Wideband millimeter-wave antenna design with hammer-shaped slot and enhanced radiation characteristics

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ABSTRACT

This paper presents the design and simulation of a novel hammer-shaped slotted microstrip patch antenna optimized for operation at 27 GHz. The proposed antenna structure features a truncated ground plane and is tailored to support wideband applications in the millimeter-wave (mmWave) frequency spectrum. Key performance parameters such as return loss (S11), voltage standing wave ratio (VSWR), far-field radiation characteristics, and gain are thoroughly analyzed. Simulation results show that the antenna achieves a wide operating bandwidth from 24.5 GHz to 30.9 GHz, with a peak gain of 6.35 dB and an excellent return loss of −37.8 dB at the central frequency. These promising results suggest that the antenna is well-suited for high-frequency applications such as 5G and radar systems.

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1. INTRODUCTION

With the rapid advancement of wireless communication technologies, the demand for compact, high-performance antennas operating in the millimeter-wave (mmWave) frequency range (FR) has significantly increased. In particular, the mmWave spectrum—typically defined from 24 GHz to 100 GHz—offers wide bandwidths that can support high data rates, ultra-low latency, and dense user connectivity, which are essential for 5G and beyond wireless systems [1]. This has accelerated research efforts in the development of novel antenna designs that are capable of meeting the strict requirements of next-generation wireless platforms.

Among various antenna configurations, microstrip patch antennas have gained widespread popularity due to their low profile, light weight, planar nature, ease of fabrication, and their compatibility with monolithic microwave integrated circuits (MMICs) [2]. They are especially suitable for compact, high-frequency systems where spatial constraints and integration with printed circuit boards (PCBs) are critical. Moreover, microstrip patch antennas can be easily adapted to different shapes and geometries to tune their electrical properties, such as bandwidth, gain, and polarization, making them attractive for mmWave applications [3].

In particular, the 27 GHz frequency band has emerged as a promising candidate for future wireless technologies, including 5G new radio (NR), automotive radar, and ultra-high-speed short-range communications. The 27 GHz band is part of the frequency range 2 (FR2) defined by 3GPP for 5G networks, offering channel bandwidths up to 400 MHz and enabling beamforming and massive MIMO implementations [4]. Furthermore, this band exhibits relatively moderate atmospheric absorption compared to higher mmWave bands like 60 GHz, providing a good trade-off between range and throughput [5].

This work proposes a novel microstrip patch antenna design featuring a hammer-shaped slot and truncated ground configuration. Such structural modifications are intended to enhance the antenna's bandwidth and radiation efficiency while preserving a compact footprint. The primary objective is to achieve wideband performance, improved radiation characteristics, and compact size, making it suitable for integration in modern mmWave communication systems.

The antenna is simulated using full-wave electromagnetic software, and performance parameters such as return loss, voltage standing wave ratio (VSWR), gain, and radiation patterns are extracted to validate the design. Simulation results demonstrate that the proposed design operates effectively across a wide FR from 24.5 GHz to 30.9 GHz, with excellent impedance matching and stable far-field characteristics. These features make the antenna a strong candidate for deployment in 5G transceivers, mmWave internet of thing (IoT) devices, and vehicular communication systems.

The remainder of this paper is structured in section 2 presents the related work on microstrip patch antenna designs, particularly for mmWave applications. Section 3 details the design methodology and structure of the proposed hammer-shaped antenna, including geometrical parameters and simulation setup. Section 3 discusses the simulation results including return loss (S11), VSWR, radiation patterns, and gain performance. Finally, section 4 concludes the paper and suggests potential directions for future work.

2. RELATED WORK

The design and implementation of a compact rectangular microstrip antenna suitable for S-band communication at 2.7 GHz are reported in [6]. The S-band plays a crucial role in various domains, including satellite communication and radar systems. The proposed antenna integrates an L-shaped slot on the radiating patch and is fabricated on a low-cost FR-4 epoxy substrate with a relative permittivity of 4.4 and a low loss tangent of 0.02. The structure is supported by a full ground plane configuration. The reported prototype exhibits excellent impedance matching, compact size, and an operating bandwidth extending from 2.66 GHz to 2.78 GHz, corresponding to 170 MHz of usable bandwidth. Furthermore, it achieves a gain of 4.49 dBi at 2.7 GHz with a return loss of −38.05 dB, demonstrating highly efficient radiation behavior.

For future radar and joint communication and sensing (JCAS) applications, advanced and flexible multiple-input multiple-output (MIMO) antenna platforms are required to support new waveform testing and system prototyping [7]. Within the framework of the German Open6GHub initiative, a broadband massive MIMO testbed covering the 24–30 GHz FR has been developed. The reported antenna element has an electrical size of approximately half a wavelength in free space and offers a 6 GHz bandwidth centered at 27 GHz. Based on this optimized single element, an 8×8 antenna array was designed and experimentally validated, confirming its suitability for high-capacity mmWave communication and sensing scenarios.

Gupta *et al*. [8], a single radiator antenna resonating at 27 GHz, located within the 5G n261 band, is presented. The proposed antenna exhibits a compact volume of 23.375 mm^3 and provides a wide impedance bandwidth of approximately 2 GHz (26–28 GHz). Parametric analysis reveals that extending the slot length on the radiating patch allows further tuning of the resonant frequency. When configured as an eight-element MIMO system, strong mutual coupling is observed along the Y-axis, while relatively weaker coupling occurs along the X-axis. To mitigate this effect, a slot wall structure is etched into the ground plane to suppress surface current interactions and enhance isolation. Additionally, on-body performance is evaluated using a realistic human-body equivalent model. The antenna demonstrates reflection coefficients of −30 dB in free space and −40 dB in on-body conditions, along with isolation exceeding 20 dB between adjacent elements. A bidirectional radiation pattern with 2.53 dB gain in free space and a broadside radiation gain of 4.64 dB on-body is reported. The design also complies with specific absorption rate (SAR) safety limits, with ECC remaining below 0.005 and DG close to 10, making it highly promising for wearable healthcare applications at 27 GHz.

An integrated dual-band microstrip antenna array operating simultaneously at 24 GHz and 77 GHz is proposed in [9]. By optimizing the radiator width, the overall antenna volume is reduced by 39.82%. A corner-series feeding network is employed to excite a 3×3 planar array configurations. The antenna achieves gains of 14.19 dBi and 15.34 dBi at 24 GHz and 77 GHz, respectively, while maintaining sidelobe levels below −9.14 dB and −12.85 dB, and cross-polarization below −29 dB. Such characteristics make the design suitable for high-precision automotive radar and mmWave sensing applications.

For upper 6 GHz 5G smartphone applications, a compact 2×2 MIMO antenna system is introduced in [10]. A metamaterial split-ring resonator (SRR) layer is incorporated to enhance radiation performance without increasing the physical footprint of the antenna. The structure achieves a gain enhancement of more than 1.5 dB across the entire operating band while maintaining isolation below −18 dB, envelope correlation coefficient below 0.025, and radiation efficiency exceeding 75%. Both simulation and experimental validation show strong agreement, demonstrating suitability for handheld 5G communication terminals and wireless channel characterization scenarios. A comparative summary of mmWave microstrip antenna designs is presented in Table 1.

Table 1. Comparative analysis of microstrip antenna for related work

Ref.	Freq (GHz)	Design type	Gain (dBi)	Bandwidth	Return loss (dB)	Application area
[6]	2.66–2.78 (S-band)	Rectangular patch with L-slot	4.49	170 MHz	−38.05	Satellite and radar communications
[7]	24–30 (mmWave)	Massive MIMO patch element (8×8)	N/A	6 GHz	N/A	5G testbeds and JCAS (Joint Comm and sensing)
[8]	26–28 (n261)	MIMO patch with ground slot wall	2.53 (on-body)/4.64 (free space)	2 GHz	−30/−40 (on-body)	5G and on-body health monitoring
[9]	24 and 77	Corner-fed 3×3 array	14.19/15.34	Not specified	<−29 (X-pol)	Automotive radar and mmWave sensing
[10]	6+	2×2 MIMO with SRR metamaterial	+1.5 (improvement)	Not specified	Not specified	5G smartphones and channel characterization
Our work	24.5–30.9	Hammer-slotted patch and truncated ground	6.35	6.4 GHz	−37.8	5G, radar, and mmWave communication systems

3. PROPOSED ANTENNA DESIGN AND METHOD

The proposed antenna consists of a single microstrip patch element with a hammer-type slot etched on the radiating surface and a truncated ground plane on the bottom layer. This particular slot configuration is intentionally introduced to disturb the surface current distribution, thereby enhancing the impedance bandwidth and improving impedance matching performance.

The antenna is designed on a dielectric substrate with relative permittivity $\varepsilon r=2.2$ and thickness $h=0.254$ mm. The detailed geometrical dimensions of the patch, hammer-shaped slot, feed line, and ground truncation are summarized in Table 1 to provide a clear structural description of the proposed design. The simulation and optimization of the structure are carried out using a full-wave 3D electromagnetic solver (CST Microwave Studio), considering a frequency sweep from 24 GHz to 32 GHz.

Key performance indicators such as return loss (S11), VSWR, 2D, and 3D far-field radiation patterns, and gain versus frequency characteristics are obtained to evaluate the antenna's effectiveness. The optimized design exhibits a wide operating bandwidth of approximately 6.4 GHz, along with a peak realized gain of 6.35 dB, validating its suitability for mmWave applications.

Figure 1 illustrates the proposed single antenna element, where Figure 1(a) represents the top view including the hammer-shaped slot configuration and Figure 1(b) shows the truncated ground plane structure. Table 2 summarizes the optimized geometrical parameters of the proposed hammer-shaped microstrip patch antenna.

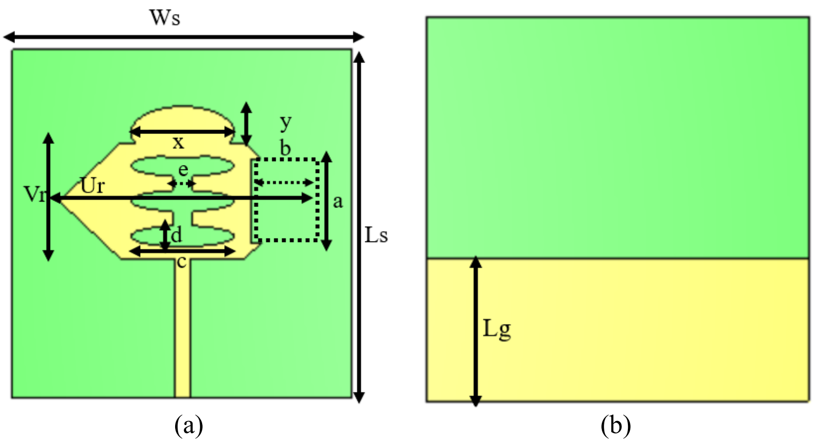


Figure 1. Proposed single unit cell; (a) top view and (b) bottom view

Table 2. Optimized geometrical parameters of the proposed antenna

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
A	1.2	e	0.6
B	1.6	x	1.5
C	1.5	y	0.74
D	0.3	Ls and Ws	9.9
Ur	3.6	Vr	1.9

3.1. Reflection coefficient (S11)

The simulated reflection coefficient of the proposed antenna is presented in Figure 2. The antenna exhibits a wide operating bandwidth ranging from 24.5 GHz to 30.9 GHz, corresponding to a −10 dB impedance bandwidth of approximately 6.4 GHz. A minimum return loss of −37.8 dB is obtained at the central operating frequency of 27 GHz, confirming excellent impedance matching performance.

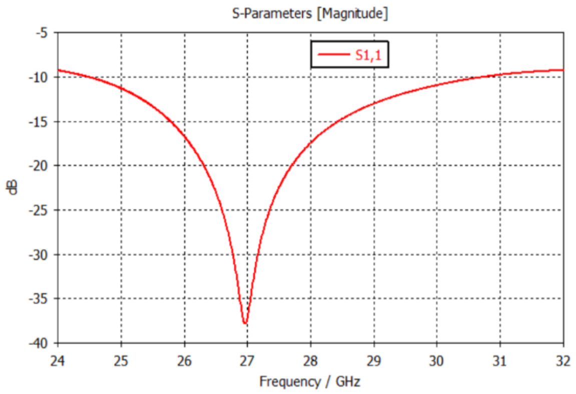


Figure 2. Simulated S11 results

3.2. Voltage standing wave ratio

For a practical antenna, the VSWR value is typically required to be less than 2 across the operational band to ensure efficient power transfer. As shown in Figure 3, the proposed antenna maintains a VSWR below 2 throughout the entire bandwidth, with a minimum value of 1.02 at 27 GHz, which further validates the impedance matching quality of the design between 24.5 GHz and 30.9 GHz.

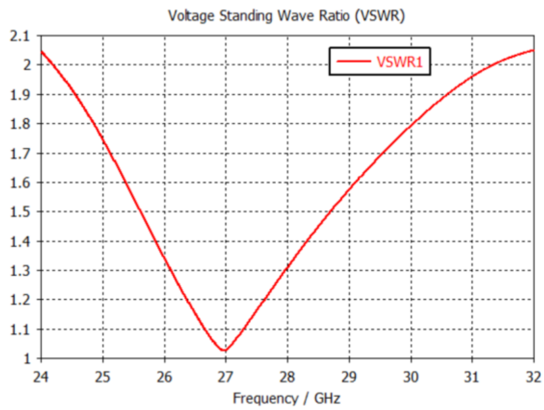
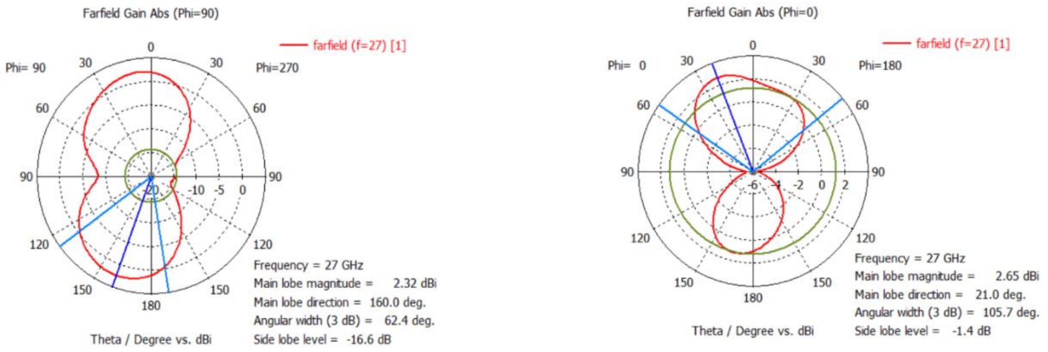


Figure 3. Simulated VSWR of proposed design

3.3. 2D radiation fields

Figure 4 illustrates the 2D radiation characteristics of the proposed antenna at 27 GHz. The E-plane (phi=90°) and H-plane (phi=0°) radiation patterns as shown in Figures 4(a) and 4(b), demonstrate stable main lobe formation with controlled side-lobe levels. These results confirm good directional radiation behavior and consistent field distribution across the operating band.



(a) (b)

Figure 4. 2D far field; (a) e-field and (b) H-field at 27 GHz

3.4. 3D radiation field

The 3D far-field radiation pattern of the proposed antenna at 27 GHz is depicted in Figure 5. The antenna exhibits a well-defined main radiation beam with a realized gain of approximately 4.95 dB at the central frequency. This value represents the instantaneous gain at 27 GHz and confirms efficient radiation capability of the structure.

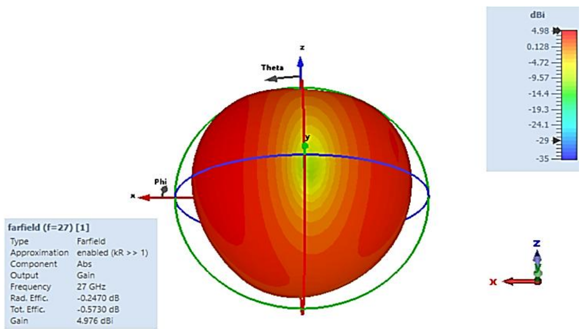


Figure 5. 3D far field radiation pattern

3.5. Gain versus frequency

The simulated gain variation across the frequency band is shown in Figure 6. The proposed antenna maintains a relatively high gain over the whole operating range, achieving a peak realized gain of 6.35 dB at 30.4 GHz. This clarifies that the 4.95 dB corresponds to the gain specifically at 27 GHz, while the 6.35 dB represents the maximum gain within the operating bandwidth.

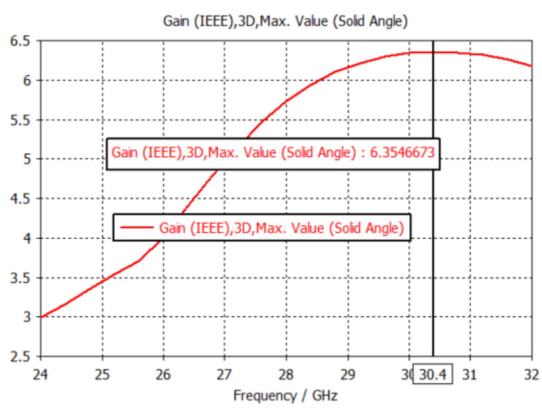


Figure 6. Gain versus frequency of the proposed antenna

4. CONCLUSION

In this study, a hammer-shaped slotted microstrip patch antenna operating at 27 GHz has been designed and simulated. The antenna achieves a wide impedance bandwidth from 24.5 GHz to 30.9 GHz, a minimum return loss of −37.8 dB, a VSWR of 1.02, and a peak realized gain of 6.35 dB, demonstrating excellent suitability for mmWave 5G and high-speed wireless communication applications. Thanks to its stable radiation and wideband behavior, the antenna also shows strong potential for future integration in mmWave energy harvesting (rectenna) systems. Future work will focus on fabrication and experimental validation.

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Chokri Baccouch		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	
Belgacem Chibani				✓			✓			✓	✓		✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data used during the current study are available from the corresponding author on reasonable request.

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