of the antenna design have been executed using the CST microwave studio tool. The CST tool was widely recognized for its effectiveness in analyzing and modeling electromagnetic properties of antenna designs, providing a comprehensive understanding of the antenna's performance characteristics. The simulations were aimed at evaluating critical parameters such as gain, directivity, reflection coefficient (S11), bandwidth, and efficiency across the targeted frequency range of 24-40 GHz. The antenna's design was meticulously optimized to the requirements of future wireless communication systems. The findings from the CST simulations are presented along with the comparative analyses to highlight consistency and reliability across different modeling approaches.

4.2. Performance Metrics

This section presents the performance metrics to compute the performance of the established 4x4 MPA model. The following are the equations of the performance metrics utilized in this research.

$$Gain = 10 \cdot log_{10}\left(\frac{Radiated\ Power\ in\ Specific\ Direction}{Input\ Power}\right) \quad (10)$$

$$S11 = 20 \cdot log_{10}(|\Gamma|) \quad (11)$$

$$\Gamma = \frac{Z_{input} - Z_{load}}{Z_{input} + Z_{load}} \quad (12)$$

$$Directivity = 10 \cdot log_{10}\left(\frac{4\pi \cdot Radiated\ Power\ in\ Specific\ Direction}{Total\ Radiated\ Power \cdot Solid\ Angle}\right) \quad (13)$$

$$Bandwidth = f_{high} - f_{low} \quad (14)$$

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (15)$$

$$Efficiency = \left(\frac{Power\ Radiated}{Input\ Power}\right) \times 100 \quad (16)$$

In the above equations, the variable Γ indicates the reflection coefficient used to calculate the S11 of the model. The variables f_{low} and f_{high} are the lower and upper limits of frequency. Where the S11≤ -10dB.

4.3. Performance Evaluation

Figure 3 displays the S-parameter results (S11 and S22) for the proposed 4x4 MPA across the frequency range of 24–40 GHz. The solid lines represent the measured values, while the dashed lines represent the simulated results for S11 (red) and S22 (blue). S11 and S22 demonstrate optimal impedance matching around the key 5G frequencies, with significant dips indicating minimal reflection at specific resonant frequencies. The graph shows two major resonant frequencies: approximately 28GHz and 38GHz, where the S11 and S22 values drop below -10 dB, indicating strong reflection suppression and effective signal transmission. The close alignment between measured and simulated results for S11 and S22 validates the design's accuracy, with minor discrepancies within acceptable ranges, likely due to fabrication tolerances and measurement conditions. The S-parameters remain below the -10 dB threshold across a broad bandwidth, suggesting that the antenna design achieves effective performance across a wide frequency range within the specified 24–40 GHz band, essential for stable and efficient operation in 5G mmW applications.

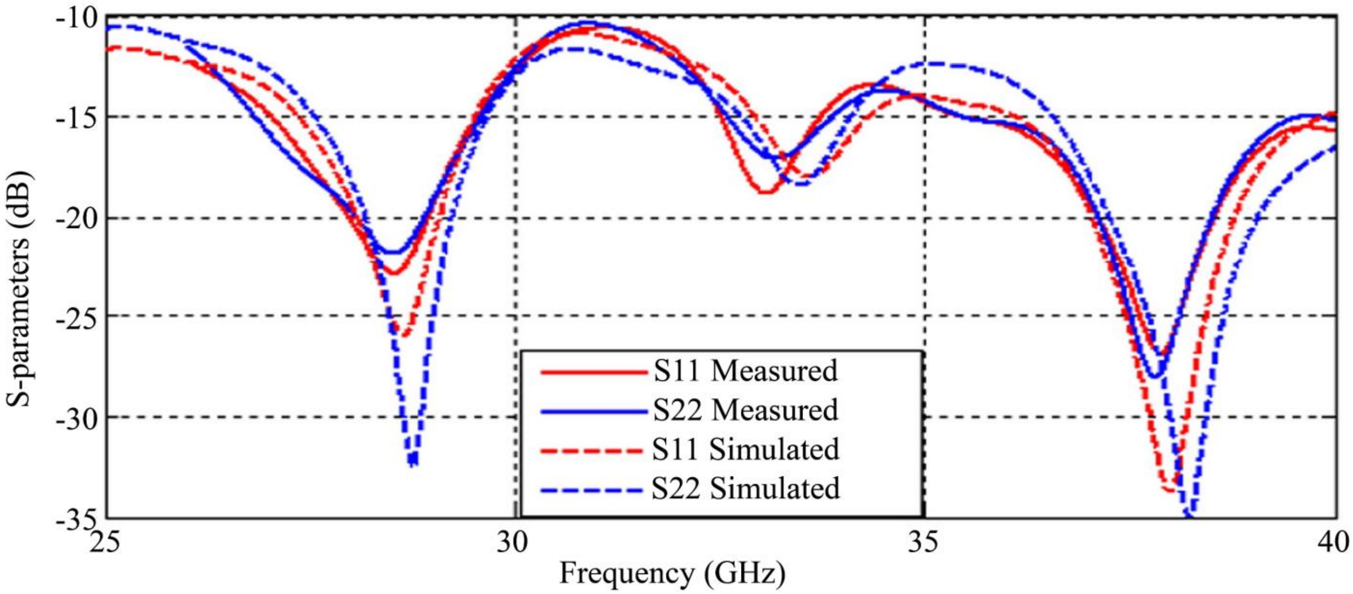

Fig. 3 Graphical plot of measured and simulated S-parameters

Figure 4 illustrates the radiation patterns of the proposed 4x4 MPA array for 5G mmW applications in different planes and perspectives. (a): This is the 3D radiation pattern of the antenna array in the E-plane (elevation plane), showing the gain and directivity of the antenna. The colors represent the gain levels, with warmer colors (red) indicating higher gain and cooler colors (blue) indicating lower gain. The pattern shows a generally symmetrical radiation, desirable for achieving consistent performance across a wide area.

(b): This is the 3D radiation pattern in the H-plane (azimuth plane). Like (a), it provides insight into the antenna's gain and directivity in a different orientation. The pattern here helps assess the antenna's horizontal radiation, demonstrating how the array distributes energy laterally. The color gradient again shows the gain levels.

(c): This is a 2D radiation pattern cut along the E-plane (vertical plane), giving a top-down view of the antenna's elevation plane radiation. It shows the distribution of the radiated signal in the vertical direction, helping to visualize how the signal propagates in the upward and downward directions. The color scale indicates gain distribution across this plane.

(d): This is a 2D radiation pattern cut along the H-plane (horizontal plane). This view highlights the azimuthal distribution, revealing how the signal spreads in the horizontal direction. The antenna design aims for a high gain in the desired directions, as indicated by the concentration of warmer colors. These figures show that the antenna provides good directivity and gain in both the E- and H-planes, which are suitable for mmW applications where focused and efficient radiation patterns are critical.

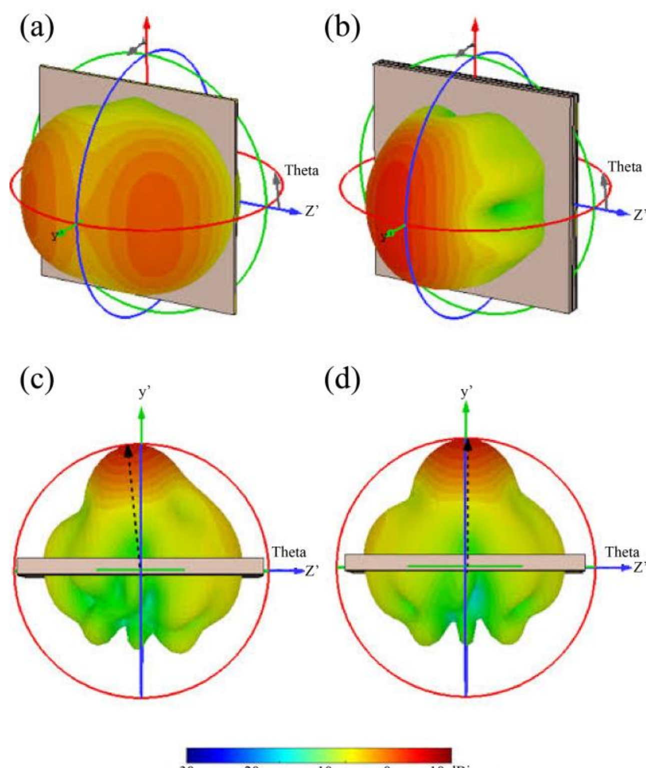

Fig. 4 Radiation Patterns of the Proposed Antenna (a) Elevation Plane; (b) Azimuth Plane; (c) Vertical Plane; (d) Horizontal Plane

Figure 5 represents the polar plot of the radiation pattern of a 4x4 MPA for 5G mmW applications. The plot shows two main planes: the xoz (red solid line) and the yoz (blue dashed line) planes, the principal planes commonly analyzed for antenna performance. The plot displays a directional pattern, suggesting the antenna's main lobe is focused around the 0°

(or 180°) direction, which is typical for array antennas designed for high gain. The antenna's gain is indicated as 8.8 dBi, which aligns with the observed concentrated main lobe, providing a strong, focused beam in the desired direction. There are additional smaller lobes visible, known as side lobes, especially around the -30°, -90°, and 120° directions. These side lobes are undesirable as they indicate radiation in unintended directions, potentially causing interference. However, for a 4x4 array, the side lobe levels appear relatively lower than the main lobe, suggesting decent suppression.

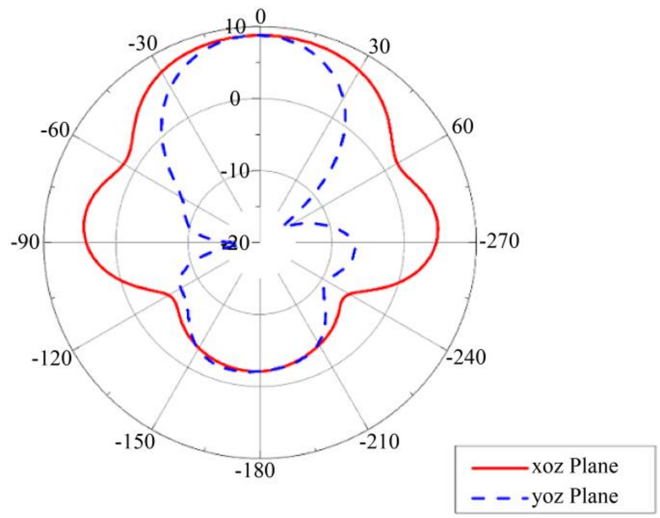

Fig. 5 Polar plot of proposed antenna's radiation pattern

The xoz and yoz planes show similar but distinct patterns due to the antenna's design and symmetry. The xoz plane (solid red line) has a broader lobe than the yoz plane (dashed blue line), suggesting the antenna radiates slightly more in the xoz plane than the yoz plane. This could be due to the positioning or feed structure of the patch elements in the array. Both planes show a certain degree of symmetry around 0°, implying that the array is reasonably well-balanced.

However, minor asymmetry is observed in the yoz plane, possibly due to element spacing or small design asymmetries in the array structure. With a gain of 8.8 dBi, this antenna is expected to have a narrow, directed beam suitable for applications in the 5G mmW range, where high directivity and gain are crucial for overcoming path losses and achieving efficient signal transmission.

Figure 6 represents the VSWR of the proposed 4x4 MPA across a frequency range of 20 to 36 GHz. The VSWR indicates how efficiently the antenna is matched to the transmission line or source impedance, with lower values indicating better matching and less reflection. For 5G mmW applications, a VSWR below 2 is generally considered acceptable. In this graph, the VSWR reaches its minimum of approximately 1.23 at 27.905 GHz, indicating an excellent impedance match at this frequency. This frequency is likely the operating frequency or resonant frequency of the antenna, as indicated by the low VSWR value. Other regions exhibit higher VSWR values, suggesting the antenna is not well-matched at those frequencies, leading to increased reflection and reduced efficiency. The low VSWR near the target frequency shows that the design is optimized for efficient operation around 27.905 GHz, aligning with mmW frequency requirements in 5G applications.

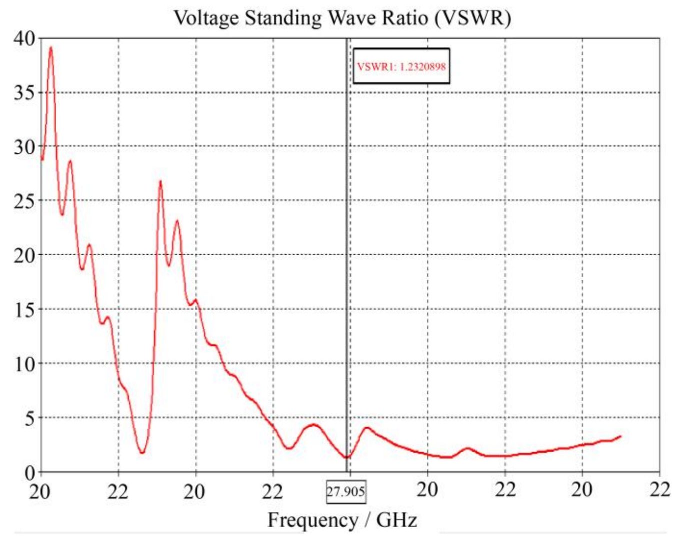

Fig. 6 Graphical plot of VSWR

Figure 7 represents the radiation patterns of the proposed antenna design in 3D. This pattern illustrates the far-field directivity of the proposed 4x4 MPA at a frequency of 28 GHz, a common frequency for 5G mmW applications. The color gradient represents the gain in dBi, ranging from -29.9 dBi (blue) to 10.1 dBi (red), with red indicating the maximum gain region.

The main lobe is concentrated along the positive z-axis (theta direction), where the antenna achieves a directivity of 10.13 dBi, showing strong directional performance ideal for 5G applications requiring focused signal transmission. The surrounding data indicate a radiation efficiency of -1.733 dB and a total efficiency of -1.906 dB, typical for microstrip antennas, reflecting some expected losses in the feed network and materials.

This pattern aligns with the aim of achieving high directivity while maintaining reasonable efficiency, which is crucial for focused coverage in mmW 5G networks. The alignment along the z-axis and the 3D shape confirms the directive nature of the antenna design, minimizing radiation in unintended directions and enhancing performance within the intended beam direction.

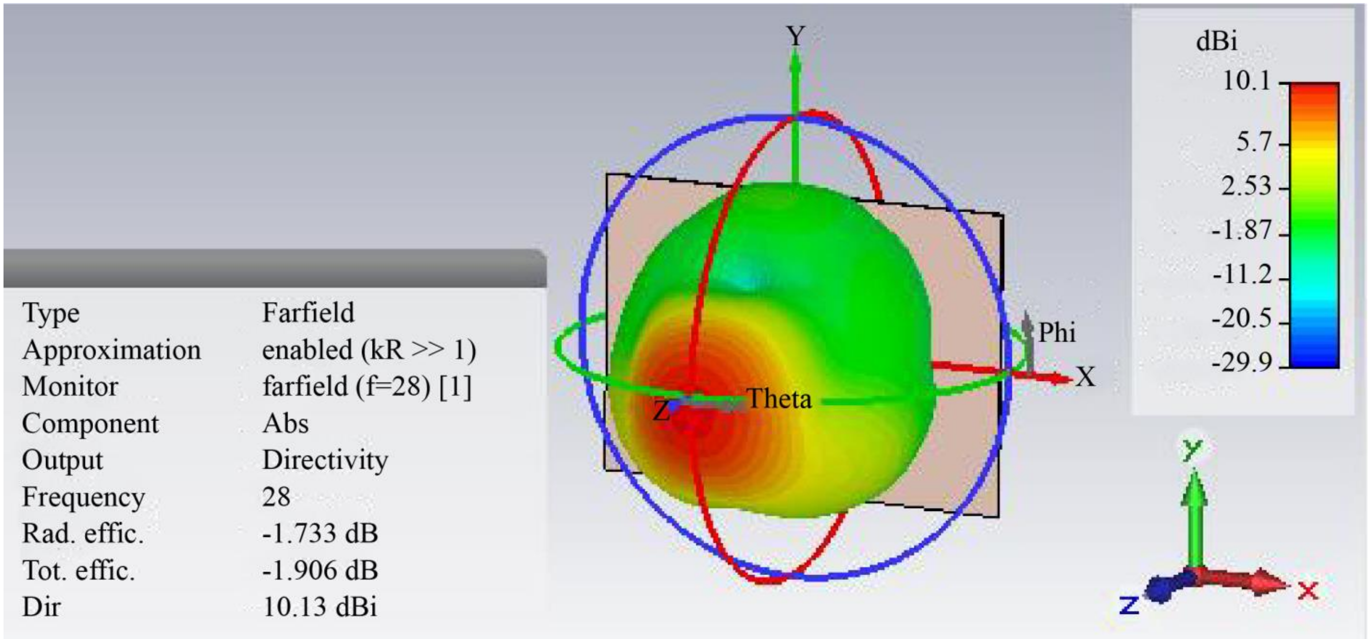

Fig. 7 Radiation patterns of proposed antenna in 3D

Table 5. Comparison of Proposed Antenna Model vs Current Models

Ref	Gain (dB)	S11 (db)	Directivity (dB)	Bandwidth (GHz)	VSWR	Efficiency (%)
[14]	2.2	NA	NA	0.28	1.24	NA
[15]	6.31	-15.84	NA	2.05	NA	NA
[16]	5.29	-40.14	7.465	14.67	1.10	60.6
[17]	9.2	-27	NA	5	NA	NA
[18]	8.2	-38.34	NA	3.46	1.02	77
[19]	7.97	-24.79	NA	1.93	NA	NA
[20]	2.87	-17.16	NA	1.24	1.32	NA
[21]	7.37	NA	NA	0.6	NA	88
[22]	16.07	-42.23	16.36	1.23	1.29	93
[23]	16	-28.98	NA	3.5	NA	96.5
[25]	12	-30	NA	1.51	NA	81.1
[26]	16.54	-40.66	16.38	1.46	1.01	81.72
[27]	9.75	25.1	NA	NA	NA	84
[28]	10.02	NA	NA	13	NA	92
Proposed	9.54	-26.71	10.13	2.52	1.23	86.82

Table 5 compares the performance of the proposed 4x4 MPA model for 5G mmW applications with various current antenna models across multiple parameters, including gain, S11, directivity, bandwidth, VSWR, and efficiency. The proposed model achieves a gain of 9.54 dB, which, while not as high as models [22] (16.07 dB), [23] (16 dB), and [26] (16.54 dB), still outperforms several others like [14] (2.2 dB) and [20] (2.87 dB). The S11 of the proposed model, at -26.71 dB, is better than some models such as [19] (-24.79 dB) and [17] (-27 dB), though it does not reach the extremely low levels seen in [16] (-40.14 dB), [18] (-38.34 dB), or [22] (-42.23 dB), which indicate stronger reflection suppression. In terms of directivity, the proposed antenna achieves 10.13 dB, placing it in the middle range, below models like [22] (16.36 dB) and [26] (16.38 dB), yet above many others that do not report directivity. The proposed antenna's bandwidth of 2.52 GHz is substantial, exceeding narrow-band models such as [14] (0.28 GHz) and [21] (0.6 GHz), though not reaching models with ultra-wide bandwidths like [16] (14.67 GHz) or [28] (13 GHz). The VSWR of 1.23 in the proposed model is well within acceptable levels, comparable to the best-performing models, indicating good impedance matching. Lastly, with an efficiency of 86.82%, the proposed antenna offers high efficiency, surpassing several models like [16] (60.6%) and [25] (81.1%), though falling slightly short of [23] (96.5%) and [26] (81.72%). Overall, the proposed antenna model demonstrates a balanced performance across key parameters. It provides a strong combination of gain, directivity, bandwidth, and efficiency, making it competitive with existing 5G mmW application models.

The designed 4x4 MPA achieves fair and better performance than state-of-the-art techniques due to its innovative design and optimization of critical parameters. The array configuration improves gain and directivity by assuring a uniform radiation pattern and minimizing grating lobes through precise control of inter-element spacing under half the wavelength. Integrating a ground plane with optimized dimensions minimizes losses, and the selected substrate thickness balances efficiency and bandwidth. Furthermore, the antenna operates with an S11 of -26.71 dB, indicating excellent impedance matching, and achieves a bandwidth of 2.52 GHz, which surpasses many existing models. These improvements are attributed to a design process focusing on maximizing radiation efficiency and minimizing reflection and insertion losses, making the designed model highly suitable for 5G mmwave applications.

4.4. Advantages and Limitations

The designed 4x4 MPA demonstrates robust performance under varying channel conditions and multipath effects, which is crucial for 5G applications. Its high directivity (10.13 dB) and gain (9.54 dB) minimize signal degradation and enhance reliability in multipath environments by focusing energy towards desired directions and reducing interference. The broad bandwidth (2.52 GHz) supports diverse channel conditions, ensuring consistent performance across wide frequency ranges. Additionally, the low S11 (-26.71 dB) and optimized VSWR (1.23) maintain efficient impedance matching, reducing reflection losses and ensuring stable operation even in dynamic channel scenarios common in 5G networks.

The 4x4 MPA that has been presented has a number of benefits, such as increased gain (9.54 dB), directivity (10.13 dB), and bandwidth (2.52 GHz) in the 24–40 GHz range. These characteristics make it appropriate for use in 5G mmWave applications. Its compact design and great efficiency (86.82%) ensure it will work reliably with minimal signal loss throughout its operation. The research, on the other hand, is limited by the relatively moderate gain and efficiency compared to some sophisticated models published in the literature. Furthermore, the design may encounter difficulties in further scalability and integration with large antenna arrays due to the possibility of increases in complexity and expense.

5. Conclusion

This research presents the design and development of a compact 4x4 MPA with coaxial feeding, specifically developed for 5G mmW application uses within the 24-40 GHz frequency range. The proposed design of the 4x4 MPA for 5G mmW applications demonstrates significant advancements in both performance and efficiency. By optimizing key parameters such as a VSWR of 1:2, a bandwidth exceeding 400 MHz, and an S11 value of less than -10 dB, the antenna effectively meets the stringent requirements for next-generation wireless communication. The design's input impedance of 50Ω ensures compatibility with standard transmission lines while selecting a copper thickness of 0.035 mm contributes to the overall robustness and durability of the structure. The successful simulation and validation of the antenna characteristics indicate its potential for high data rate transmission, reliable connectivity in 5G networks, and enhanced performance in various applications, including IoT, autonomous vehicles, and smart cities. The proposed antenna achieved 9.54 dB Gain, -26.71 dB S11, 10.13 dB directivity, 2.52 GHz bandwidth, 1.23 VSWR, and 86.82% efficiency. The proposed antenna model demonstrates a balanced performance across key parameters, providing a strong combination of gain, directivity, bandwidth, and efficiency, making it competitive with existing models for 5G mmW applications.

In the future, this research will explore advanced materials to enhance the antenna's performance further in terms of gain, bandwidth, and efficiency. Integrating beamforming techniques and reconfigurable elements can improve adaptability for dynamic 5G environments. The design can also be extended to larger antenna arrays to support massive MIMO systems for enhanced spatial diversity and capacity [29-30]. Lastly, optimizing the antenna for integration with compact, multi-functional 5G devices remains a key focus.

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