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Research Article

Development and Performance Analysis of a Square Shaped Microstrip Patch Antenna for Next-Generation 5G Communication

Gagan Pal [1*], Dr. Ram Milan Chadhar [2]

[1*] Research Scholar, Dept. of Electronics & Comm. Engineering, Patel College of Science & Technology, Bhopal, INDIA
gaganpal9173@gmail.com

[2] Assistant Professor, Dept. of Electronics & Comm. Engineering, Patel College of Science & Technology, Bhopal, INDIA
rammilanchadhar@gmail.com

**Corresponding Author* gaganpal9173@gmail.com

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Abstract: The need for compact, high-gain, wideband antennas that can facilitate high-speed and low-latency transmission has increased due to the rapid expansion of fifth-generation (5G) wireless communication. For 5G millimeter-wave applications, this paper details the design and performance analysis of a square microstrip patch antenna operating at a resonant frequency of 18.305 GHz. In order to achieve improved radiation characteristics and impedance matching, the antenna was constructed and examined using a full-wave electromagnetic modeling environment. With a return loss (S11) of -17.27 dB, the recommended antenna demonstrates effective impedance matching at the operating frequency. Additionally, it has an impedance bandwidth of 3.1 GHz, which makes it perfect for broadband 5G communication systems. The anticipated VSWR of 1.31 confirms effective power transmission with minimum reflection losses.Additionally, the antenna's gain of 6.49 dBi and directivity of 8.41 dBi demonstrate adequate radiation performance for high-frequency wireless applications. The simulation results show that the proposed square microstrip patch antenna offers a well-balanced combination of compact dimensions, broad bandwidth, constant radiation characteristics, and effective performance. The proposed antenna is a feasible choice for next-generation 5G wireless communication systems, including fixed wireless access, high-speed mobile networks, and other millimeter-wave communication applications.

Keywords: Microstrip Patch Antenna, 5G Communication, Millimeter-Wave Antenna, Return Loss, VSWR, Bandwidth, Gain, Directivity.

I. Introduction

The continuous advancement of wireless communication technologies has resulted in a significant increase in the need for communication systems that offer higher data rates, lower latency, improved reliability, and more network capacity. Fifth-generation (5G) wireless communication has emerged as a promising solution to satisfy these objectives by enabling massive machine-type connection, ultra-reliable low-latency communication, and better mobile broadband. In order to deliver these characteristics, 5G systems are increasingly operating in the millimeter-wave (mmWave) frequency spectrum, which offers higher bandwidth and spectral efficiency than previous frequency bands.

The antenna is one of the most important components of any wireless communication system as it directly influences signal transmission, reception quality, and overall system performance. The microstrip patch antenna has become one of the most popular antenna layouts due to its low-profile construction, compact size, lightweight design, ease of manufacturing, low production cost, and compatibility with printed circuit board technology. Microstrip patch antennas are perfect for modern wireless applications such satellite communication, radar systems, Internet of Things (IoT) devices, and 5G communication because of their features.

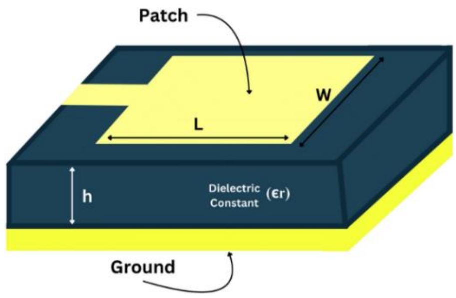


Fig. 1 Basic Design of Microstrip Patch Antenna

Traditional microstrip patch antennas might have disadvantages despite these advantages, such as a narrow bandwidth and extremely low gain, particularly at higher operating frequencies. Numerous approaches, including as modifications to patch form, substrate composition, feeding procedures, and optimization techniques, have been proposed by researchers to overcome these problems. The square microstrip patch antenna has attracted a lot of interest among these designs and is an excellent choice for high-frequency wireless communication applications due to its symmetrical construction, simple design, and constant radiation qualities.

In this study, a square microstrip patch antenna for millimeter-wave 5G communication is designed and analyzed. The antenna design aims to provide the necessary radiation characteristics, a wide operating bandwidth, and excellent impedance matching while maintaining a compact structure. The proposed antenna is modeled and simulated using a full-wave electromagnetic modeling tool to evaluate its electromagnetic performance.

II. Literature Review

The increasing need for high-speed wireless communication has spurred research on small and high-performance microstrip patch antennas for fifth-generation (5G) communication systems. Due to its low profile, lightweight construction, low manufacturing cost, and ease of integration with microwave circuits, microstrip patch antennas are currently among the most widely used antenna technologies for modern wireless applications. Recent research has mostly focused on improving antenna bandwidth, gain, impedance matching, polarization, and radiation characteristics to fulfill the demanding requirements of millimeter-wave (mmWave) communication.

Numerous academics have proposed different antenna forms and optimization techniques to enhance the performance of microstrip patch antennas. Rezaeipour and Sadeghzadeh [1] created a multi-polarization square patch antenna with a programmable feeding network to improve polarization diversity and communication reliability. Rasheda et al. [2] created a fractal microstrip patch antenna using a partial ground plane and a genetic algorithm, demonstrating significant improvements in bandwidth and impedance matching. Similar to this, Ali et al. [3] developed a dual-band 27/39 GHz millimeter-wave MIMO antenna for 5G applications, while Kim and Kim [4] proposed a dual-polarized broadband microstrip patch antenna on a FR4 substrate to enhance bandwidth and polarization performance.Pathak et al. [5] suggested a dual-feed multiband microstrip patch antenna that may offer circular polarization for 5G wireless communication, highlighting the importance of feed network design in achieving superior antenna features.

Researchers have also investigated new materials and structural modifications to overcome the inherent limitations of conventional microstrip patch antennas. Milias et al. [6] evaluated metamaterial-inspired antenna technologies and demonstrated how they may improve antenna gain, bandwidth, and compactness. Wang et al. [7] suggested a hybrid metamaterial transmission-line-based omnidirectional antenna with enhanced radiation characteristics for indoor 5G communication. Saeed and Nwajana's [8] design of a rectangular linear microstrip patch antenna array for 5G communication shows how antenna arrays may significantly boost gain and directivity. Djouimaa and Bencherif [9] introduced a compact circular microstrip patch antenna with efficient radiation performance and a lower physical size.In a similar vein, Gatea and Ali developed a low-profile, high-gain microstrip patch antenna array suitable for 5G base station applications [10].

Recent research has focused increasingly on compact antenna layouts that can support many wireless services. Nguyen-Huy et al. [11] developed a tiny microstrip patch antenna with low cross-polarization properties for 5G Internet of Things (IoT) applications. Sarkar and Gupta [12] suggested a triple-band slotted patch antenna with metasurface loading to manage RFID, satellite communication, and 5G systems simultaneously. Kornprobst et al. demonstrated a millimeter-wave patch antenna with large bandwidth and wide angular radiation characteristics suitable for high-frequency wireless communication [13]. Ding et al. [14] presented a tiny single-layer dual-band microstrip patch antenna for 5G terminal applications, emphasizing dual-band functioning and structural simplicity.Furthermore, Al-Hiti et al. [16] suggested a broadband and multiband millimeter-wave microstrip patch antenna with improved radiation performance and frequency coverage for 5G and future 6G communication systems.

Furthermore, other research have focused on bandwidth expansion, multiband operation, and radiation pattern improvement. To improve channel capacity and communication reliability for Internet of Things applications, Farghaly et al. [17] developed a 28 GHz microstrip patch antenna paired with a 4 × 4 MIMO arrangement. A single wideband microstrip patch antenna with enhanced bandwidth characteristics that can support 5G, WiMAX, and WLAN applications was developed by Prasad et al. [18]. Janarthanan [19] proposed a miniaturized high-efficiency microstrip patch antenna intended for tiny wireless devices, whereas Iqbal et al. [20] provided a pattern-diversity patch antenna operating in the Sub-6 GHz 5G range to improve signal stability and communication reliability.Giannakopoulos and Shaikh [21] have demonstrated how to build microstrip patch and multiband monopole antennas using the High Frequency Structure Simulator (HFSS), highlighting the importance of electromagnetic modeling in antenna creation and performance evaluation.

III. Antenna Design Methodology

The recommended antenna for fifth-generation (5G) millimeter-wave communication applications is a square microstrip patch antenna. The antenna's conventional microstrip patch architecture consists of three main layers: a radiating patch, a dielectric substrate, and a ground plane. For high-frequency wireless communication systems, the square form is preferred because of its simple design, compact size, ease of manufacture, and consistent radiation characteristics.

The antenna is built using a dielectric substrate that possesses the necessary electrical properties to guarantee efficient electromagnetic performance. The substrate features a continuous metallic ground plane on the bottom surface and a conductive square patch printed on the top. The antenna is excited by a microstrip feed line that provides efficient impedance matching between the transmission line and the radiating element. The feed's size and location are carefully adjusted to reduce reflection losses and boost power transfer.

The beginning size of the square patch is determined using standard microstrip antenna design formulas based on the expected operating frequency and the dielectric constant of the substrate. These theoretical dimensions serve as the foundation for the antenna design. Additional optimization is done using full-wave electromagnetic simulations to improve impedance matching, radiation characteristics, and operating bandwidth. Throughout the optimization process, patch dimensions, feed line width, feed position, substrate dimensions, and ground plane size are all changed frequently until the desired antenna performance is achieved.

The suggested antenna is modeled and simulated using CST Studio Suite. The antenna's electromagnetic behavior is accurately examined using the Finite Integration Technique (FIT). The simulation evaluates several important performance parameters, including resonant frequency, return loss (S11), voltage standing wave ratio (VSWR), impedance bandwidth, gain, directivity, radiation pattern, and surface current distribution. These variables are used to assess the antenna's compatibility for high-frequency 5G wireless communication applications.

Table 1: Design parameters for proposed antenna

Sr No.	Parameter	Value
1	Substrate Length& Width	20 mmx 20 mm
2	Ground Length &Width	5 mm x 20 mm
3	Feed patch length	8.50 mm
4	Feed patch width	3.13 mm
5	Frequency(f_r)	18.305 GHz
6	Dielectric constant(ε_r)	4.3 / FR4
7	Ground Height	0.035mm
8	Substrate Height (Hs)	1.6 mm
9	Patch Length & Width	15 mm x 15 mm

Table I displays the ideal design features of the proposed square microstrip patch antenna. The dielectric constant of the 1.6 mm thick FR4 substrate on which the antenna is constructed is 4.3. The entire substrate is 20 mm by 20 mm, and the square patch measures 15 mm by 15 mm. To enhance antenna performance, a 5 mm x 20 mm partial ground plane and an 8.50 mm x 3.13 mm impedance matching microstrip feed line are used. The antenna is designed to operate at a resonance frequency of 18.305 GHz for 5G communication applications.

The transmission line model, which offers a straightforward and precise method of determining the antenna dimensions for a specific resonance frequency, is the foundation for the mathematical design of a microstrip patch antenna. The dielectric constant, substrate thickness, patch width, and patch length are the primary determinants of antenna performance. In order to achieve appropriate impedance matching, effective radiation, and stable operation in 5G wireless communication systems, these features are computed using conventional design formulas.

A. Patch Width

The width of the radiating patch is calculated as

$$\mathrm{W} \equiv \frac{c \sqrt{\frac{2}{1+\epsilon r}}}{2fr} \qquad (1)$$

B. Effective Length

The effective resonant length is

$$Leff = \frac{c}{2fr\sqrt{\epsilon reff}} \qquad (2)$$

C. Effective Dielectric Constant

The effective dielectric constant is expressed as

$$\epsilon reff \equiv \frac{(\epsilon r+1)}{2} + \frac{(\epsilon r-1)}{2\sqrt{1+12\left(\frac{h}{w}\right)}} \qquad (3)$$

D. Fringing Length Extension

The fringing field extension is given by

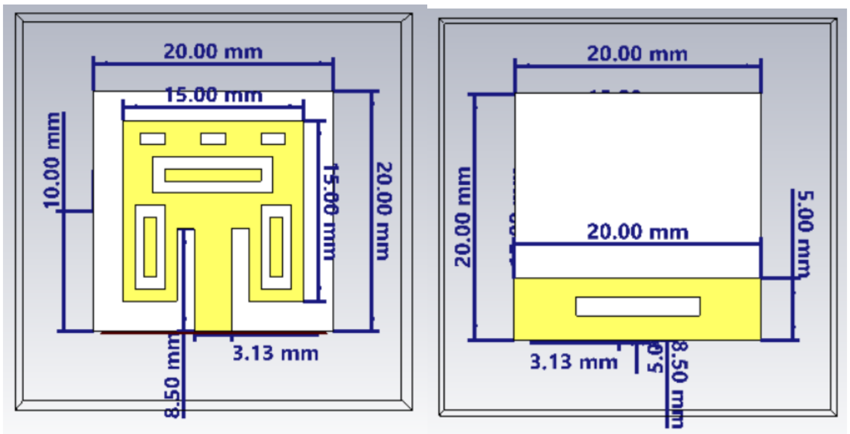
$$\Delta \mathrm{L} = 0.412 \frac{(\epsilon reff+0.3)\left(\frac{W}{h}+0.2264\right)}{(\epsilon reff-0.258)\left(\frac{W}{h}+0.8\right)} \qquad (4)$$

E. Actual Patch Length

The actual patch length is

$$\mathrm{L} = \mathrm{L}eff - 2\Delta \mathrm{L} \qquad (5)$$

Figure 2 shows a square patch radio wire with a coaxial feed from above. The surrounding fields created by the patch and ground plane are what trigger the radiation coming from the receiving wire. The microstrip patch reception equipment was recommended because to its improved reference and lower size. The calculated resonance frequency of 18.305 GHz indicates that the proposed receiving device operates in the K-band. The recommended microstrip patch structure for Ku band applications is depicted in Figure 2. The building is carved on fire resistant 4 (FR4) and measures 20 x 20 x 1.64 mm (L × W × H).



(a) Front View (b) Back View

Fig. 2: Antenna Design Front & Back view

The proposed microstrip patch antenna is seen in Figure 2. The substrate is made of FR4 material with a dielectric stable value of 4.3, while the top and bottom layers are made of lossy copper material.

IV. Simulation & Result

The recommended square microstrip patch shape for Ku-band applications is shown in Figure 3. The structure has an overall dimensions of 20 x 20 x 1.64 mm, an overall permittivity of 4.3, a loss digression of 0.024, and is etched on fire resistant 4 (FR4). Table 1 lists the antenna components used in this proposal. The antenna is handled via a straightforward connection or a 50- and 0.5-W micro thin link.

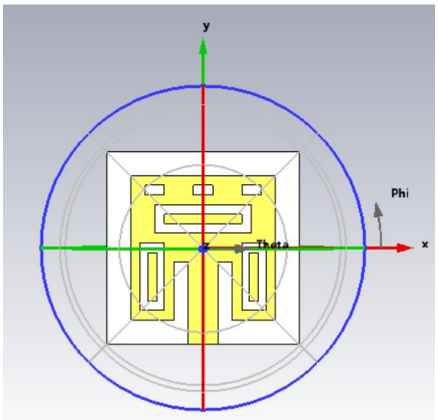


Figure 3: Simulation and fields of proposed antenna

CST Microwave Studio was used to develop and simulate the suggested antenna design. The electromagnetic properties, such as the distributions of the electric and magnetic fields, were examined using the program. The computed electric and magnetic field patterns of the suggested antenna are shown in Figure 3.

Return loss

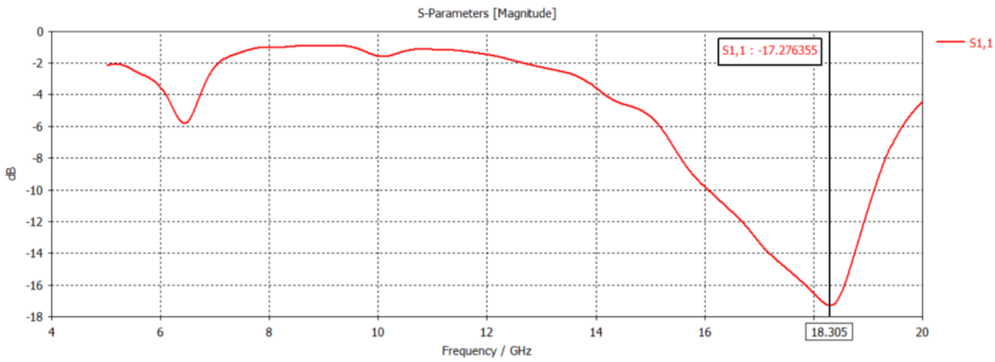


Figure 4: Return loss

The simulated return loss (S11) of the suggested square microstrip patch antenna is shown in Figure 4. The antenna is appropriate for 5G millimeter-wave communication applications since it has a return loss of −17.27 dB at the resonance frequency of 18.305 GHz, suggesting good impedance matching and effective signal transmission.

Bandwidth

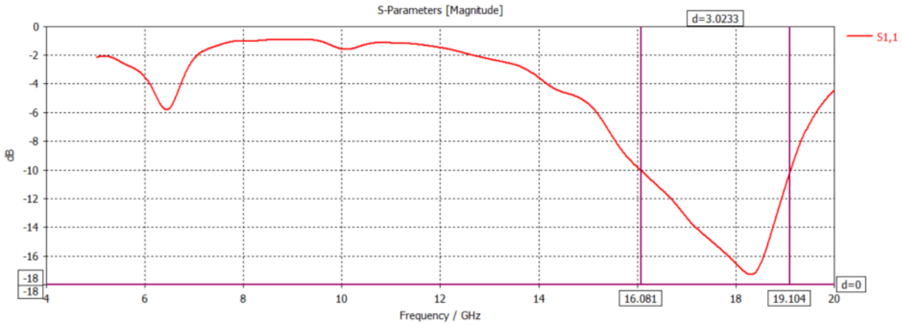


Figure 5: Bandwidth

The frequency range that an antenna can function well over is known as its bandwidth. With a bandwidth of 3.02 GHz, which spans from 16.081 GHz to 19.104 GHz, the suggested square microstrip patch antenna offers enough frequency coverage for wideband 5G millimeter-wave communication applications.

Voltage Standing Wave Ratio (VSWR)

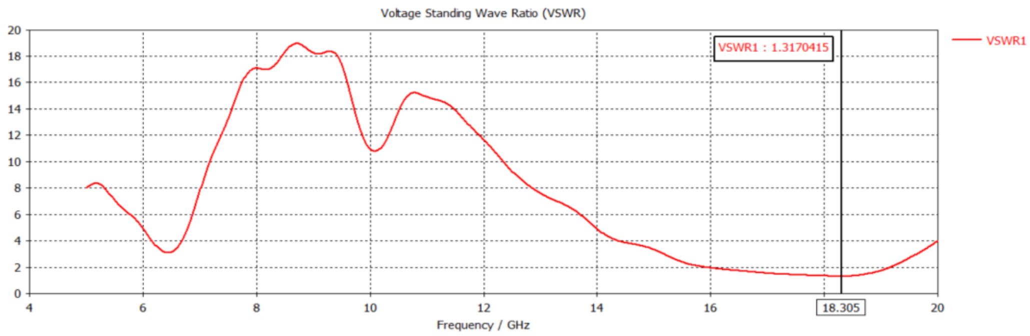


Figure 6: VSWR

The suggested square microstrip patch antenna's simulated Voltage Standing Wave Ratio (VSWR) is displayed in Figure 6. At the resonant frequency of 18.305 GHz, the antenna achieves a VSWR of 1.31, indicating minimum power reflection and good impedance matching.

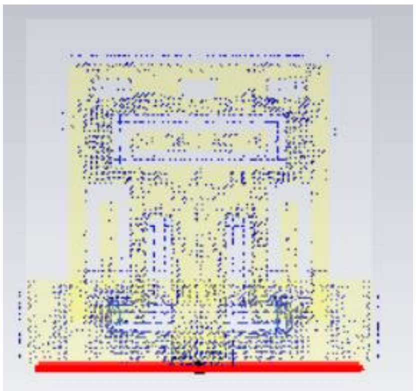


Figure 7: Surface current of proposed antenna

The suggested square microstrip patch antenna's predicted surface current distribution is shown in Figure 7. In order to illustrate the antenna's electromagnetic behavior at the resonant frequency, the figure also shows the distributions of the electric and magnetic fields, with blue contours representing the electric field and green contours representing the magnetic field.

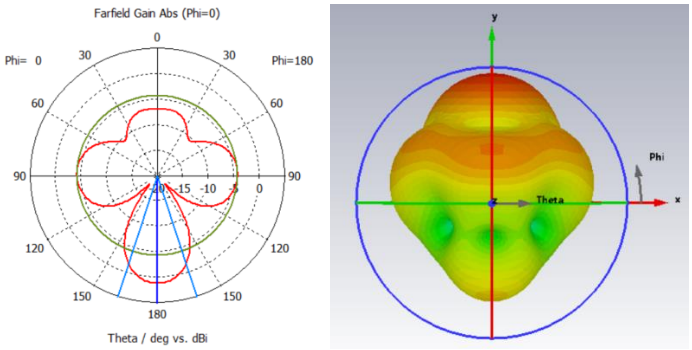


Figure 8: Radiation pattern

The suggested square microstrip patch antenna's predicted radiation pattern is shown in Figure 8. The antenna is appropriate for 5G communication applications since the radiation pattern shows the directed distribution of the emitted electromagnetic energy, showing steady radiation characteristics and effective signal transmission at the operating frequency of 18.305 GHz

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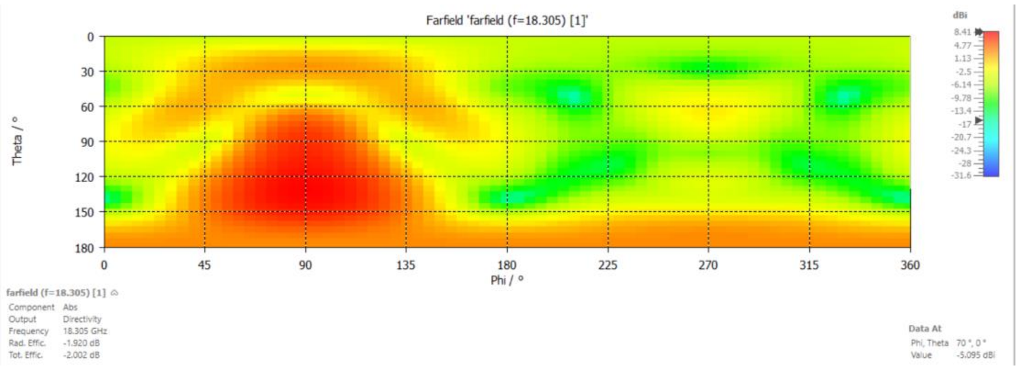

Figure 9: Directivity Analysis

The computed directivity of the suggested square microstrip patch antenna is shown in Figure 9. For 5G millimeter-wave communication applications, the antenna's directivity of 8.41 dBi indicates efficient directed radiation and enhanced signal transmission.

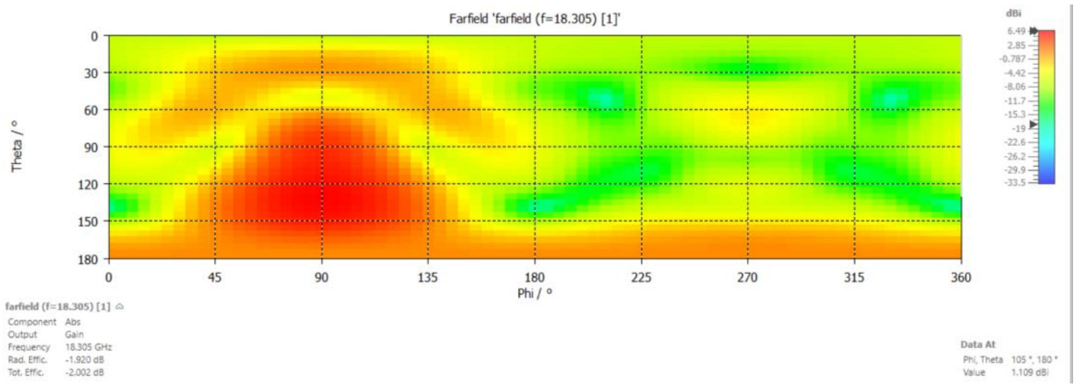

Figure 10: Gain Analysis

The computed gain of the suggested square microstrip patch antenna is shown in Figure 10. At the working frequency of 18.305 GHz, the antenna achieves a gain of 6.49 dBi, indicating effective radiation performance and improved signal transmission, making it appropriate for 5G millimeter-wave communication applications.

Table 2: Simulated Results of Proposed Antenna

Sr No.	Parameter	Value
1	Directivity	8.41 dBi
2	Gain	6.49 dBi
3	S11 or Return loss	-17.27 dB
4	Bandwidth	3.1 GHz
5	VSWR	1.31
6	Resonant Frequency	18.305 GHz

Table II displays the simulated performance results for the proposed square microstrip patch antenna. The antenna exhibits good impedance matching with a resonance frequency of 18.305 GHz and a return loss of −17.27 dB. The antenna's 3.1 GHz bandwidth makes it suitable for wideband 5G transmission. The VSWR of 1.31 confirms effective power transmission with little reflection. With a gain of 6.49 dBi and a directivity of 8.41 dBi, the antenna also demonstrates acceptable radiation performance for millimeter-wave 5G applications.

V. Conclusion

This work presented the design and performance analysis of a square microstrip patch antenna for 5G millimeter-wave communication. The antenna was created on a FR4 substrate with a compact square patch topology and examined using full-wave electromagnetic modeling. The proposed design focused on achieving excellent impedance matching, a wide operating bandwidth, and acceptable radiation properties while maintaining a simple and small construction suitable for modern wireless communication systems.

According to the simulated findings, the proposed antenna operates at a resonant frequency of 18.305 GHz with a return loss of −17.27 dB, successfully matching impedance. The antenna is suitable for broadband 5G applications due to its 3.1 GHz impedance bandwidth. A VSWR of 1.31, gain of 6.49 dBi, and directivity of 8.41 dBi further confirmed its effective radiation performance and directional characteristics. These results indicate that the proposed antenna may allow reliable high-frequency wireless communication while maintaining a compact design.

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