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Design and Analysis of a Compact Multiband Millimeter-Wave Patch Antenna for High-Frequency Wireless Applications

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Abstract- A compact planar antenna operating in the millimeter-wave frequency range is presented in this work for high-frequency wireless communication applications. The proposed antenna features a stepped and slotted radiating patch with a centrally fed microstrip line, designed to achieve multiband and broadband performance while maintaining a small physical footprint of 12 mm × 10 mm. The antenna geometry is carefully optimized to enhance the effective current path, resulting in improved impedance matching and radiation efficiency across a wide frequency range. Detailed electromagnetic analysis, including electric and magnetic field distributions, surface current behavior, and far-field radiation patterns, confirms stable radiation characteristics at multiple resonant frequencies. The antenna demonstrates good impedance matching with $|S_{11}|$ below -10 dB and VSWR less than 2 over most of the 35-100 GHz band. The achieved peak directivity of up to 11 dBi at higher frequencies highlights the antenna's suitability for millimeter-wave applications such as 5G communication, short-range high-speed links, and emerging wireless systems

Keywords - Millimeter-wave antenna, Compact planar antenna, Microstrip antenna, Multiband communication, Broadband antenna, 5G wireless communication, High directivity, Impedance matching.

I. INTRODUCTION

The increasing demand for high-data-rate wireless communication has accelerated the adoption of millimeter-wave frequency bands, particularly for applications such as 5G networks, point-to-point links, and advanced sensing systems. Millimeter-wave communication offers large available bandwidth and high spectral efficiency; however, antenna design at these frequencies presents several challenges, including compact size requirements, impedance matching, radiation stability, and fabrication sensitivity.

Microstrip patch antennas are widely used in high-frequency systems due to their low-profile structure, ease of integration, and compatibility with planar fabrication technologies. Despite

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these advantages, conventional patch antennas typically suffer from narrow bandwidth and limited multiband capability. To overcome these limitations, various design techniques such as slot loading, stepped geometries, defective ground structures, and optimized feeding mechanisms have been proposed to enhance bandwidth and radiation performance without increasing antenna size.

In this work, a compact millimeter-wave antenna with a modified radiating structure is proposed. The antenna employs a stepped and slotted patch geometry combined with a central feed line to improve impedance matching and extend the effective electrical length of the radiating element. The design supports multiple resonant modes across a wide frequency range, as confirmed through S-parameter analysis, field distribution studies, and radiation pattern evaluation. The antenna's performance is analyzed at representative frequencies, including 45 GHz and 75 GHz, to demonstrate its suitability for broadband and multiband millimeter-wave applications

II. ANTENNA GEOMETRY

The antenna is designed with a compact footprint of 12 mm × 10 mm, making it suitable for millimeter-wave applications where miniaturization and easy integration are essential. The lower portion of the structure represents the substrate and feeding region, with a thickness of approximately 1.67 mm, which plays a key role in impedance matching and electromagnetic field confinement.

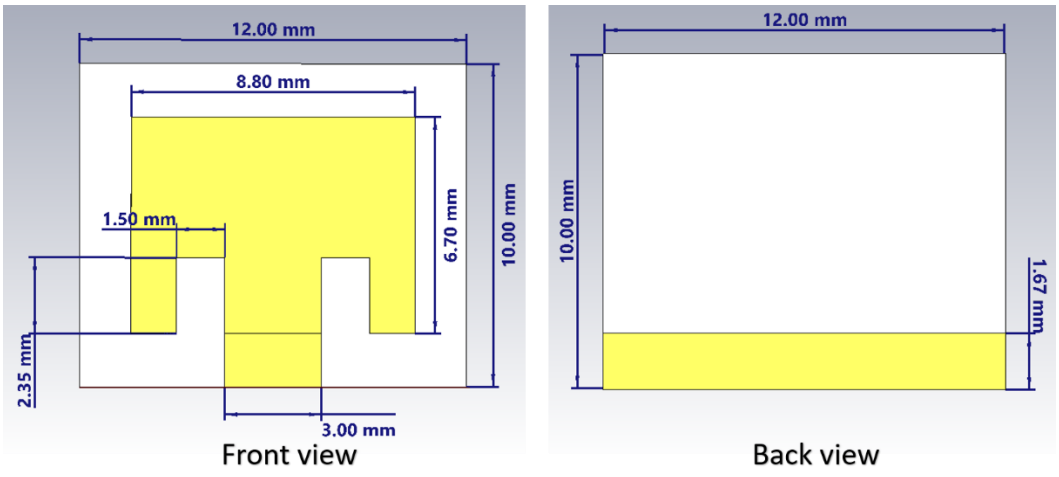

Figure 1. Design layout of the proposed antenna

The radiating patch, highlighted in the figure, has an effective width of 8.8 mm and a height of 6.7 mm. To enhance bandwidth and matching performance, a stepped and slotted geometry is

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introduced at the lower section of the patch. This modification increases the electrical path length without enlarging the physical size of the antenna. A centrally positioned microstrip feed line of 3.0 mm width is used to efficiently excite the radiating element.

Additionally, asymmetric cut sections on either side of the feed help redistribute surface currents, resulting in stable radiation characteristics and controlled side-lobe behavior at higher frequencies. Overall, the compact geometry combined with the stepped patch and central feeding enables broadband operation with improved radiation efficiency, making the antenna well suited for high-frequency wireless communication system.

The design evolution of the antenna was carried out in multiple stages to achieve the final optimized structure, as illustrated in Figure 2.

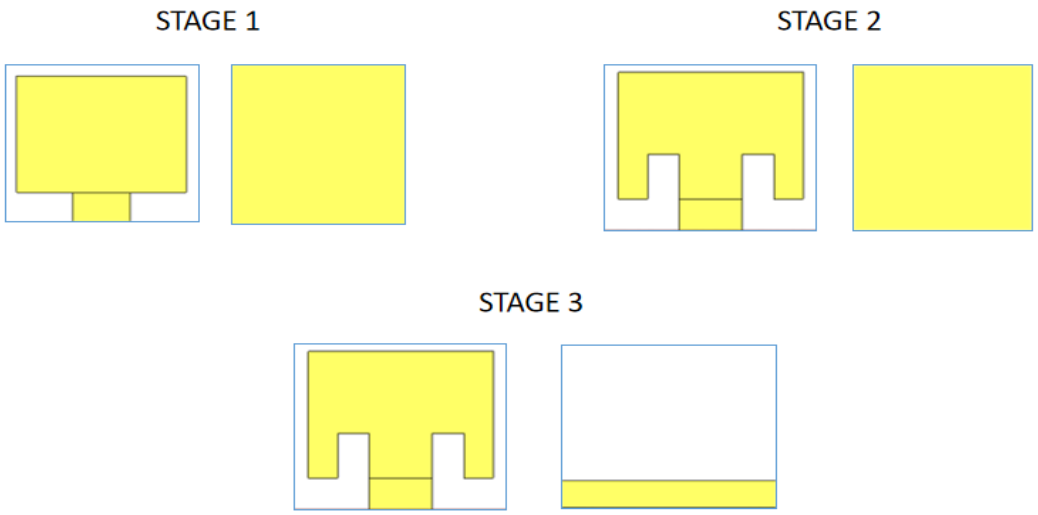

Figure 2. Evolution stages of the proposed antenna

• Stage 1:

In the first stage, a conventional rectangular microstrip patch antenna fed by a 50 Ω microstrip line with a full ground plane is used as the initial reference design.

• Stage 2:

In the second stage, inset sections are introduced in the radiating patch to improve impedance matching and modify the current distribution, resulting in enhanced bandwidth.

• Stage 3:

In the final stage, the ground plane is modified to a partial ground structure, which improves coupling between the feed and radiating patch, leading to wider impedance bandwidth and more stable radiation characteristics.

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III. SIMULATED RESULTS

S-Parameters (|S_{11}|) vs Frequency

The magnitude of the reflection coefficient (|S_{11}|) over the frequency range of 35–100 GHz is illustrated in this figure. Several distinct resonant modes can be observed where the |S_{11}| value drops well below −10 dB, indicating efficient impedance matching at those frequencies. Deep resonance minima are noticeable around approximately 47 GHz, 59 GHz, 74 GHz, and 90 GHz, with the lowest return loss reaching nearly −28 dB. These resonances confirm that the proposed antenna supports multiband operation in the millimeter-wave region. The wide regions where |S_{11}| remains below −10 dB further demonstrate stable antenna performance and effective power transfer between the feed and the radiating structure.

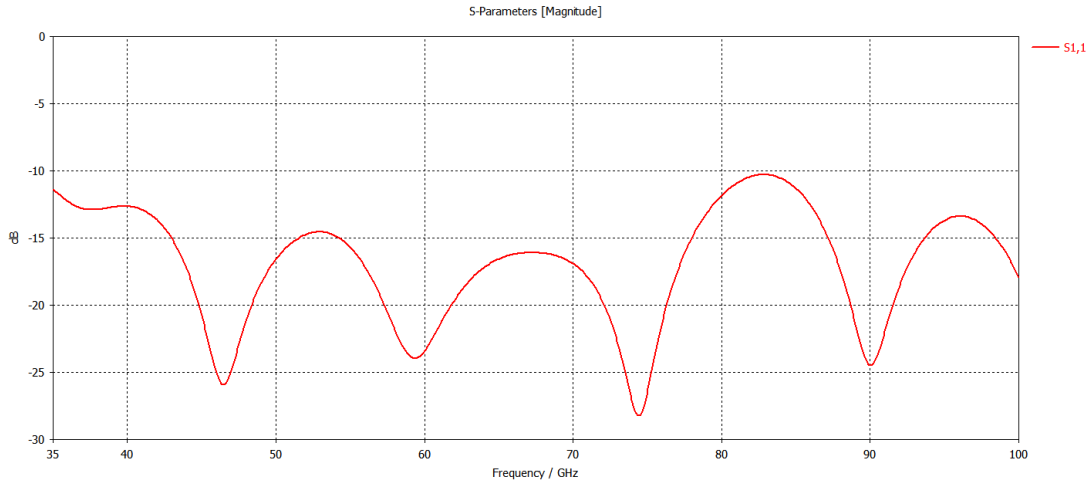

Figure 3. Simulated return-loss (S_{11}) characteristics of the proposed antenna.

Voltage Standing Wave Ratio (VSWR) vs Frequency

The VSWR characteristics of the proposed antenna across the operating band are presented in this figure. It is observed that the VSWR remains below 2 for most of the frequency range from 35 GHz to 100 GHz, which satisfies the standard requirement for practical antenna operation. Minimum VSWR values close to unity are obtained at the resonant frequencies, corresponding well with the |S_{11}| minima observed in the return-loss plot. This behavior confirms good impedance matching between the antenna and the transmission line, resulting in reduced signal reflections and improved radiation efficiency across multiple millimeter-wave bands.

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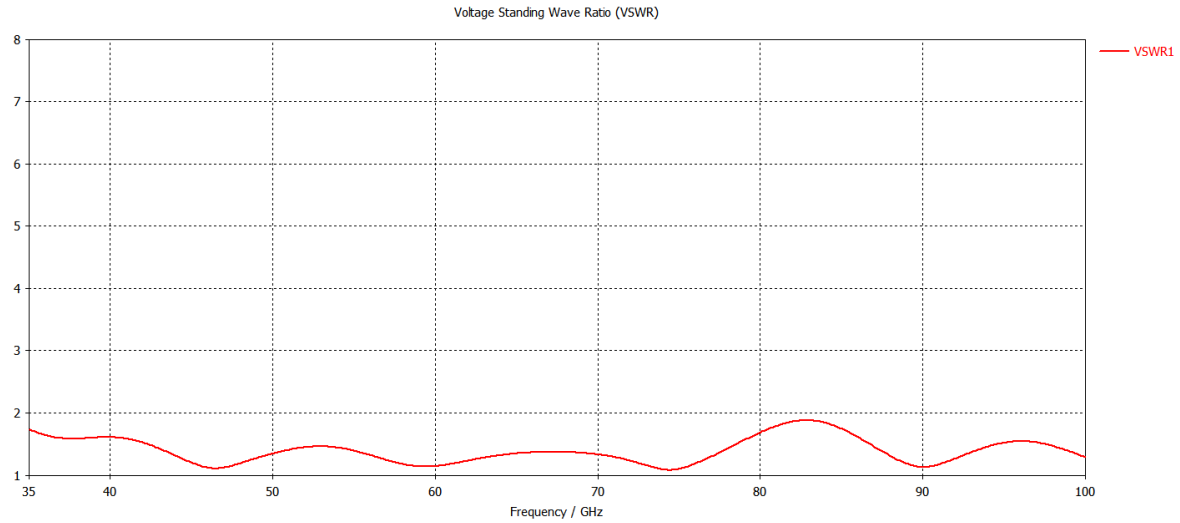

Figure 4. VSWR of proposed Antenna.

Input Impedance (Z_{11}) vs Frequency

The variation of the input impedance magnitude (Z_{11}) with frequency is shown in this figure. The impedance oscillates around the desired 50 Ω reference value, particularly near the resonant frequencies identified in the S-parameter analysis. At these frequencies, the impedance approaches close to 50 Ω, which explains the observed low reflection coefficient and VSWR values. The smooth variation of impedance over the operating range indicates stable electromagnetic behavior of the antenna structure and validates the effectiveness of the proposed design in achieving proper impedance matching in the millimeter-wave spectrum.

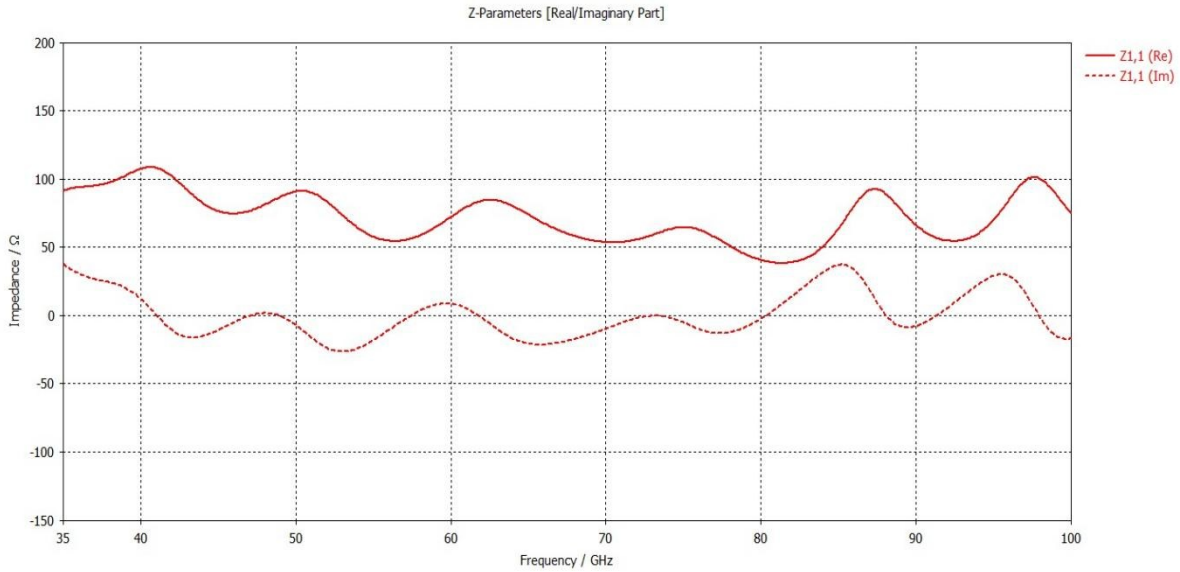

Figure 5. Input Impedance of proposed Antenna.

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2D and 3D Far-Field Radiation Patterns

The Figure 6.A illustrates the far-field radiation characteristics of the antenna at 45 GHz. The main radiation lobe is directed at approximately 106°, with a peak directivity of 8.98 dBi. The measured 3-dB angular width of 58.4° reflects a slightly wider beam compared to the broadband case, which can be attributed to frequency-dependent current distribution on the radiating surface. The side-lobe level of −5.3 dB indicates improved suppression of secondary lobes, enhancing radiation purity at this frequency. The Figure 6.B shows the antenna radiation pattern at 75 GHz, where the antenna achieves a higher peak directivity of approximately 11 dBi. The main beam is oriented around 76°, and the 3-dB beamwidth is about 57.9°. The increase in directivity at higher frequency is mainly due to electrical size enlargement of the antenna structure. Although additional minor lobes appear, the side-lobe level remains controlled at -6.3 dB, confirming stable radiation performance even at millimeter-wave frequencies. The Figure 6.C depicts the broadband far-field directivity of the antenna in the Φ = 90° plane. The antenna exhibits a well-defined main lobe with a peak directivity of approximately 8.18 dBi, oriented around 100°. The 3-dB beamwidth of about 49.7° indicates a moderate directional behavior suitable for point-to-point or short-range communication systems. Side-lobe levels are maintained below -2.9 dB, demonstrating effective suppression of unwanted radiation and improved radiation efficiency across the operating band.

This 3D radiation shown in Figure 7.A plot provides a comprehensive visualization of the antenna's spatial radiation behavior at 45 GHz. The dominant radiation is observed along the main lobe, confirming directional radiation with a peak directivity close to 9 dBi. The smooth radiation envelope indicates good impedance matching and minimal power loss. The orthogonal theta and phi planes further demonstrate symmetrical radiation behavior, validating the antenna's suitability for directional wireless applications.

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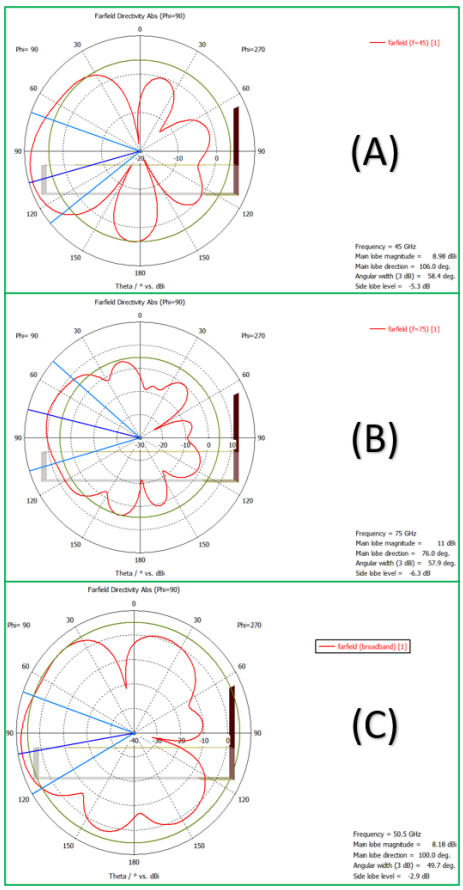

Figure 6 (A-C). Simulated 2D far-field radiation patterns of the antenna

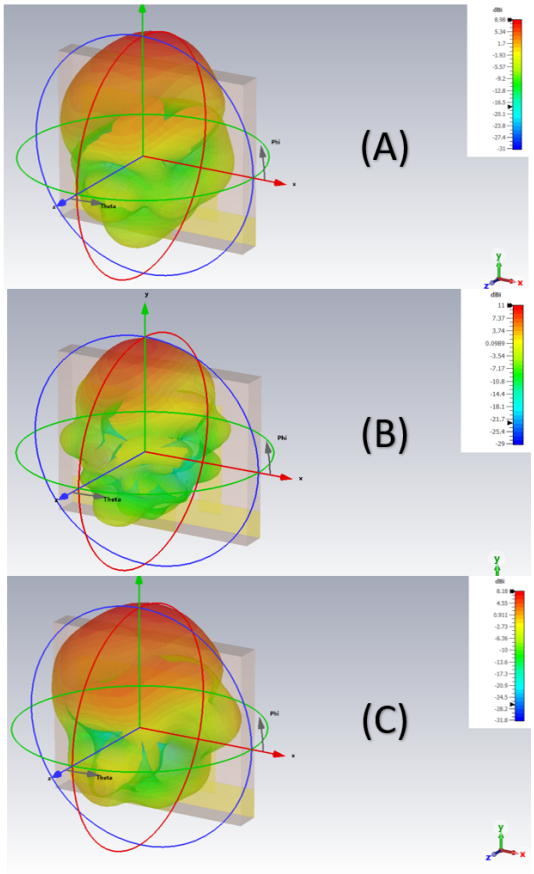

Figure 7(A-C) 3D far-field radiation patterns of the antenna

The **Figure 7.B** illustrates the 3D far-field radiation pattern at **75 GHz**. Compared to lower frequencies, the radiation becomes more focused, achieving a peak directivity of approximately **11 dBi**. The presence of mild pattern distortion is expected at higher frequencies due to increased sensitivity to geometry and material properties. Nevertheless, the main lobe remains dominant, confirming reliable radiation characteristics across the millimeter-wave band. This **Figure 6.C** presents the broadband three-dimensional far-field radiation pattern of the antenna at **50.5 GHz**. The antenna achieves a directivity of approximately **8.18 dBi**, with a stable and well-distributed radiation shape across theta and phi planes. The smooth color transition indicates uniform radiation without abrupt nulls, demonstrating consistent broadband performance. This confirms the antenna's ability to support wideband millimeter-wave communication systems.

Surface Current Distribution

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The surface current distribution at 45 GHz is shown on both the front and back sides of the proposed antenna structure shown in **Figure 8 A** and **Figure 8 B**. A strong concentration of current is observed along the feed line and the central radiating region, indicating effective excitation of the fundamental resonant mode. The current flows smoothly across the patch edges and couples efficiently with the ground plane, as seen from the back-side current distribution. The relatively uniform current spread confirms that the antenna radiates efficiently at this frequency, which is consistent with the low return loss and good impedance matching obtained at 45 GHz.

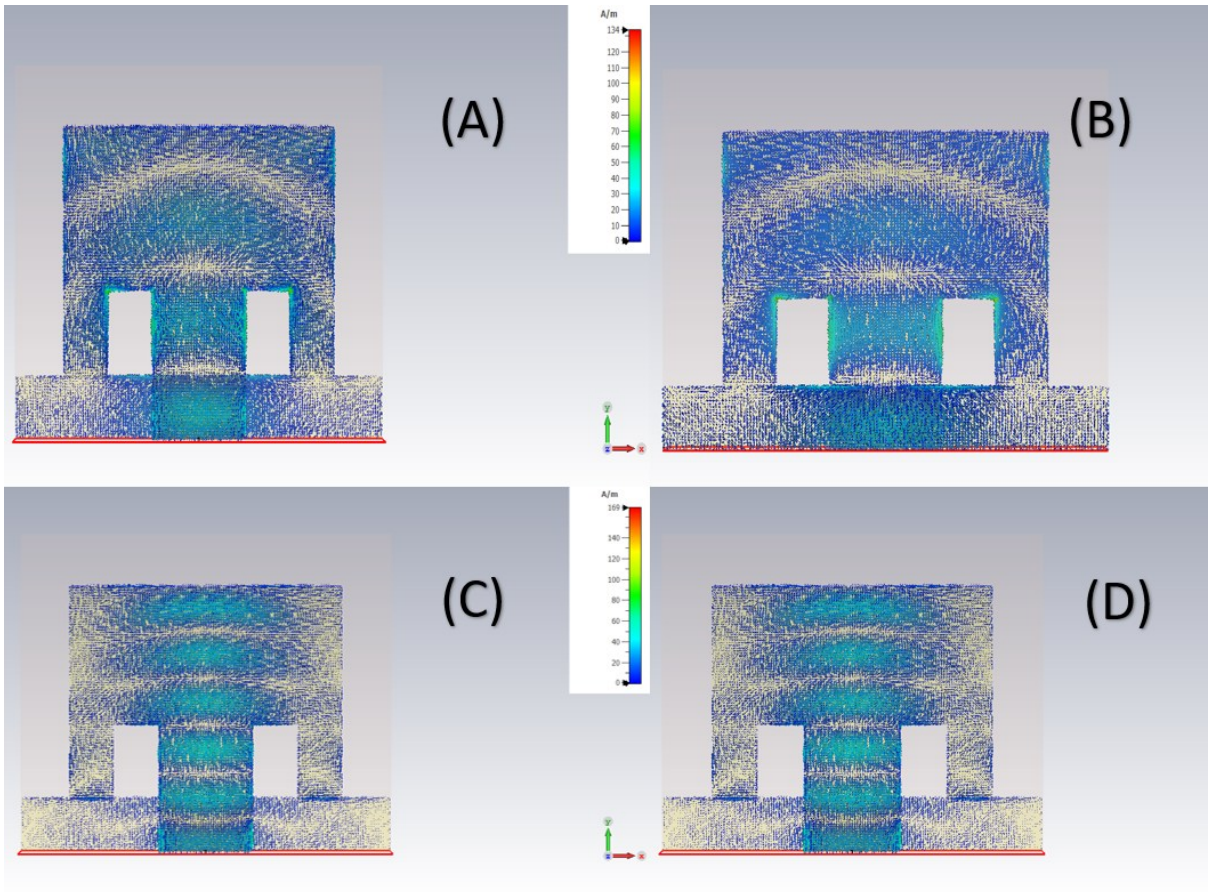

Figure 8. (A&B) front and back view of surface current distribution at 45 GHz, (C&D) front and back view of surface current distribution at 75 GHz.

The surface current distribution at 75 GHz is shown on both the front and back sides of the proposed antenna structure shown in Figure 8 C and Figure 8 D, at 75 GHz, the surface current distribution exhibits a more complex pattern compared to the lower frequency case, reflecting the excitation of higher-order resonant modes. The current is strongly localized around the modified patch sections and the edges of the slots, indicating their significant role in achieving

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multiband operation. On the back side, enhanced current density is observed near the defective ground structure, which contributes to improved impedance matching and bandwidth enhancement at higher millimeter-wave frequencies. The increased current intensity and redistribution validate the antenna's ability to support stable radiation at 75 GHz.

Table 1. Comparison Between the Proposed Antenna and Reported Works

Author / Year	Antenna Type / Geometry	Frequency Band (GHz)	Peak Gain (dB)	Substrate Used	Size (mm³)	Key Features / Innovations
Johari et al., 2018 [1]	Rectangular patch array	28 GHz	8.39 dB	Rogers substrate	26.5 × 20.4 × —	Inset-fed compact array for 5G applications
Nahas et al., 2022 [2]	Slotted microstrip patch	26–28 GHz	7.41 dB	Rogers substrate	Compact structure	Slot-based design for high gain in 5G bands
Dejen et al., 2023 [3]	Optimized quadband patch	mm-wave bands	High gain reported	Standard microwave substrate	Compact	Genetic-algorithm-optimized patch geometry
Didi et al., 2023 [4]	Modified rectangular patch	60 GHz	~7–9 dB (typical reported range)	Microwave substrate	Compact	T-shaped perturbation for bandwidth enhancement
Gaid et al., 2024 [5]	Rectangular microstrip patch	28 GHz	High gain reported	Low-loss substrate	Low-profile	Simple geometry with improved radiation efficiency
Zakariyya et al., 2024 [6]	Patch with modified ground	28 GHz	8.19 dB	Rogers RT5880	Compact	U-shaped ground element for bandwidth improvement
Mohammed et al., 2025 [7]	Modified circular patch	45–58 GHz	Up to 12.5 dB	Rogers RT5880	10 × 9 × 0.508	High efficiency and wide impedance bandwidth
Krishna et al., 2025 [8]	Multiband patch antenna	24–31 GHz	High gain reported	Microwave substrate	Compact	Multiband operation for 5G/6G
Soothar et al., 2025]9]	Trowel-shaped radiator	15–54 GHz	9.67 dB	Rogers RT5880	Electrically compact	Wideband, high efficiency, tapered feed
Al-Hiti et al., 2025 [10]	Multiband mm-wave patch	29–138 GHz	High efficiency	Rogers substrate	Compact	Broadband and multiresonant design
Proposed Antenna	Inset-modified microstrip patch antenna with partial ground	35–100 GHz	≈11 dBi	Rogers RT/Duroid 5880	12 × 10 × 1.5	Compact wideband design, multiresonant behavior, stable radiation patterns

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IV. CONCLUSION

A compact and efficient millimeter-wave antenna has been designed and analyzed in this work. The proposed antenna occupies a small area of 12 mm × 10 mm and utilizes a stepped and slotted radiating patch with a centrally fed microstrip line to achieve multiband and broadband performance. The geometric modifications effectively increase the electrical path length, resulting in improved impedance matching and stable radiation behavior across the 35–100 GHz frequency range.

Simulation results demonstrate multiple resonant modes with deep return-loss minima, VSWR values below 2, and input impedance close to 50 Ω at the resonant frequencies. Electric and magnetic field distributions confirm effective excitation of both fundamental and higher-order modes, while surface current analysis highlights the role of the slots and modified patch regions in achieving wideband operation. The antenna exhibits directional radiation with peak directivity reaching approximately 11 dBi at higher frequencies, along with controlled side-lobe levels.

Overall, the proposed antenna design offers a compact, broadband, and high-performance solution for millimeter-wave wireless communication systems and can be effectively integrated into next-generation high-frequency devices.

Author Contribution

Aditya Yadav: Conceptualization, antenna design, simulation, data analysis, and manuscript writing. **Devansh Bhoi**: literature review, and manuscript review and editing.

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Data Availability Statement

No new data were generated during the study. All the data are contained within the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Ethics Declaration

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This manuscript is a review article and does not involve any studies with human participants or animals performed by the authors. Therefore, ethical approval and informed consent were not required. The authors declare no conflict of interest, and all referenced works have been properly cited.

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