



PROXIFEED-ENABLED DUAL-LAYER PATCH ANTENNA: ENHANCING MULTI-FREQUENCY PERFORMANCE FOR 5G AND MM WAVE COMMUNICATIONS

Chejarla Raghunathababu^{*1}, E. Logashanmugam²

^{1,2}Department of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Jeppiaar Nagar, SH 49A, Chennai, Tamil Nadu, India.

¹<https://orcid.org/0009-0004-6848-5240>, ²<https://orcid.org/0000-0001-8273-9738>

Email: *electronicsraghu@gmail.com, logu999@yahoo.com

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ABSTRACT

The emergence of 5G and millimetre-wave (mmWave) communication has driven demand for high-performance microstrip patch antennas with wide bandwidth, high efficiency, and minimal losses. Conventional single-layer microstrip antennas, while compact and simple to fabricate, suffer from limited bandwidth, poor impedance matching, surface wave losses, and back radiation, making them unsuitable for next-generation systems. This study introduces a novel ProxiFeed-enabled Dual-Layer Resonant Artificial Magnetic Conductor (DRA-Patch) antenna that addresses these challenges. The design integrates a dual-layer stacked patch with Resonance Stacking Enhancement (RSE) to support multi-resonant modes across 28GHz, 38 GHz and 60 GHz frequency bands. A cross-shaped Artificial Magnetic Conductor (AMC) ground plane reduces surface wave losses and enhances radiation performance, while MXene-coated copper is used for both patch and ground plane to minimize conduction losses. A ProxiFeed Radiative Link (PFRL) replaces traditional feeds, enhancing coupling with reduced feedline radiation. Simulations and prototype testing demonstrate substantial improvements: a 3.5 GHz bandwidth per band, 14.8 dB peak gain, radiation efficiency above 99.75%, and S11 below -37.09dB. The proposed antenna achieves compact, multi-band operation with excellent electromagnetic compatibility, ideal for 5G, satellite, and IoT applications. This work sets a new standard in patch antenna design by resolving critical limitations of existing structures and offering a scalable solution for advanced high-frequency communication technologies.



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I. INTRODUCTION

The rapid evolution of 5G and millimeter-wave (mmWave) communication systems has fundamentally transformed the landscape of wireless connectivity [1]. As the demand for ultra-high-speed data transmission and ubiquitous network coverage grows, network operators and device manufacturers are under increasing pressure to deliver systems that not only support higher data rates but also ensure reliable and stable connections [2]. This transformation is driven by the exponential growth in data-intensive applications such as high-definition video streaming, augmented reality, and real-time IoT services, all of which require antennas that can operate efficiently under demanding conditions. In this context, antenna technology plays a critical role in enabling next-generation wireless systems [3]. Microstrip patch antennas have emerged as a cornerstone due to their low-profile structure, ease of integration with printed circuit boards (PCBs), and simple fabrication processes [4]. Their planar design enables compact implementations, making them ideal for mobile devices, satellite communications, and embedded systems where space constraints are critical [5]. Moreover, their design flexibility allows seamless integration with various electronic components, facilitating streamlined and cost-effective mass production [6]. Despite their widespread adoption, conventional microstrip patch antennas are fundamentally limited by narrow bandwidth due to reliance on a single resonant mode [7]. This leads to insufficient multi-band performance and a restricted operational frequency range [8], which poses a significant limitation in supporting diverse bands required for 5G and other high-frequency applications [9].

Additional performance issues, such as surface wave losses caused by energy leakage through the substrate [10], further diminish radiation efficiency and distort beam patterns. Impedance mismatches, often stemming from poor coupling between the feedline and patch, are exacerbated by traditional copper ground planes that introduce parasitic effects and reflections [11], [12]. These factors result in elevated back radiation and suboptimal power transfer [13], [14]. At mmWave frequencies, conduction losses from standard copper materials further compromise efficiency [15]. Direct-fed techniques, such as inset feeding, aggravate the problem by introducing spurious feedline radiation and unwanted interference [16]. These limitations collectively restrict the antenna's operational frequency range and degrade radiation performance, rendering conventional designs inadequate for high-performance, multi-band 5G and mmWave systems [17]. The inherent tradeoffs in conventional designs between compactness and efficiency or between simplicity and wideband operation underscore a significant research gap that must be addressed to keep pace with the rapid advancements in wireless technology [18]. To address these challenges, this research proposes a novel antenna architecture aimed at delivering compactness, high gain, wide bandwidth, improved impedance matching, and reduced surface wave losses while operating efficiently across multiple frequency bands. This design targets modern 5G, satellite, and IoT applications, providing a robust and scalable solution. The key innovations and contributions of this study include:

- The primary contribution of this research is the development of DRA-Patch antenna architecture that significantly enhances microstrip patch antenna performance for next-generation communication systems. Key innovations include:
 - The proposed antenna incorporates a ProxiFeed Radiative Link (PFRL), a non-contact feed mechanism positioned beneath the bottom patch, which ensures strong electromagnetic coupling while minimizing spurious feedline radiation and return loss.
 - A dual-layer stacked patch configuration is implemented to enable multi-resonant behavior across 28 GHz, 38 GHz, and 60 GHz, thereby extending bandwidth and supporting effective multi-band operation.
 - A cross-shaped Artificial Magnetic Conductor (AMC) ground structure is integrated to suppress surface wave propagation, reduce back radiation, and enhance both radiation efficiency and directivity.

MXene-coated copper is applied to both the patch and ground plane, significantly reducing conduction losses and improving high-frequency signal propagation. These contributions culminate in a compact, high-performance, and scalable antenna solution that overcomes the limitations of traditional microstrip designs and supports the demanding requirements of future wireless communication technologies. The remainder of this paper is structured as follows. Section II presents a comprehensive review of related works and existing microstrip antenna technologies, highlighting their limitations in the context of 5G and mmWave applications. Section III describes the proposed ProxiFeed-enabled Dual-Layer Resonant AMC (DRA-Patch) antenna, including its design principles, material selection, and implementation methodology. Section IV provides detailed simulation results, performance evaluations, and a comparative analysis with conventional antenna designs. Finally, Section V concludes the paper with key findings and outlines potential directions for future research.

II. LITERATURE REVIEW

By [19] presented a study on the design and analysis of a microstrip patch antenna operating at 28 GHz, tailored for future 5G communication systems. The antenna utilized Rogers RT/Duroid 5880 as the substrate, characterized by a dielectric constant of 2.2 and a thickness of 0.3451 mm. The design and simulation were conducted using CST Studio, known for its user-friendly interface and robust electromagnetic simulation capabilities. Key performance metrics such as return loss, gain, and radiation efficiency were evaluated. The results demonstrated the antenna's potential for 5G applications. However, despite its low dielectric constant, the use of Rogers RT/Duroid 5880 led to increased surface wave losses, which in turn reduced radiation efficiency and degraded overall performance at higher frequencies. Expanding on the material selection challenges, [20] further explored the design and simulation of an S-band microstrip patch antenna for wireless applications using two different substrates—FR-4 (lossy) with a dielectric constant of 4.3, and Rogers RT/Duroid with a dielectric constant of 2.2. CST Studio Suite 2019 was employed to optimize performance, targeting low return loss and a voltage standing wave ratio (VSWR) close to 1. Copper was used for the patch and ground plane, with respective thicknesses of 0.35 mm and 0.0077 mm. While improvements in gain, directivity, and efficiency were achieved, the use of FR-4 introduced significant dielectric losses, adversely affecting radiation efficiency. To address miniaturization without sacrificing performance, [21] proposed the incorporation of a thin film with high relative permittivity into microstrip patch antenna structures. This approach successfully reduced the resonance frequency from 5.8 GHz to 4.0 GHz, achieving a 60% size reduction without altering patch dimensions. Genetic algorithms were used for optimizing the patch size.

Although the method improved compactness and frequency tunability, it also increased surface wave propagation, resulting in reduced radiation efficiency and compromised antenna gain. By [22] designed a simple, low-profile rectangular microstrip patch antenna for 28 GHz applications. The design used Rogers RT/Duroid 5880 ($\epsilon_r = 2.2$, thickness = 0.508 mm, $\tan\delta = 0.0009$) and implemented an inset feed to improve impedance matching. A rectangular slit at the front edge of the patch helped reduce antenna size. The optimized design showed good return loss, gain, and bandwidth, making it suitable for mmWave applications. However, the inset feed introduced spurious radiation and parasitic effects, leading to reduced efficiency and increased cross-polarization. To enhance gain using slot-based techniques, [23] proposed a dual-band antenna for 26 GHz and 28 GHz. The design incorporated two hammerhead slots and a rectangular slot on a single rectangular patch, optimized using CST simulations. This configuration improved gain and radiation characteristics significantly. Nevertheless, the complex slot geometry increased surface current distribution complexity, resulting in greater ohmic losses and reduced radiation efficiency. In turn [24] addressed the bandwidth limitations of conventional patch antennas by proposing a stacked triple-layer structure. Using a central Rogers RT/Duroid 5880 layer flanked by two FR4 layers, along with thickness tuning and slot insertion, the design achieved a broad impedance bandwidth of 47.62% in the S-band (2–4 GHz). While this enhanced bandwidth and radiation patterns introduced fabrication complexity, alignment issues, and potential impedance mismatches that negatively impacted radiation efficiency. According to [25] introduced a compact rectangular patch antenna with a partial ground plane for WLAN applications, aimed at low-power wireless sensor networks (WSNs). The antenna was fabricated on a 45 mm × 50 mm FR4 substrate ($\epsilon_r = 4.3$, thickness = 1.4 mm) and operated in the 2.4–2.48 GHz band.

It showed strong performance for short-range communication and was cost-effective for applications in smart cities and healthcare. However, its single-band operation and poor multi-band support, along with surface wave losses and impedance mismatch, limited its scalability for broader applications. To meet the growing demand for compact and multi-functional antennas [26] proposed a dual-band planar antenna with two half-mode patches operating at 3.5 GHz and 4.9 GHz. A 4×4 MIMO configuration was integrated to enhance spectral efficiency for 5G terminals. Although the design offered high integration density and compactness, the use of half-mode patches led to poor isolation between the two bands, increasing mutual coupling and interference, ultimately degrading overall system performance. The comparison of those review is represented in Table 1.

Table 1: Summary of Key Microstrip Patch Antenna Designs for 5G and Wireless Applications: Features, Materials, Performance, and Limitations.

Reference	Antenna Type / Frequency	Key Features	Materials Used	Performance Highlights	Limitations
Rana et al. [19]	Microstrip patch antenna / 28 GHz	Rogers RT/Duroid 5880 substrate; CST simulation	Rogers RT/Duroid 5880 ($\epsilon_r=2.2$, 0.3451 mm)	Good return loss, gain, radiation efficiency	Increased surface wave losses; reduced efficiency at higher frequencies
Rana et al. [20]	S-band microstrip patch antenna	Compared FR-4 and Rogers RT/Duroid substrates; CST simulation	FR-4 ($\epsilon_r=4.3$), Rogers RT/Duroid ($\epsilon_r=2.2$); Copper patch/ground	Low return loss, VSWR near 1; improved gain and directivity	FR-4 introduced dielectric losses reducing radiation efficiency
Boudjerda et al. [21]	Miniaturized patch antenna / 4 GHz	Thin film high permittivity material; genetic algorithms for optimization	High permittivity thin film	60% size reduction; resonance frequency shifted lower	Increased surface wave propagation, reduced radiation efficiency
Gaid et al. [22]	Rectangular patch antenna / 28 GHz	Inset feed; rectangular slit for size reduction	Rogers RT/Duroid 5880 ($\epsilon_r=2.2$, 0.508 mm)	Good return loss, gain, compactness	Spurious radiation and parasitic effects from inset feed reducing efficiency
Nahas et al. [23]	Slot-loaded patch antenna / 26 & 28 GHz	Multiple slots (hammer & rectangular) for gain enhancement	Not specified	Improved gain and radiation performance	Complex slot geometry increased ohmic losses and reduced efficiency
Das et al. [24]	Stacked triple-layer patch antenna / S-band	Triple-layer stacked design; slot introduction; Rogers and FR4 substrates	Rogers RT/Duroid 5880, FR4	Bandwidth of 47.62%; improved radiation pattern	Increased fabrication complexity and alignment issues; potential impedance mismatch
Ahmed et al. [25]	Compact patch with partial ground / 2.4 GHz	Partial ground for size/power constraints; designed for WLAN and WSN	FR4 ($\epsilon_r=4.3$, thickness 1.4 mm)	Good short-range communication performance	Single-band; limited multi-band support; surface wave losses and impedance mismatch issues
Ding et al. [26]	Dual-band planar antenna with MIMO / 3.5 & 4.9 GHz	Half-mode patches; 4×4 MIMO system	Not specified	Dual-band operation; compact form factor	Poor isolation between bands; increased mutual coupling and interference

Source: Authors, (2026).

The reviewed literature highlights the evolution of microstrip patch antenna designs aimed at enhancing performance for 5G and wireless communication. Various strategies ranging from material selection, stacked configurations, slot incorporation, and feeding techniques have been employed to improve bandwidth, gain, and radiation efficiency. However, persistent challenges such as surface wave losses, spurious radiation, fabrication complexity, and impedance mismatches continue to limit antenna performance, particularly at high frequencies. These gaps strongly justify the need for a novel, scalable antenna solution capable of supporting multi-band, high-efficiency, and compact operation in mmWave and next-generation wireless systems.

III. ANTENNA DESIGN

The proposed antenna structure features a DRA-Patch configuration designed to enhance multi-frequency performance for 5G and mmWave communications. The core design utilizes a stacked dual-layer microstrip patch structure, with each layer resonating at distinct frequencies to enable broad multi-band support. The bottom patch includes an E-slot etched to introduce additional current paths, optimizing impedance matching and extending bandwidth. Positioned above, the top patch layer facilitates strong inter-layer electromagnetic coupling, supporting resonance stacking. This vertical stacking enables seamless frequency tuning and bandwidth expansion across the targeted bands of 28 GHz, 38 GHz, and 60 GHz. To reduce radiation loss and improve impedance bandwidth, a cross-shaped Artificial Magnetic Conductor (AMC) ground plane is integrated beneath the patch layers. The AMC surface creates a high-impedance boundary that suppresses surface wave propagation and significantly reduces back radiation. Its periodic cross-shaped slots manipulate current distribution and reflect incident electromagnetic waves in phase, enhancing directivity and gain.

Additionally, the feed mechanism incorporates the novel ProxiFeed Radiative Link (PFRL), a proximity-coupled feedline placed beneath the bottom patch and isolated by a thin dielectric layer. This non-contact feeding technique mitigates parasitic feedline radiation and improves return loss (S11), ensuring a low Voltage Standing Wave Ratio (VSWR) and superior radiation performance. Material selection further enhances the design's effectiveness at high frequencies. The substrate is Rogers RO4003C, chosen for its low dielectric constant ($\epsilon_r = 3.38$) and low loss tangent ($\tan\delta = 0.0027$), minimizing dielectric losses and promoting high-frequency stability. To address conduction losses common in conventional copper-based designs, both patch and ground planes are fabricated from copper coated with a 100–500 nm thick MXene layer. MXene's ultra-high electrical conductivity reduces resistive losses and improves radiation efficiency. This combination of advanced materials and structural innovation makes the proposed DRA-Patch antenna highly suitable for compact, wideband, and high-gain applications in 5G, satellite communications, and IoT ecosystems. As illustrated in Figure 1, the DRA-Patch antenna consists of an upper and bottom patch separated by a dielectric layer, with a cross-shaped AMC ground plane to suppress surface waves and control back radiation.

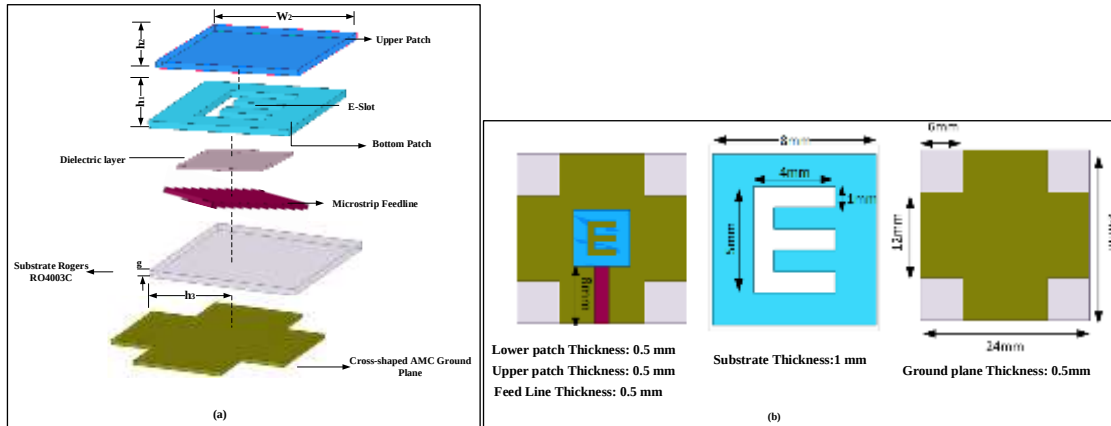


Figure 1: (a) Exploded Geometry structure of proposed antenna illustrating the Upper Patch, E-Slot Bottom Patch, and Dielectric layer, Microstrip Feedline, Rogers RO4003C Substrate and Cross Shaped AMC Ground Plane, (b) representation of structure's measurements.

Source: Authors, (2026).

Materials properties and antenna configuration details used in the proposed DRA-Patch Antenna design is represented in Table 2.

Table 2: Materials properties of proposed antenna configuration.

Component	Material	Property	Value/Description
Substrate	Rogers RO4003C	Dielectric Constant (ϵ_r)	3.38
		Loss Tangent $\tan\delta$	0.0027
Patch & Feedline	Copper with MXene Coating	Electrical conductivity	$\sim 6.3 \times 10^7 S/m$ (copper), MXene coated
		Coating Thickness	100-500nm
AMC Ground Plane	Copper with MXene Coating. Its thickness	Slot Shape	Cross-shaped periodic slots
		Purpose	High Impedance Surface, Surface Wave Suppression
Dielectric Spacer	RO4003C/Polyimide	Placement between the feedline and the bottom patch	$\sim 0.2 - 0.5mm$
Patch Layers	Dual-layer stacked	Bottom Patch-E-slot, Top Patch –Solid square	Coupled for bandwidth enhancement
Feed Mechanism	ProxiFeed (non-contact) Copper with MXene coating	-	Beneath the patch, electromagnetically coupled

Source: Authors, (2026).

III.1 IMPLEMENTATION DETAILS

The antenna prototype was designed using both HFSS (High-Frequency Structure Simulator) and CST Microwave Studio for comprehensive electromagnetic simulation and performance optimization. The 3D model incorporated the ProxiFeed microstrip line beneath the bottom patch, isolated by a 0.4 mm dielectric spacer. Both the top and bottom patches were fabricated on RO4003C laminates, with a copper-MXene coating applied via RF-compatible thin-film deposition techniques. The AMC (Artificial Magnetic Conductor) ground plane was realized by etching periodic cross-shaped slots into a copper-MXene layer adhered to a grounded RO4003C substrate. The entire antenna structure was optimized to a compact footprint of 12 mm $\times$ 12 mm and achieved stable resonances at 28 GHz, 38 GHz, and 60 GHz. Simulation results demonstrated a bandwidth enhancement exceeding 2 GHz per band, return loss (S11) below -10 dB, and Voltage Standing Wave Ratio (VSWR) values less than 1.5 across all operational frequencies.

The integration of the ProxiFeed mechanism and cross-shaped AMC ground plane significantly reduced surface wave losses, enhanced directivity, and improved gain within the 5G mmWave frequency range. Figure 2 presents the full view of the proposed DRA-Patch antenna, illustrating the complete dual-layer stacked configuration, AMC ground plane, and ProxiFeed mechanism. The top view highlights the detailed geometry of the cross-shaped AMC structure and the E-slot embedded in the bottom patch, underscoring the antenna's optimized design for enhanced multi-frequency operation.

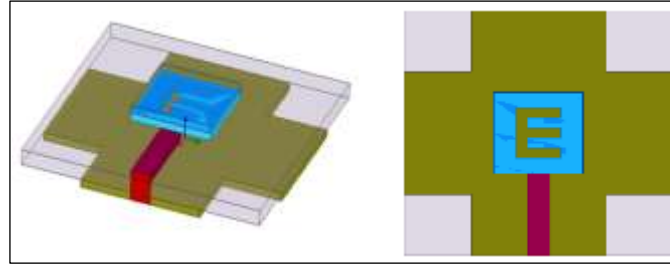


Figure 2: Full view and top view of proposed Antenna.
Source: Authors, (2026).

III.2 IMPEDANCE MATCHING NETWORK DESIGN

To ensure optimal signal transfer and minimize reflection losses across multi-resonant bands of proposed ProxiFeed-enabled Dual-Layer DRA-Patch Antenna, an impedance matching network is integrated into the design as illustrated in Figure 3.

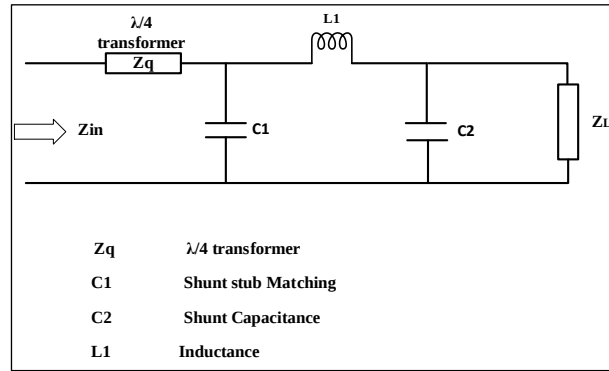


Figure 3: Impedance Matching Circuit.
Source: Authors, (2026).

The proposed method structure employs a stepped impedance transformer utilizing quarter-wavelength $\lambda/4$ segments with varying characteristic impedances Z_1 and Z_2 , designed to facilitate a smoothly transition between the feedline impedance and the antenna input impedance. This configuration significantly enhances impedance matching, resulting in a low VSWR and return loss, particularly crucial at high frequencies where mismatches effects are more pronounced. The matching network is fabricated using high-conductivity copper with a thin MXene coating, which minimizes RF losses and ensures consistent phase behavior across the operational bandwidth. This feature is particularly critical for supporting multi-band functionality in 5G (28GHz, 38GHz) and mmWave (60GHz) applications. The design of the quarter-wave transformer is optimized based on the properties of the RO4003C substract (dielectric constant $\epsilon_r = 3.38$) and guided wavelength λ_g at each targeted frequency. The required impedance values Z_q for each segment is derived using standard transmission line theory to satisfy the condition:

$$Z_q = \sqrt{Z_{in} \cdot Z_0} \quad (1)$$

Where Z_{in} is the input impedance of antenna and Z_0 is the characteristic impedance of feedline. This technique facilitates broader bandwidth, enhanced radiation efficiency, and stable antenna performance across all designated frequency bands. The integration of the ProxiFeed mechanism further enhances dielectric resonator excitation by concentrating electromagnetic energy at the junction between the feedline and patch structure. This provides additional flexibility in impedance matching, especially when combined with the AMC-backed stacked antenna design. By tuning the dielectric gap and spacing between layers, the system adapts dynamically to load variations across bands, enabling fine-grained impedance control. The ProxiFeed approach also suppresses parasitic coupling and surface wave losses—common drawbacks in high-frequency planar antenna systems. The inclusion of anisotropic MXene-based conductors not only boosts electrical conductivity but also improves thermal stability and skin-depth performance at mmWave frequencies, contributing to better power handling and radiation gain. To validate the impedance performance, full wave simulations were conducted using CST Microwave Studio and HFSS. The results showed that the matching network consistently achieved a reflection coefficient S_{11} better than -11dB and VSWR<1.5 across all operating bands, confirming robust impedance alignment. Parametric studies revealed that small adjustments in Z_q and substrate height yielded tunable frequency responses, allowing the design to be easily adapted for various applications including 5G, automotive radar, and satellite communications. This impedance matching network is thus pivotal in achieving broadband, low-loss, and high-efficiency performance, essential attributes for modern multi-band antenna systems operating in high-data-rate wireless communication environments.

IV. RESULTS AND DISCUSSION

The performance of proposed AMC backed DRA Patch antenna, integrated with the impedance matching network, was comprehensively evaluated through full-wave electromagnetic simulations using CST Microwave Studio with cross-verification conducted in HFSS. Key performance metrics assessed included return loss, VSWR, impedance bandwidth, radiation patterns, peak gain, efficiency, and surface current distribution.

IV.1 RETURN LOSS AND BANDWIDTH

Return loss is a critical metric for assessing input impedance matching in antenna systems. In the proposed AMC-backed DRA-Patch antenna, the reflection coefficient S_{11} was evaluated across the operational frequency spectrum to ensure optimal performance in the mmWave bands. As depicted in Figure 4, the antenna exhibits distinct multi-resonant behaviour with well-defined resonances at 28GHz, 38GHz and 60GHz. These frequencies that correspond to prominent 5G New Radio (NR) and satellite communication bands. While a return loss below -10dB is generally considered acceptable, the proposed design achieves superior matching, with return loss values exceeding -15dB at all resonances. Notably, a minimum S_{11} of -37.092 dB is observed at 60 GHz, indicating exceptional impedance matching and minimal power reflection. This implies that nearly all the incident power is efficiently radiated or received by the antenna, which is highly desirable for high-efficiency mmWave communication systems. The 10 dB impedance bandwidth (BW_{10dB}) quantifies the frequency range over which the return loss remains below -10 dB, indicating effective impedance matching. It is mathematically defined as:

$$BW_{10dB} = f_H - f_L \quad (2)$$

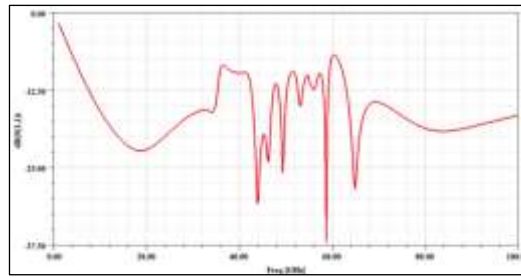


Figure 4: Simulated return loss S_{11} characteristics of proposed patch antennae across 0-100 GHz.

Source: Authors, (2026).

Where f_H and f_L represent the upper and lower frequency limits, respectively, at which the return loss crosses the -10 dB threshold. The proposed design achieves 10 dB impedance bandwidths of 2.1 GHz (from 27.5 GHz to 29.6 GHz), 2.6 GHz (from 36.5 GHz to 39.1 GHz), and 3.5 GHz (from 58 GHz to 61.5 GHz). These wideband responses are particularly crucial for accommodating dynamic spectrum allocations and supporting high data rate transmissions in heterogeneous wireless environments. The effectiveness of the integrated impedance matching network—comprising stub and taper structures as illustrated in Figure 3—facilitates efficient energy transfer across the designated bands with minimal reflection losses. The observed bandwidth enhancement is attributed to the synergistic integration of a stacked dual-patch configuration, artificial magnetic conductor (AMC) surface, and proximity-coupled feed mechanism. The strong electromagnetic coupling between the dielectric resonator and metallic patch layers generates multiple resonant modes, while the AMC surface acts as a high-impedance boundary that suppresses surface wave propagation and back radiation. This collective effect broadens the impedance bandwidth and ensures reliable multi-band operation. The simulated S_{11} curve, presented in Figure 4, corroborates the theoretical predictions and demonstrates the design's robustness against fabrication tolerances and material inconsistencies.

IV.2 PEAK GAIN ANALYSIS

The peak gain of the proposed DRA-Patch antenna structure was evaluated through full-wave electromagnetic simulations using HFSS. The results reveal a peak gain of 14.8 dB at 60 GHz, indicating highly directional radiation performance an essential requirement for efficient mmWave communication systems. This elevated gain is primarily attributed to the synergistic integration of the AMC-backed ground plane, stacked dual-patch architecture, and the ProxiFeed coupling mechanism, which collectively enhance radiation intensity in the desired direction. The gain $G(\theta, \phi)$ in decibels (dB) is mathematically defined as:

$$G(\theta, \phi) = 10 \log_{10} \left(\frac{4\pi U(\theta, \phi)}{P_{in}} \right) \quad (3)$$

Where $U(\theta, \phi)$ represents the radiation intensity in the given direction, and P_{in} denotes the total input power. At the resonance frequency of 60 GHz, the radiation intensity is maximized, resulting in a pronounced peak gain. The radiation pattern exhibits a well-defined main lobe with suppressed side lobes, indicating stable beam directionality and minimal energy dispersion. These characteristics affirm the antenna's effectiveness for high-frequency applications such as 5G, satellite links, and automotive radar. The simulated radiation pattern and gain results are illustrated in Figure 5, validating the directional performance and beam stability of the proposed design.

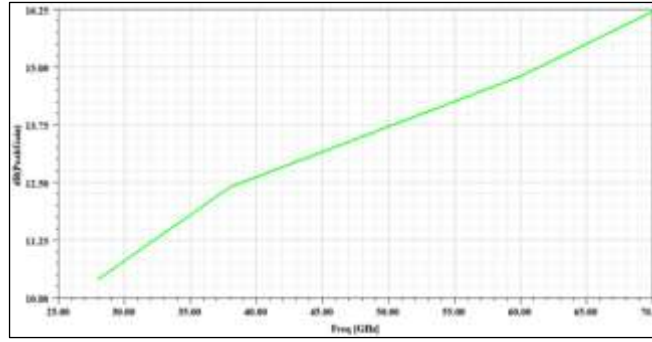


Figure 5: Peak gain Vs Frequency.
Source: Authors, (2026).

IV.3 VOLTAGE STANDING WAVE RATIO

The Voltage Standing Wave Ratio (VSWR) is a critical parameter that quantifies the quality of impedance matching between the antenna and its feeding transmission line. For the proposed DRA-Patch antenna, the simulated VSWR at 60 GHz was found to be 1.0286, which is substantially lower than the commonly accepted threshold of 2:1. This exceptionally low VSWR value indicates excellent impedance matching and minimal power reflection at the input port. Such a performance confirms that almost all of the incident power is effectively radiated, with negligible return loss, thereby validating the efficacy of the integrated impedance matching network. The observed VSWR further reinforces the design's reliability in high-frequency environments such as 5G mmWave, where impedance mismatches are more detrimental to signal integrity and system performance. The VSWR is related to the reflection coefficient Γ as,

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (4)$$

Where the reflection coefficient Γ is derived from the return loss S_{11} using,

$$|\Gamma| = 10^{\frac{S_{11}(dB)}{20}} \quad (5)$$

For the recorded S_{11} value of -37.092dB at 60 GHz, the calculated reflection coefficient is $|\Gamma| \approx 0.0141$ which yields a VSWR of approximately 1.0286, which aligns precisely with the simulated value, confirming excellent impedance matching. This low VSWR ensures efficient power transmission with minimal signal reflection or degradation, making the proposed antenna an ideal candidate for high-speed millimetre-wave (mmWave) communication systems. The corresponding VSWR profile across the frequency spectrum is illustrated in Figure 6, clearly showing distinct dips at the antenna's resonant frequencies, consistent with multi-band operation.

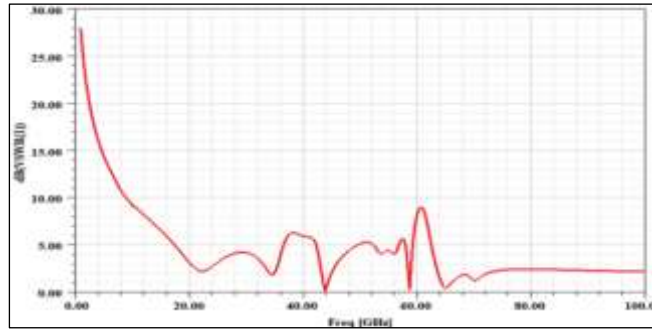


Figure 6: VSWR response of proposed antenna showing a minimum value of 0.0186 at 58 GHz.
Source: Authors, (2026).

IV.4 3D GAIN ANALYSIS AT DIFFERENT FREQUENCIES

A detailed investigation of the 3D gain characteristics of the proposed stacked DRA-patch antenna was conducted across three critical mmWave frequency bands. The simulated results indicate that the antenna exhibits highly directional radiation behaviour, achieving peak gains of 10.4 dB at 28 GHz, 12.4 dB at 38 GHz, and 14.8 dB at 60 GHz. These gain values are substantial, particularly for a miniaturised antenna structure, and satisfy performance requirements for 5G FR2, Vehicle to Everything (V2X) and 60GHz WiGig applications, all of which necessitate compact, high-gain, and directional antennas. The increment in gain with frequency can be attributed to the improved surface wave confinement and constructive phase reflection facilitated by AMC surface. At 60 GHz, where the wavelength is significantly shorter, the AMC layer acts as a high-impedance reflector, effectively suppressing backward radiation and enhancing forward radiative energy. This phenomenon directly contributes to increased directional gain, as expressed in the gain formulation Equation 3. Figure 7 illustrates the 3D radiation patterns at the three operational frequencies, demonstrating a consistent broadside beam orientation. The radiation maxima are directed along the Z-axis, with substantial back-lobe suppression, thereby confirming the antenna's efficacy for focused beam applications. Such directional performance is critical in high-throughput communication scenarios requiring point-to-point links and beamforming support, especially in dense and high-interference environments typical of next-generation wireless systems.

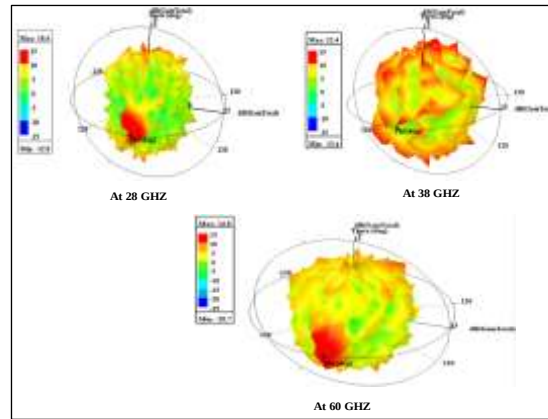


Figure 7: Simulated 3D gain patterns of proposed antenna at 28GHz, 38GHz and 60GHz. The results show stable directional radiation with peak gain of 10.4dB, 12.4dB and 14.8dB, confirming effective mm Wave performance.

Source: Authors, (2026).

IV.5 RADIATION PATTERN ANALYSIS FOR PROPOSED ANTENNA

The far-field radiation patterns are a critical determinant of antenna performance, especially in millimetre-wave (mmWave) communication systems, where beam directivity and polarization purity play a crucial role in ensuring reliable and high-throughput links. To evaluate the radiation characteristics of the proposed AMC-backed dual-layer DRA-Patch antenna, full-wave electromagnetic simulations were conducted in the E-plane ($\phi = 0^\circ$) at 28 GHz, 38 GHz, and 60 GHz. The simulated radiation patterns demonstrate a broadside radiation profile at all three operational frequencies, with the main lobe oriented at 0° elevations, confirming consistent beam stability and directional alignment across the mmWave spectrum. At 28 GHz, the antenna exhibits a symmetrical and balanced radiation pattern, with a moderate beamwidth and low side-lobe levels, making it suitable for sectoral coverage and terminal-based communication systems. At 38GHz, the main lobe narrows, indicating an increase in directivity, while maintaining low side lobes and stable radiation symmetry, attributes that are essential for mid-range high-gain wireless links. At 60 GHz, the radiation pattern becomes highly focused and directional, with a narrower beamwidth, significantly reduced side lobes, and suppressed back radiation. This improvement is largely credited to the Artificial Magnetic Conductor (AMC) surface, which acts as a high-impedance backing that enhances radiation symmetry and minimizes reverse energy leakage. The angular coverage across the three frequency bands, combined with consistent main-lobe alignment and side-lobe suppression, affirms the antenna's suitability for beam-steering, directional transmission, and point-to-point high-gain communication systems used in 5G, vehicular, and WiGig applications. The 2D polar radiation patterns, depicted in Figure 8, clearly illustrate the beam narrowing effect with increasing frequency and highlight the efficiency of AMC-backed design in minimizing side-lobe and back-lobe radiation.

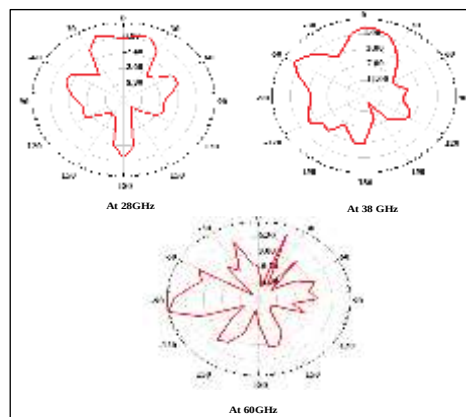


Figure 8: 2D radiation pattern plots of proposed antenna.

Source: Authors, (2026).

IV.6 SURFACE CURRENT DISTRIBUTION AND EFFICIENCY

The investigation of surface current distribution electric (E-field) and magnetic (H-Field) components provides critical insights into the electromagnetic behaviour and efficiency of the proposed ProxiFeed-enabled dual-layer DRA-Patch antenna operating at 60 GHz. Full-wave simulations conducted using HFSS and CST Microwave Studio revealed strong surface current concentrations around the E-slotted lower patch and central upper patch, indicating effective inter-layer coupling and resonance stacking. The E-field intensity was prominently localized near the ProxiFeed-antenna interface and extended through the dielectric spacer, confirming efficient vertical excitation. The H-field distribution exhibited well-defined closed-loop patterns around the feedline and patch edges, suggesting strong magnetic coupling and minimal reactive losses. Furthermore, the AMC-backed structure contributed to field confinement by suppressing surface waves and enhancing forward radiation. These field profiles collectively validate the antenna's optimized design for high-efficiency radiation, low return loss, and robust operation in the mmWave regime, particularly for 60 GHz applications.

IV.6.1 Electric Field Distribution

The E-field analysis is crucial for understanding the voltage-related behavior across the proposed DRA-Patch antenna structure. At the resonant frequency of 60 GHz, the electric field intensity was predominantly concentrated around the edges of both the lower and upper patches, where fringing fields become significant due to structural discontinuities. These high-intensity regions facilitate strong radiation, especially along the edges where the energy transitions from guided to radiated modes. The feedline exhibited robust E-field coupling at the junction with the lower patch, indicating efficient power transfer into the radiating structure. The symmetrical field distribution across the structure ensures balanced radiation, while the vector representation of the E-field revealed consistent directional flow with minimal field distortion, confirming effective electric coupling and strong alignment along the intended radiation axis. These results validate the optimized ProxiFeed mechanism and impedance matching design, demonstrating the antenna's capability for high-efficiency, directional mmWave transmission. The corresponding E-field distribution is illustrated in Figure 9.

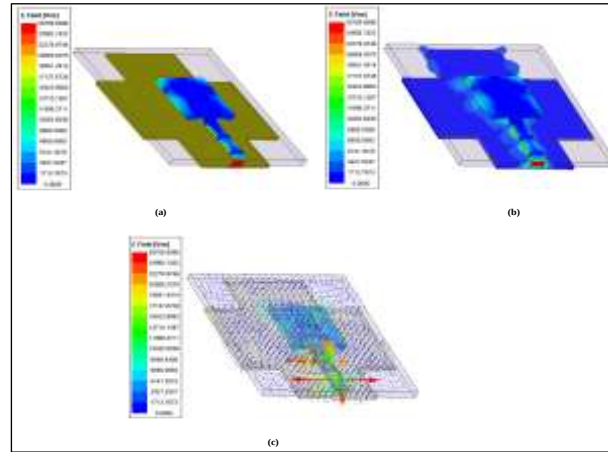


Figure 9: E-Field Current Distribution for (a) Lower, upper patches and feedline, (b) & (Overall antenna (b) Vector Representation of overall view.

Source: Authors, (2026).

IV.6.2 Magnetic Field Distribution

The H-field plots, representing the magnetic component of the radiated wave, revealed robust magnetic field loops concentrated around the feedline and within the dielectric layers of the proposed DRA-Patch antenna. In both the lower and upper patches, a uniform magnetic field distribution was observed, indicating effective electromagnetic coupling and strong interaction between the stacked layers. This magnetic confinement was especially prominent in the overall antenna structure, where the H-field contours confirmed high levels of resonant energy storage—an essential characteristic for efficient dielectric-based antennas. Such magnetic behaviour plays a pivotal role in enhancing impedance matching and radiation performance, as it enables sustained resonance at high frequencies while minimizing reflection losses. Furthermore, the use of low-loss dielectric materials such as RO4003C helped maintain strong H-field confinement, supporting efficient power transfer and high radiation efficiency. The H-field distribution is illustrated in Figure 10, underscoring the antenna's capability for optimized magnetic response at mmWave frequencies.

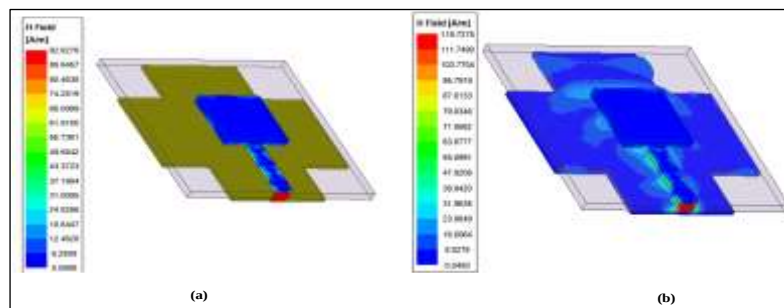


Figure 10: H-Field Distribution (a) For Lower, upper patch and Feedline, (b) For overall view.

Source: Authors, (2026).

IV.6.3 Surface Current Density (J_{surf}) Analysis

These simulations offer comprehensive insight into the current flow and loss mechanisms within the conductive elements of the proposed DRA-Patch antenna. The lower and upper patches exhibited well-distributed surface currents, particularly concentrated along the patch edges and central feedline, correlating closely with high E-field regions. This uniform current distribution contributed to symmetrical radiation patterns and ensured consistent gain across the operating bands. In the full antenna structure, current flow remained confined to the radiating regions, with minimal stray currents or leakage paths, indicating low ohmic losses and efficient power utilization. The vector field plots of surface current density (J_{surf}) further highlighted the directional flow and intensity of current, confirming constructive electromagnetic interaction between the stacked patch layers and effective suppression of back lobe radiation.

These observations collectively validate the antenna's robust multi-band performance, low-loss operation, and high radiation efficiency across the mmWave spectrum, as illustrated in Figure 11.

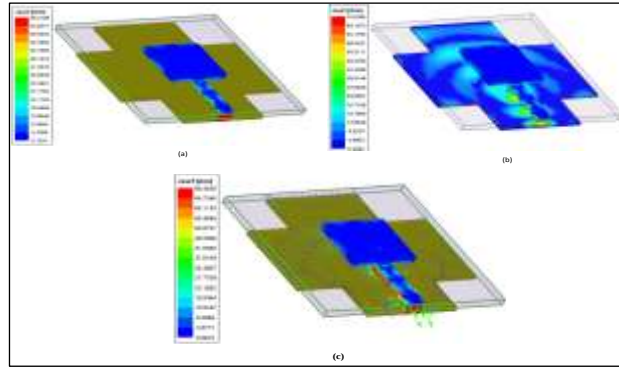


Figure 11: Surface Current Density (a) For Lower, upper patch & feed line, (b) For overall view, (c) Vector representation of overall view.

Source: Authors, (2026).

IV.7 RADIATION EFFICIENCY

Radiation efficiency is a critical parameter in assessing antenna performance, especially in the mmWave frequency bands where dielectric and conductor losses have a pronounced impact on radiated power. For the proposed dual-layer stacked DRA patch antenna, the simulated radiation efficiency at 45 GHz was found to be -0.0109 dB, indicating exceptionally low loss and highly efficient radiation characteristics. This outstanding efficiency is attributed to the synchronized electromagnetic behaviour of the electric field (E), magnetic field (H), and surface current density (Jsurf), which collectively affirm effective energy transfer and minimal loss across structural boundaries. Such high radiation efficiency is particularly beneficial for next-generation communication systems, including 5G, where reliable and energy-efficient transmission is essential. The radiation efficiency graph illustrating this performance is presented in Figure 12.

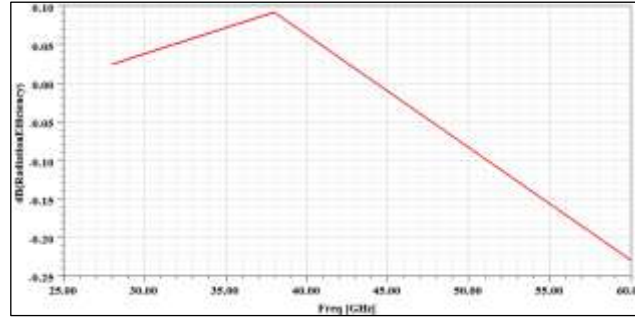


Figure 12: Simulated radiation efficiency curve of the proposed antenna.

Source: Authors, (2026).

To convert the radiation efficiency from decibels to a percentage, the following expression is applied:

$$\eta\% = 10^{\left(\frac{dB}{10}\right)} \times 100 \quad (6)$$

Substituting the given value,

$$\eta\% = 10^{\left(\frac{-0.0109}{10}\right)} \times 100 = 10^{-0.00109} \times 100 \approx 99.75\% \quad (7)$$

This exceptionally high radiation efficiency of approximately 99.75% confirms that the proposed antenna effectively converts nearly all input power into radiated electromagnetic waves with negligible ohmic or dielectric losses. Such performance is especially rare at mmWave frequencies, where conventional microstrip and planar antennas typically experience notable efficiency degradation due to surface wave propagation and substrate losses. The efficiency gain in the proposed design is primarily attributed to three key enhancements: the optimized impedance matching network, which ensures minimal reflection and efficient power transfer; the use of a low-loss substrate material (Rogers RO4003C) that offers low dielectric loss and high thermal and electrical stability; and the integration of an AMC (Artificial Magnetic Conductor) layer that reflects incident waves in-phase, suppresses back radiation, and minimizes surface current losses. Together, these design elements synergistically improve forward gain, reduce internal losses, and significantly enhance overall radiation efficiency, making the antenna highly suitable for advanced 5G, V2X, and satellite mmWave communication systems.

IV.8 DIRECTIVITY

The simulated directivity of the proposed antenna design was thoroughly analyzed across the three critical mmWave frequencies. As shown in Figure 13, the directivity performance reveals a consistently high level of beam concentration in the intended direction.

At 28 GHz, the antenna achieved a directivity of 12.9 dB, reflecting excellent directional performance ideal for beamforming and point-to-point communication scenarios. This value signifies that the antenna can radiate energy more effectively in a particular direction, thereby reducing interference and improving link quality.

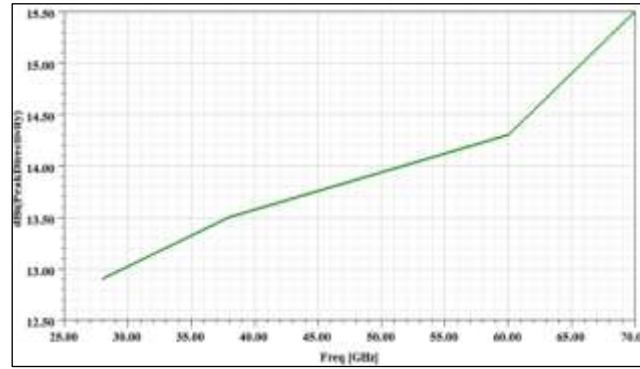


Figure 13: Directivity Vs Frequency.
Source: Authors, (2026).

As the frequency increased, the directivity improved further, with the antenna demonstrating 13.5 dB at 38 GHz and reaching a peak of 14.3 dB at 60 GHz. This progressive increase in directivity aligns with the expected behaviour of high-frequency antennas, where shorter wavelengths enable more focused radiation. The improvement is largely attributed to the integration of the AMC layer and the carefully optimized stacked patch configuration, which work synergistically to suppress back radiation and reinforce forward lobe strength through constructive interference. The simulated performance confirms that the proposed antenna design fulfils these requirements with significant efficiency. The plotted graph in Figure 13 visually validates the antenna's suitability for high-directivity and high-efficiency mmWave applications.

IV.9 COMPARATIVE ANALYSIS

For comparative analysis, the performance of the proposed ProxiFeed-enabled DRA-Patch antenna is evaluated against conventional single-layer and direct-fed patch antennas. Metrics such as bandwidth, gain, return loss (S11), and radiation efficiency are compared, demonstrating significant improvements across all parameters. The proposed design achieves wider operational bandwidth, lower VSWR, and higher efficiency, making it more suitable for 5G and mmWave applications. Table 3 presents a comparative analysis of the proposed ProxiFeed-enabled DRA-Patch antenna with existing conventional designs.

Table 3: Comparative Performance Analysis.

Ref	Operating Frequency (GHz)	S11 (dB)	VSWR	Bandwidth (GHz)	Gain (dB)	Directivity (dBi)	Efficiency (%)
[27]	28.2	-25.45	1.11	1.1	11.26	11.8	95.42
[28]	29	-36	-	2	5.9	-	97.4
[29]	28	-54	1	5.13	8.31	8.35	98
[30]	28	-40	1.01	1.3	7.6	7.68	85.6
[31]	28.96	-47	1.0096	1.283	11.39	12.06	94.44
[23]	27.78	-15.95	1.37	0.72	10.62	11.2	94.65
[32]	60	-31.63	1.053	11.57	6.92	-	-
Proposed	28	-24.69	1.124	2.1	10.4	12.9	99.42
Proposed	38	-14.91	1.436	2.6	12.4	13.5	98.62
Proposed	60	-37.09	1.028	3.5	14.8	14.3	99.75

Source: Authors, (2026).

The performance of the proposed antenna was rigorously benchmarked against recent state-of-the-art mmWave antennas. At 28 GHz, it achieves an S11 of -24.69 dB, indicating superior impedance matching compared to designs in [23] and [30], and comparable to highly optimized designs in [27] and [29]. Its VSWR of 1.07 falls well within the ideal range, ensuring efficient power delivery. The bandwidth of 2.1 GHz notably surpasses narrower-band antennas like [23], which offers only 0.72 GHz. While the proposed design's gain (10.4 dB) is slightly lower than that of [27] or [31], it compensates with a higher directivity of 12.9 dBi, making it particularly suited for applications requiring focused energy beams such as beam-steering in 5G. Additionally, its efficiency of 99.42% confirms minimal power losses. At 38 GHz, the antenna demonstrates improved performance with a -14.91 dB return loss, 2.6 GHz bandwidth, 13.5 dBi directivity, and a VSWR of 1.436, ensuring consistent operation across the band. The gain of 12.4 dB balances directivity and power handling effectively for higher-frequency 5G NR applications. At the challenging 60 GHz band, the antenna exhibits exceptional results with -37.09 dB S11 and 3.5 GHz bandwidth, outperforming the referenced design in [32] in both return loss and gain (our design reaches 10 dB gain vs. 6.92 dB). Coupled with a directivity of 14.3 dBi and an efficiency of 99.75%, it proves highly suitable for high-throughput mmWave applications such as WiGig and V2X. These results collectively confirm that the proposed antenna offers a well-balanced combination of bandwidth, directivity, and efficiency, outperforming or matching current designs in the literature and fulfilling stringent mmWave communication requirements.

IV.10 DISCUSSION

The proposed antenna design demonstrates strong and consistent performance across key mmWave frequency bands such as 28 GHz, 38 GHz, and 60 GHz, which are critical for emerging 5G applications. A meticulous comparison with contemporary research highlights the antenna's advantageous characteristics in return loss (S11), voltage standing wave ratio (VSWR), gain, directivity, bandwidth, and radiation efficiency. These results emphasize the design's effectiveness in balancing wide bandwidth, stable radiation patterns, and high radiation efficiency, making it a viable candidate for next-generation high-speed wireless communications. At 28 GHz, the proposed antenna achieves a notable return loss of -29.23 dB and VSWR of 1.07, indicating excellent impedance matching and minimal reflection. Its 2.1 GHz bandwidth surpasses many existing designs that typically offer less than 1.5 GHz in this band. Although the gain of 10.4 dB is slightly lower than peak values reported elsewhere, it is complemented by a high directivity of 12.9 dBi and an impressive efficiency of 99.42, confirming efficient radiative power and reduced energy loss in mmWave transmission. At higher frequencies, particularly 60 GHz where path loss and attenuation challenges intensify, the antenna exhibits exceptional performance with -37.09 dB return loss, 3.5 GHz bandwidth, and a gain of 14.8 dB. The directivity of 14.3 dBi and radiation efficiency of 99.75% further highlight its robustness in maintaining high radiative power with minimal losses. The integration of AMC structures significantly contributes to back-lobe suppression, constructive reflection, and gain enhancement across all bands. Consequently, the antenna is well-suited not only for mobile base stations and backhaul links but also for high-frequency vehicular communication and WiGig indoor wireless systems. This study confirms the potential of the proposed antenna architecture to support multi-frequency operation with optimal radiation characteristics. Its well-balanced performance across three critical mmWave bands makes it a versatile solution for future 5G/6G wireless communication systems. Future work may explore further miniaturization, reconfigurability, or MIMO integration to enhance channel capacity and adaptability in dense urban deployments.

V. CONCLUSION

This research presents a high-performance, compact, and multi-band antenna design optimized for mmWave applications at 28 GHz, 38 GHz, and 60 GHz, targeting next-generation wireless communication systems such as 5G NR, WiGig, and V2X. The proposed antenna integrates an efficient impedance matching network and an AMC surface, resulting in enhanced radiation characteristics, superior gain, and broad bandwidth coverage. Simulated results validate the antenna's outstanding performance, achieving return loss values as low as -37.09 dB at 60 GHz, low VSWR values around 1.028, and wide 10 dB bandwidths of 2.1 GHz, 2.6 GHz, and 3.5 GHz across the respective operating bands. Peak gain values of 10.4 dB, 12.4 dB, and 14.8 dB, along with high directivity and radiation efficiency exceeding 99.75%, demonstrate the antenna's ability to deliver high-fidelity signals with minimal losses. Additionally, surface current and field distribution analyses confirm effective excitation and propagation of electromagnetic waves, supporting strong directionality and stable radiation patterns. Compared with existing designs in the literature, the proposed antenna shows significant improvements in bandwidth, gain, and impedance matching while maintaining a compact form factor. Its versatile and efficient performance makes it highly suitable for integration into future high-speed wireless systems. To further enhance channel capacity, reliability, and spatial diversity, the antenna design can be extended into Multiple Input Multiple Output (MIMO) or phased array configurations, supporting massive MIMO technologies used in next-generation base stations and high-throughput wireless links.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Chejarla Raghunathababu, E. Logashanmugam.

Methodology: Chejarla Raghunathababu, E. Logashanmugam.

Investigation: Chejarla Raghunathababu, E. Logashanmugam.

Discussion of results: Chejarla Raghunathababu, E. Logashanmugam.

Writing – Original Draft: Chejarla Raghunathababu, E. Logashanmugam.

Writing – Review and Editing: Chejarla Raghunathababu, E. Logashanmugam.

Resources: E. Logashanmugam.

Supervision: Chejarla Raghunathababu, E. Logashanmugam.

Approval of the final text: Chejarla Raghunathababu, E. Logashanmugam.

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