A High Gain Dual Band Hexagonal Metamaterial Inspired Antenna for 5G Applications

Sneha Talari
Department of Electronics and Communication Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India
talarisneha02@gmail.com (corresponding author)

P. Chandra Sekhar
Department of Electronics and Communication Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India
sekharpaidimarry@gmail.com

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ABSTRACT

Microstrip patch antennas play an important role in wireless communications to improve speed. Some of their benefits are low cost, low profile, and easy to fabricate. Existing research on microstrip patch antennas examines difficulties such as limited diversity performance, low radiation characteristics, and low efficiency. To address these issues, metamaterials are used to enhance diversity. This study focuses on designing a dual-band microstrip patch antenna for 5G applications to meet user demands with high data rates and enhance communication speed. To improve isolation and gain, a hexagonal-shaped Split Ring Resonator (SRR) was added to the substrate of the antenna. The proposed antenna model operates at frequencies greater than 28 GHz. The antenna dimensions are 25×25×0.15 mm, designed on a polyamide substrate with a loss tangent tan δ of 0.004, dielectric constant ε_r of 4.3, and relative permeability of 1. The suggested model was evaluated using several performance parameters, such as reflection coefficient, axial ratio, Voltage Standing Wave Ratio (VSWR), gain, and radiation patterns. The proposed model has S-parameter values of -17.6192 dB and -20.3264 dB, and gain values of 7.1 dB and 7.3 dB at 28.900 and 33.7400 GHz, respectively.

Keywords-microstrip patch antenna; metamaterials; hexagonal split ring resonator; polyamide; dual-band; hexagonal patch

I. INTRODUCTION

Wireless communication plays a vital role in fast data transfer. Due to the rapid increase in data usage and data sharing, there is a lack of resources for users. 5G applications have solved the demand for billions of connected devices and provide better connectivity to all users. [1-2]. Long-distance communication and the demand for higher data rates can be solved using 5G applications. Electromagnetic waves are transmitted with the help of radiation devices called antennas [3]. The key factors that determine an antenna are bandwidth and efficiency. 5G applications have been developed to satisfy future demands for channel capacity, high data rates, and traffic volume. Microstrip patch antennas are used in wireless communications to satisfy desirable conditions and are very popular due to being lightweight and easy to fabricate [4-5]. There are many shapes of patch antennas, such as rectangular, circular, square, triangular, and dipole antennas. However, the most commonly used shapes in microstrip patch antennas are rectangular and circular. This study uses a hexagonal shape to improve antenna parameters. Numerous methods have been employed to improve the operational bandwidth of microstrip antennas. 5G applications provide better coverage with less power consumption and use a wide signal bandwidth and high-frequency bands to enhance bit rate transmission [6-8]. The proposed microstrip patch antenna was developed with a substrate material on the ground structure. Several types of substrate are available, namely RogersRT5880, Polyamide, and Flame Retardant (FR4). This study used a Polyamide substrate with a dielectric constant of 4.3, which exhibits low dielectric loss and helps to improve antenna efficiency. A high dielectric constant helps to achieve size reduction, as the wavelength of a signal within the substrate decreases.

To enhance antenna bandwidth, a feed line is included in the antenna model. Various types of feed lines are used, namely microstrip feed lines, Coplanar Waveguides (CPW), and coaxial feed probes. A microstrip feed line was added to increase bandwidth, which helped it resonate at two additional frequencies. Mutual coupling can be minimized by the inserted ground structure into the antenna model. The microstrip antenna resonates at 28 GHz, improving efficiency, bandwidth, and energy consumption in 5G applications. By incorporating metamaterials into the design, antenna isolation and bandwidth can be improved while decreasing its size. Different metamaterials, such as SRR and Complementary SRR, are used in antenna designs. Considering all these factors, a metamaterial-inspired hexagonal-shaped patch antenna was developed to enhance gain, provide good bandwidth and reflection coefficient, and improve efficiency.

II. PROPOSED METHOD

In recent years, patch antennas have become crucial in wireless communications and are widely used in various applications, such as space-borne systems, missiles, airplanes, biomedical devices, the Internet of Things, etc. Previous studies proposed traditional microstrip patch antennas that had some limitations, such as less gain and directivity. To resolve these problems, this study proposes a dual-band hexagonal metamaterial-inspired hexagonal patch antenna for 5G applications to improve gain, resonated at 28.900 GHz and 33.7400 GHz, and designed on a substrate with dimensions of 25×25×0.15 mm. The patches are printed on a polyamide substrate with a thickness of 0.15 mm, a dielectric constant ε_r of 4.3, a relative permeability of 1, and a ground plane printed on the back of the substrate. In this instance, the signal is fed to the radiating patch through a microstrip feed line. The simulations were carried out in the HFSS software. The geometry of the hexagonal patch antenna was meant for its circular polarization. The modal distributions were found to be similar to those of circularly polarized microstrip patch antennas. For the calculation of the dimensions of the hexagonal patch antenna, the equations given below were used on an operating frequency of 28 GHz.

The side of the hexagonal patch antenna (s) was calculated by:

$$s = \frac{c}{23.1033 * f\sqrt{\varepsilon_r}} \quad (1)$$

The radius of the hexagonal patch antenna (r) was calculated by:

$$r = s \times \sqrt{\frac{2.598}{\pi}} \quad (2)$$

The resonant frequency of the hexagonal patch antenna was calculated by:

$$f = \frac{X_{mn}c}{2\pi s\sqrt{\frac{2.598}{\pi}}.\sqrt{\varepsilon_r}} \quad (3)$$

For the TM_{11} mode, X_{11} = 1.84118. For TE_{21} mode X_{21} = 3.05424. The dimensions of the substrate were calculated by:

$$L_s = 6h + \lambda \quad (4)$$

$$W_s = 6h + \lambda \quad (5)$$

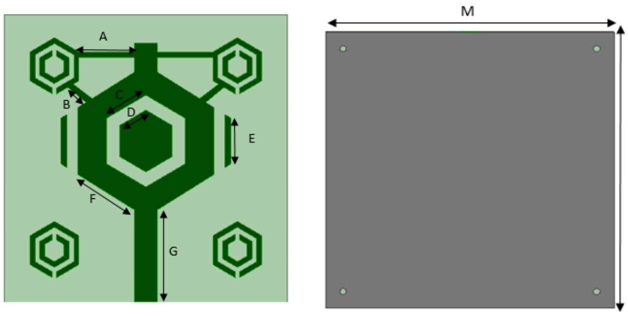
where $\lambda = \frac{c}{f \ *\sqrt{\varepsilon_r}}$, $c = 3 \times 10^8$ m/s (speed of light) and f is the operating frequency. The microstrip feed line's length (L_m) was given by:

$$L_m = \frac{\lambda_g}{4} \quad (6)$$

where λ_g is a guided wavelength.

A. *Antenna Topology*

Figure 1 shows the hexagonal patch antenna topology.



(a) (b)

Fig. 1. Proposed hexagonal patch antenna: (a) Top view, (b) Bottom view.

B. *Metamaterial-based Split Ring Resonator (SRR)*

In the proposed antenna model, a hexagonal SRR was used in the substrate to enhance radiation characteristics and gain. The metamaterial is composed of SRR and a strip line. Using SRR negative permeability can be achieved and using strip line negative permittivity can be achieved. In metamaterials, SRRs are commonly used because they exhibit negative permeability and negative permittivity at frequencies nearly equal to the resonant frequency. The SRR consists of two concentric rings separated by a gap and splits at opposite sides. With the gap between the inner and outer rings and the splits at the rings, magnetic resonance is induced. SRRs can have different shapes, such as square and circular, but multiple SRRs, spiral SRRs, and triangular SRRs are rare [9-10]. To obtain two resonant frequencies, two hexagonal-shaped rings were designed and combined, as shown in Figure 2. The resonant frequency of the hexagonal SRR was calculated using:

$$f_0 = \frac{1}{(2\pi\sqrt{(2a_{eq}.L_{net}.C_{net})})} \quad (7)$$

where a_{eq} is the effective radius of the hexagonal SRR, given by:

$$a_{eq} = 2a\, sin(\frac{\pi}{N}) - \frac{g}{N} \text{ where } N = 6 \quad (8)$$

L_{net} is the equivalent inductance, given by:

$$L_{net} = 0.00508 \times 2.303 \log_{10}\frac{4l}{c} - 2.636 \quad (9)$$

where c is the width of the strip and l is the perimeter of SRR, where:

$$l = 2aN\, sin\frac{\pi}{N} \quad (10)$$

C_{net} is the equivalent capacitance, given by:

$$C_{net} = \left\{ \frac{(N\,sin\{\frac{\pi}{N}\}+\beta)^2-\left(\frac{\Delta}{a}\right)^2}{2(N\,sin\{\frac{\pi}{N}\}+\beta)} \right\}$$

where:

$$\beta = \frac{C_g}{a} \quad (11)$$

$$\Delta = a\,sin\left\{\frac{\pi}{N}\right\}.(2m+1) - a\,cos\left\{\frac{\pi}{N}\right\}.tan\left\{\frac{\pi}{N}-\Phi\right\} \quad (12)$$

The capacitance of the upper half rings (C_u) and lower half rings(C_l) can be computed from Δ as:

$$C_u = \left[Na\,sin\left\{\frac{\pi}{N}\right\} - \Delta\right].C_{pul} \quad (13)$$

$$C_l = \left[Na\,sin\left\{\frac{\pi}{N}\right\} + \Delta\right].C_{pul} \quad (14)$$

where C_g is the capacitance due to split gaps in the rings and can be evaluated using:

$$C_g = \frac{\varepsilon_0\varepsilon_r ch}{g} \quad (15)$$

where ε_0 is the permittivity of free space and ε_r is the permeability of free space.

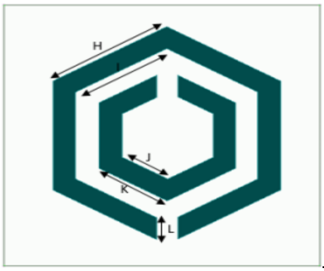


Fig. 2. Hexagonal SRR.

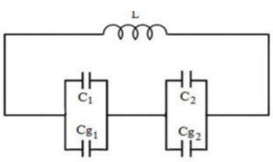


Fig. 3. Equivalent.circuit diagram of the hexagonal SRR.

Figure 2 shows the hexagonal-shaped SRR. In the equivalent circuit shown in Figure 3, the inductance L is due to the rings, C_1 and C_2 are the capacitances of the upper and lower half rings and C_{g1} and C_{g2} are due to the split gaps in the hexagonal SRR. The parameters and values of the hexagonal patch antenna were: A = 4.92mm, B = 2.09 mm, C = 4 mm, D = 2.69 mm, E = 4 mm, F = 5.87 mm, G = 8 mm, H = 2.5 mm, I = 2 mm, J = 1 mm, K = 1.5 mm, L = 0.5 mm, M = 25 mm, N = 25 mm.

III. RESULTS AND DISCUSSION

The proposed antenna model was designed for 5G applications at a resonating frequency of more than 28 GHz. Its performance, including radiation pattern, reflection coefficient, surface current distribution, axial ratio, gain, and VSWR, was evaluated to measure its diversity performance.

A. *Reflection Coefficient*

The reflection coefficient is defined as the ratio of incident power to the reflected power, expressed in dB. It measures the antenna's reflection and transmission loss to evaluate its performance. The mathematical description of the return loss is:

$$Reflection\ Coefficient = 10\,log_{10}\left(\frac{P_i}{P_r}\right) \quad (16)$$

Figure 4 shows that the proposed antenna model can obtain reflection coefficient values of -17.6192 dB and -20.3264 dB at the resonating frequencies of 28.900 and 33.7244 GHz.

B. *VSWR*

The quantity of impedance matching can be determined by VSWR values. The relationship between the antenna's performance and VSWR values is inverse. The standard values of VSWR lie between 1 and 2 and are never less than 1.

$$VSWR = \frac{V_{max}}{V_{min}} \quad (17)$$

Here, the maximum and minimum values are denoted as V_{max} and V_{min}. Figure 5 shows the results of the VSWR plot for the proposed hexagonal microstrip patch antenna, which can obtain VSWR values of 2.2983 and 1.7445 at 28.900 and 33.7400GHz. Figure 6 depicts the performance evaluation of the axial ratio of the proposed antenna.

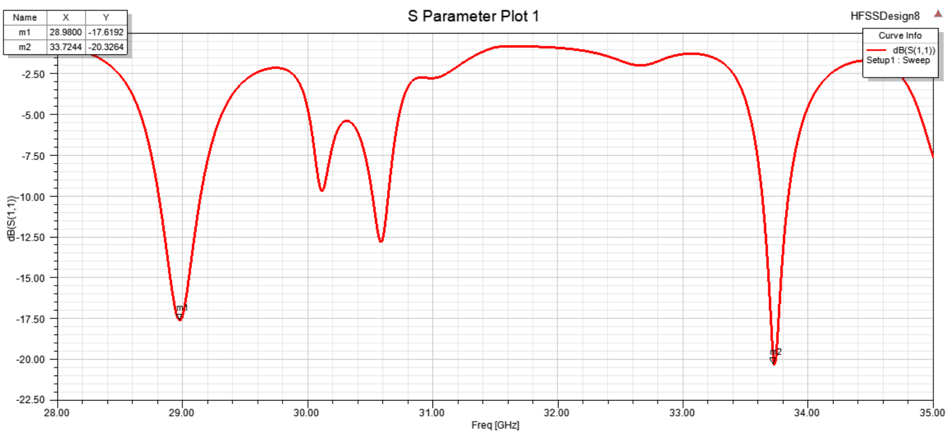


Fig. 4. Return loss of the metamaterial-inspired hexagonal patch antenna.

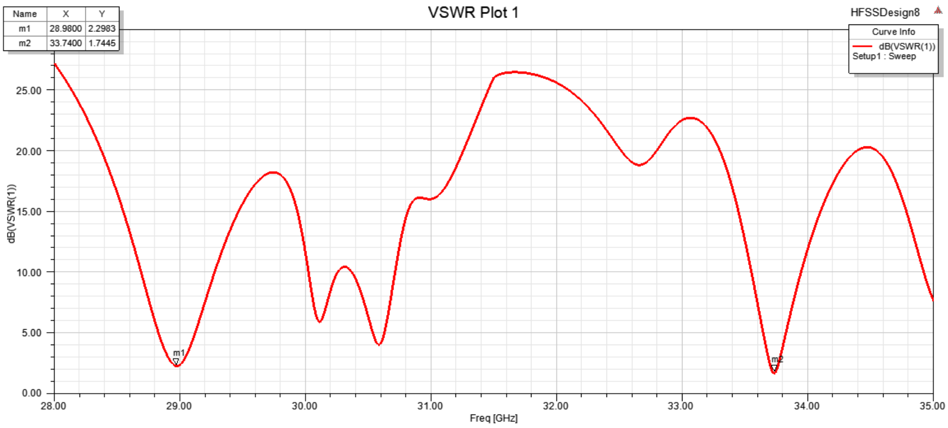


Fig. 5. VSWR of the metamaterial-inspired hexagonal patch antenna.

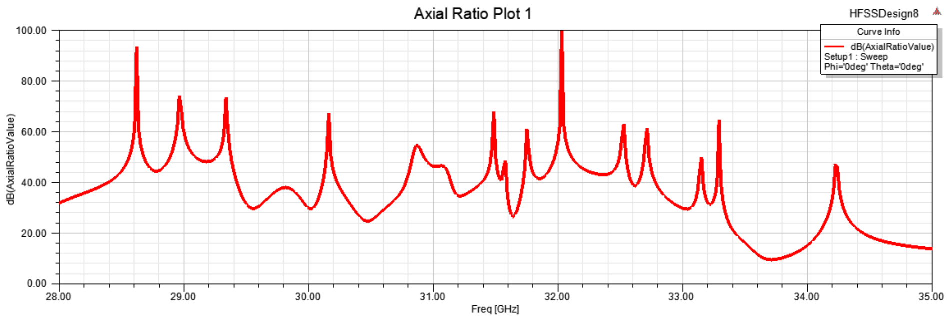


Fig. 6. Graphical representation of axial ratio vs frequency.

(a)

(b)

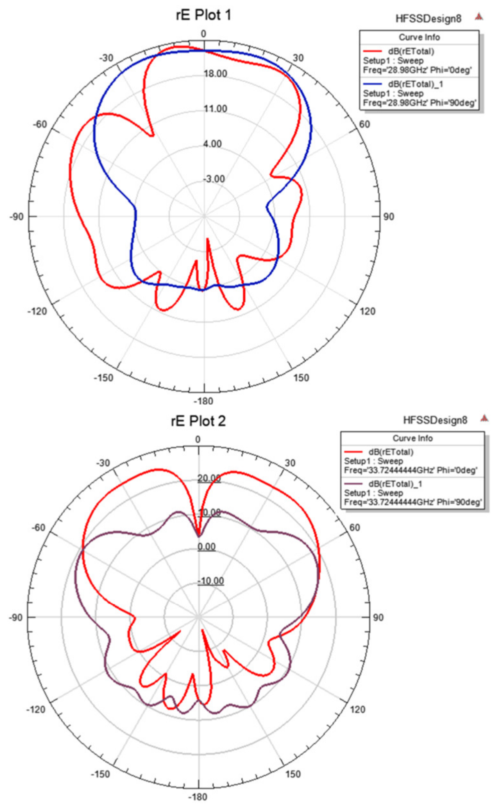


Fig. 7. Performance analysis of radiation pattern at resonating frequencies of (a) 28.900 GHz and (b) 33.740 GHz.

(a)

(b)

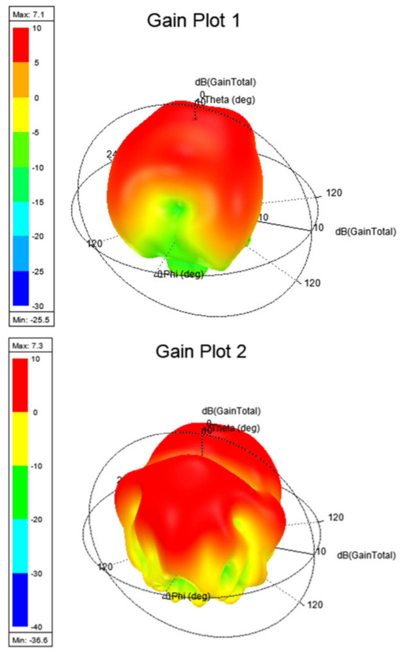


Fig. 8. 3D gain plot at resonating frequencies of (a) 28.900 GHz, (b) 33.740 GHz.

The radiation pattern was evaluated in a microwave anechoic chamber, which was used to measure the polarization and co-polarization of the antenna. Figure 7 depicts the radiation patterns of the antenna. The antenna can obtain more than 18.00 dBi at 28.900 GHz and about 20dBi at 33.740 GHz. Figure 8 depicts the analysis of the 3D gain plot.

From this analysis, the proposed antenna can obtain gain values of 7.1 dB and 7.3 dB at frequency ranges of 28.900 and 33.7400 GHz, respectively. The proposed antenna model is mainly focused on improving gain compared to other existing designs. The radiation characteristics and diversity performance of the antenna are shown using a directivity plot in Figure 8, where the results are expressed in dB.

(a)

(b)

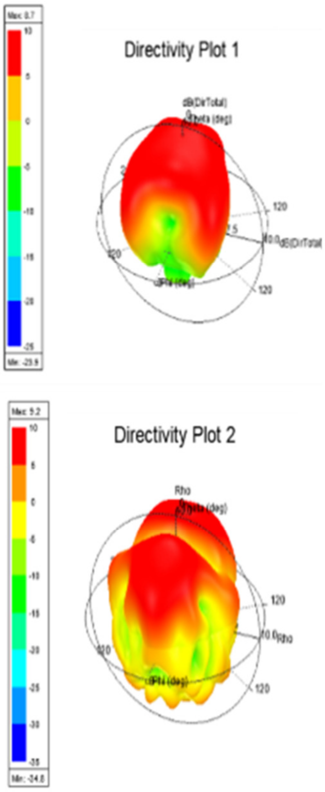


Fig. 9. Directivity plot: (a) 28.900 GHz and (b) 33.740 GHz.

The proposed antenna model can obtain directivity values of 8.7 dB and 9.2 dB at 28.9000 and 33.7400 GHz, respectively. The directivity plot shows the diversity performance of the proposed antenna. A distribution analysis shows the flows of current as well as the intensity of radiation in antenna-radiating regions. Figure 10 shows an analysis of the current distribution for the proposed model, where blue indicates the minimal flow and red represents the maximum flow of current. The results of the proposed design are shown in Table I.

TABLE I. SUMMARY OF RESULTS OF METAMATERIAL-INSPIRED HEXAGONAL PATCH ANTENNA

Parameters	Values
Operating frequency	28.900 GHz and 33.7400 GHz
Return loss	-17.6192 dB and -20.3264 dB
VSWR	2.2983 and 1.7445
Gain	7.1 dB and 7.3 dB
Directivity	8.7 dB and 9.2 dB

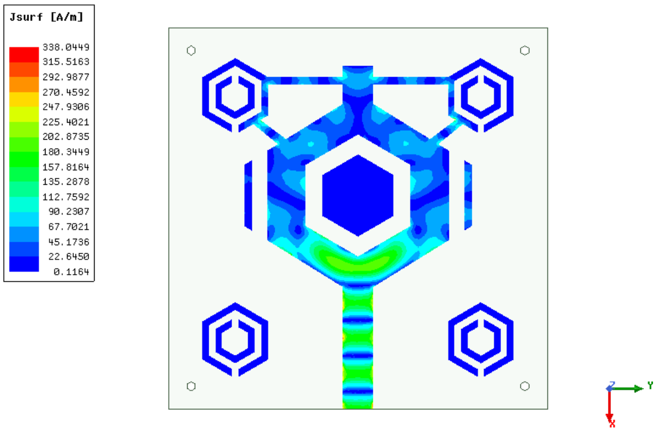


Fig. 10. Surface current distribution.

C. Discussion

Previous studies proposed different antenna models, such as circular, rectangle patch antenna for 5G [11], high gain patch antenna [12], dual-band planar antenna [13], low profile microstrip patch antenna [14], miniature dual-band patch for 5G [15], fractal antenna 5G [16] and patch antenna [17]. These antennas have some issues such as less gain, minimum diversity performance, high signal loss, and so on. This study aimed to address these issues by designing a novel metamaterial-inspired antenna for 5G applications. Here, the gain was improved by adding a metamaterial, and signal strength was improved by adding a microstrip feed line to the antenna model. Table II shows a performance comparison of the proposed and existing antenna designs.

TABLE II. COMPARISON TABLE

Study	Substrate	Resonant frequency (GHz)	Band	Gain (dB)	S-parameter (dB)
[18]	Commercial substrate	28	Dual	6.83 6.9	-18.25 -15.5
[19]	Rogers RT5880	28	Single	2.2	-24.78
[20]	FR4 substrate	39	Single	4	-31
[21]	Rogers RT/Duroid 5880	28.5	Single	6.83	-18.25
[22]	Rogers-RT/Duroid 5800	24.7 29.93	Dual	5.23	-
[23]	Rogers-RT/Duroid 5800	28	Single	7.3 free space &7.2 with body	-21
[24]	Rogers-RT/Duroid 5800	28	Single	8.198	-38.348
[25]	FR-4 substrate	28	Single	7.19	-24.507
Proposed	Polyamide	28.9 33.7	Dual	7.1 7.3	-17.6192 -20.3264

The proposed antenna can achieve better gain compared to previous designs, due to its hexagon-shaped metamaterial. The limitation of the proposed design is the need for precise control of the frequency response. Frequency response is determined by physical dimensions, substrate dielectric constant, and thickness of the substrate. Small variations in these parameters result in significant changes in frequency response. To address this challenge, a filter was designed and integrated into the antenna structure to improve frequency selectivity, reliability, and performance.

IV. CONCLUSION

This study presented a novel dual-band hexagonal antenna with hexagonal metamaterial for 5G applications at resonating frequencies of 28.900 GHz and 33.740 GHz. The hexagonal metamaterial was designed to improve antenna gain. The antenna design was developed on a polyamide substrate with a dielectric constant of 4.3 and a loss tangent of 0.004. The proposed antenna resonated at the two frequency bands with high gain and good VSWR. The results shown in Table I indicate that this antenna is suitable for 5G applications. The novelty of the proposed antenna model is that by adding a metamaterial into a hexagonal-shaped antenna, it is resonated at dual band frequencies above 28GHz with enhancement in gain for 5G applications. The proposed antenna can be analyzed using several performance parameters, such as gain, S-parameter, VSWR, axial ratio, and radiation pattern. The proposed model obtained S-parameter values of -17.6192 dB and -20.3264 dB, gain values of 7.1 and 7.3 dB, and directivity of 8.7 dB and 9.2 dB for 28.900 and 33.7400 GHz, respectively. The future scope involves the design and integration of a band-pass filter into the antenna structure to select the desired range of frequencies in the operating bandwidth for 5G applications and improve the proposed design using Finite Difference Time Domain (FDTD) technology to analyze electromagnetic fields while saving storage space and calculation time.

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