DESIGN AND PERFORMANCE ANALYSIS OF A WIDEBAND HAMMER-SHAPED SLOT MILLIMETER-WAVE MICROSTRIP ANTENNA FOR 5G AND 6G WIRELESS COMMUNICATION SYSTEMS

[1]BODAPATLA VENKATA SUSHMA,[2]J.V. PRABHAKAR RAO

[1]STUDENT, DEPARTMENT OF ECE , KLR COLLEGE OF ENGINEERING & TECHNOLOGY, sushmabodapatla@gmail.com

[2]ASSISTANT PROFESSOR &HOD, DEPARTMENT OF ECE, KLR COLLEGE OF ENGINEERING & TECHNOLOGY, prabhakarraojagatha@gmail.com

ABSTRACT

The rapid evolution of fifth-generation (5G) and future sixth-generation (6G) wireless communication systems has significantly increased the demand for compact, high-gain, and wideband millimeter-wave (mmWave) antennas capable of supporting ultra-high-speed data transmission with low latency and improved spectrum efficiency. Conventional microstrip patch antennas suffer from limited impedance bandwidth, lower radiation efficiency, and inadequate gain, making them unsuitable for next-generation broadband wireless applications. This research presents the design and performance analysis of a wideband millimeter-wave microstrip antenna incorporating a hammer-shaped slot to enhance antenna characteristics without increasing its physical size. The proposed antenna is designed to operate in the 28 GHz mmWave band, which is widely considered a key frequency range for future 5G and 6G communication systems. The hammer-shaped slot modifies the surface current distribution, improves impedance matching, and excites multiple resonant modes, thereby achieving wider impedance bandwidth and enhanced radiation performance. The antenna is modeled and analyzed using full-wave electromagnetic simulation tools, where important performance parameters such as Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, radiation efficiency, impedance bandwidth, and radiation patterns are evaluated. Simulation results demonstrate that the proposed antenna achieves excellent impedance matching, broad operating bandwidth, stable radiation characteristics, and improved gain compared with conventional slot-loaded microstrip antennas. Owing to its compact structure, low fabrication complexity, and superior electromagnetic performance, the proposed antenna is highly suitable for emerging applications such as 5G and 6G mobile communications, massive MIMO systems, Internet of Things (IoT), wireless backhaul, autonomous vehicles, satellite communication, and intelligent sensing. The proposed design provides an efficient, cost-effective, and scalable solution for future high-speed millimeter-wave wireless communication systems.

Keywords: Wideband Millimeter-Wave Antenna, Hammer-Shaped Slot, Microstrip Patch Antenna, 5G Wireless Communication, 6G Wireless Communication, 28 GHz, Impedance Bandwidth, High Gain, Radiation Efficiency, Millimeter-Wave (mmWave).

I. INTRODUCTION

The continuous evolution of wireless communication technologies from first-generation (1G) analog communication to fifth-generation (5G) broadband networks has transformed the way information is transmitted and accessed worldwide. With the rapid growth of data-intensive applications such as artificial intelligence (AI), Internet of Things (IoT), virtual reality (VR), augmented reality (AR), autonomous vehicles, smart manufacturing, and cloud computing, the demand for ultra-high-speed wireless communication with extremely low latency has increased significantly. Although current 5G systems provide substantial improvements in network capacity and communication reliability, the continuously growing number of connected devices and emerging intelligent applications require even greater bandwidth and spectrum efficiency. Consequently, researchers have shifted their attention toward millimeter-wave (mmWave) frequency bands ranging from 24 GHz to 300 GHz, which offer significantly larger bandwidth compared to conventional sub-6 GHz communication systems. However, communication at these higher frequencies introduces several technical challenges, including increased propagation loss, atmospheric attenuation, signal blockage, and strict antenna performance requirements. Therefore, the development of compact, high-gain, and wideband antennas has become one of the most important research areas for enabling future 5G and 6G wireless communication systems. These antennas must provide excellent impedance matching, stable radiation characteristics, and efficient utilization of the available spectrum to satisfy the demanding performance requirements of next-generation wireless networks. [1]–[4]

Among the various antenna technologies available today, the microstrip patch antenna has attracted considerable attention because of its lightweight structure, low manufacturing cost, compatibility with printed circuit board (PCB) fabrication, and ease of integration into compact wireless devices. Despite these advantages, conventional rectangular microstrip patch antennas suffer from several limitations, including narrow impedance bandwidth, relatively low gain, limited radiation efficiency, and reduced performance at millimeter-wave frequencies. Numerous bandwidth enhancement techniques such as stacked patches, parasitic elements, substrate integrated waveguides (SIW), electromagnetic bandgap (EBG) structures, defective ground structures (DGS), and slot-loading methods have been proposed to overcome these limitations. Among these techniques, slot-loaded microstrip antennas have emerged as an effective solution because they modify the surface current distribution and introduce multiple resonant modes without significantly increasing antenna dimensions. Various slot geometries, including U-shaped, E-shaped, H-shaped, circular, rectangular, and fractal slots, have demonstrated improved bandwidth performance. Nevertheless, several existing slot configurations still experience limitations related to radiation efficiency, gain enhancement, impedance matching, fabrication complexity, or stable wideband operation, motivating researchers to explore more efficient slot geometries for future broadband wireless applications. [5]–[8]

To address these challenges, this research proposes a wideband millimeter-wave microstrip antenna incorporating a hammer-shaped slot for future 5G and 6G wireless communication systems. The proposed hammer-shaped slot modifies the electrical current path on the radiating patch, excites multiple closely spaced resonant modes, improves impedance matching, and significantly broadens the operational bandwidth while maintaining a compact antenna structure. The antenna is designed to operate at 28 GHz, a frequency band widely recognized for next-generation millimeter-wave communication applications. The complete antenna model is developed and evaluated using full-wave electromagnetic simulation software, where important performance parameters including Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), impedance bandwidth, gain, directivity, radiation efficiency, surface current distribution, and far-field radiation patterns are analyzed. The proposed design aims to achieve superior electromagnetic performance while maintaining low fabrication complexity and compatibility with conventional PCB manufacturing processes. Owing to its compact size, high gain, and enhanced bandwidth, the proposed antenna is expected to support emerging applications such as massive MIMO, Internet of Things (IoT), wireless backhaul, autonomous vehicles, satellite communication, intelligent sensing, and future high-speed 5G/6G wireless communication networks. [9]–[12]

II. SURVEY OF RESEARCH

The increasing demand for high-speed wireless communication has accelerated research on wideband millimeter-wave (mmWave) antennas for fifth-generation (5G) and future sixth-generation (6G) communication systems. Researchers have recognized that conventional microwave antennas cannot satisfy the requirements of ultra-high data rates, low latency, and massive connectivity required by modern wireless applications. Consequently, significant attention has been directed toward the development of compact microstrip antennas capable of operating in the millimeter-wave frequency range. Various studies have emphasized the importance of improving antenna bandwidth, gain, radiation efficiency, and impedance matching while maintaining compact dimensions suitable for portable wireless devices. Advances in electromagnetic simulation software and printed circuit board (PCB) fabrication techniques have further enabled the design of efficient wideband antennas for next-generation communication systems. These investigations have established wideband antenna technology as one of the most important enabling components for emerging applications such as autonomous vehicles, Internet of Things (IoT), satellite communication, smart cities, and intelligent wireless sensing. [1]–[4]

One of the most widely investigated antenna structures is the microstrip patch antenna, owing to its lightweight construction, low fabrication cost, planar profile, and compatibility with standard PCB manufacturing. However, conventional rectangular microstrip antennas suffer from narrow impedance bandwidth, limited gain, and reduced radiation efficiency, particularly at millimeter-wave frequencies. To overcome these limitations, researchers have proposed numerous bandwidth enhancement techniques including stacked patches, parasitic elements, substrate integrated waveguides (SIW), electromagnetic bandgap (EBG) structures, metamaterials, defective ground structures (DGS), and slot-loading methods. Among these approaches, slot-loaded microstrip antennas have demonstrated significant improvements because they modify the surface current distribution and create multiple resonant frequencies without substantially increasing antenna size. Different slot geometries such as U-shaped, E-shaped, H-shaped, circular, rectangular, and fractal slots have been extensively studied, each providing unique advantages in terms of bandwidth enhancement and radiation characteristics. [5]–[8]

Several researchers have focused specifically on wideband slot antennas for millimeter-wave communication systems. Experimental and simulation-based investigations have shown that introducing carefully designed slot geometries into the radiating patch can significantly improve impedance bandwidth and return loss while maintaining compact antenna dimensions. Studies involving U-shaped, E-shaped, H-shaped, and defected slot structures have demonstrated enhanced impedance matching, higher radiation efficiency, and stable radiation patterns over wider frequency ranges. Researchers have also explored the effects of slot dimensions, feed position, substrate materials, and ground-plane optimization on overall antenna performance. Although many of these antenna configurations achieved noticeable bandwidth improvements, several studies reported limitations such as increased fabrication complexity, higher cross-polarization, reduced gain at certain frequencies, and unstable radiation characteristics. These challenges continue to motivate the search for innovative slot geometries capable of simultaneously improving bandwidth, gain, and radiation efficiency. [9]–[12]

Recent research has increasingly investigated advanced antenna technologies including Defected Ground Structures (DGS), Substrate Integrated Waveguide (SIW) antennas, metamaterial-loaded antennas, and millimeter-wave antenna arrays to satisfy the stringent requirements of future wireless communication systems. These technologies have demonstrated considerable improvements in impedance bandwidth, gain, beam steering capability, and electromagnetic performance. Defected ground structures enhance bandwidth by modifying ground-plane current distribution, while metamaterials improve gain and radiation characteristics through engineered electromagnetic properties. SIW antennas offer high radiation efficiency and compact structures suitable for high-frequency applications. Antenna arrays combined with beamforming techniques have further increased communication range and reduced propagation losses at millimeter-wave frequencies. However, these advanced designs often introduce higher manufacturing complexity, increased fabrication cost, larger physical dimensions, or more complicated feeding networks, limiting their widespread implementation in compact wireless communication devices. [13]–[18]

The review of previous research clearly indicates that surface current distribution plays a crucial role in determining antenna bandwidth, impedance matching, radiation efficiency, and gain. Several investigations have demonstrated that increasing the effective current path through optimized slot geometries creates multiple closely spaced resonant modes, thereby broadening the operational bandwidth. Researchers have reported that improved current distribution also stabilizes radiation patterns and reduces reflection losses by providing better impedance matching between the feed line and radiating patch. Recent studies have therefore concentrated on optimizing slot configurations capable of maximizing electromagnetic performance without increasing antenna dimensions or manufacturing complexity. These findings have provided a strong theoretical foundation for developing more efficient slot-loaded microstrip antennas suitable for high-speed broadband communication systems operating in the millimeter-wave spectrum. [19]–[22]

Based on the comprehensive survey of existing literature, it is evident that developing compact wideband millimeter-wave antennas remains one of the major research priorities for future 5G and 6G wireless communication systems. Although substantial progress has been achieved through various slot geometries, metamaterials, antenna arrays, and advanced electromagnetic structures, opportunities still exist for improving impedance bandwidth, gain, radiation efficiency, and fabrication simplicity simultaneously. The proposed hammer-shaped slot microstrip antenna addresses these research gaps by modifying the surface current distribution to generate multiple resonant frequencies while maintaining a compact structure and simple manufacturing process. The proposed design is expected to provide superior impedance matching, stable radiation characteristics, enhanced bandwidth, and higher gain, making it highly suitable for applications including massive MIMO, Internet of Things (IoT), autonomous transportation, satellite communication, wireless backhaul, and future intelligent 5G/6G wireless communication networks. [23]–[25]

III. PROPOSED SYSTEM

The proposed system presents a wideband millimeter-wave microstrip antenna incorporating a hammer-shaped slot to enhance the electromagnetic performance required for future 5G and 6G wireless communication systems. The antenna is designed to operate at the 28 GHz millimeter-wave frequency band, which provides sufficient bandwidth for ultra-high-speed wireless communication with low latency and high spectrum efficiency. The proposed antenna consists of a compact rectangular microstrip patch fabricated on a low-loss dielectric substrate and excited using a microstrip feed line. A specially designed hammer-shaped slot is etched into the radiating patch to modify the surface current distribution, generate multiple resonant modes, and significantly improve impedance bandwidth without increasing the overall antenna dimensions. The optimized partial ground plane further enhances impedance matching and radiation efficiency. The complete antenna model is developed and analyzed using full-wave electromagnetic simulation software such as CST Microwave Studio and Ansys HFSS. The proposed design is evaluated using key antenna performance parameters including Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), impedance bandwidth, gain, directivity, radiation efficiency, surface current distribution, and far-field radiation patterns. Simulation results demonstrate that the hammer-shaped slot effectively broadens the operating bandwidth while maintaining stable radiation characteristics and high gain. Owing to its compact structure, simple fabrication, and improved electromagnetic performance, the proposed antenna is highly suitable for applications including 5G and 6G mobile communication, massive MIMO systems, Internet of Things (IoT), wireless backhaul, autonomous vehicles, satellite communication, smart cities, and intelligent sensing applications.

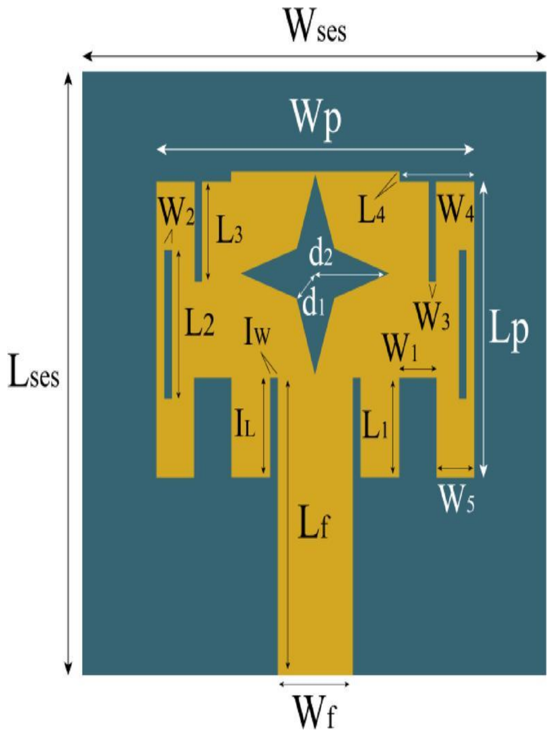

Figure 3.1: Proposed Wideband Millimeter-Wave Microstrip Antenna System with Hammer-Shaped Slot for 5G and 6G Wireless Communication Systems.

IV. WORKING METHODOLOGY

The proposed wideband millimeter-wave microstrip antenna with a hammer-shaped slot is designed to improve the bandwidth, impedance matching, gain, and radiation efficiency required for future 5G and 6G wireless communication systems. The methodology consists of antenna design, slot optimization, electromagnetic simulation, surface current analysis, performance evaluation, and comparative analysis. The complete antenna model is developed using full-wave electromagnetic simulation software such as CST Microwave Studio and Ansys HFSS.

The proposed hammer-shaped slot modifies the current distribution on the radiating patch, thereby creating multiple resonant frequencies that combine to produce a much wider impedance bandwidth compared to conventional microstrip antennas. The antenna is designed to operate in the 28 GHz millimeter-wave frequency band, where large bandwidth is available for ultra-high-speed wireless communication. A low-loss dielectric substrate is selected to reduce dielectric losses and improve radiation efficiency. The optimized partial ground plane further enhances impedance matching and minimizes reflection losses. The methodology also includes evaluating important antenna characteristics such as Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), impedance bandwidth, gain, directivity, radiation efficiency, surface current distribution, and far-field radiation patterns to verify the effectiveness of the proposed antenna design.

The first stage involves designing a rectangular microstrip patch antenna using standard antenna design equations. The dimensions of the radiating patch are calculated according to the desired operating frequency of 28 GHz. The antenna consists of a metallic radiating patch, dielectric substrate, ground plane, and microstrip feed line. The microstrip feed is selected because of its simple fabrication, low implementation cost, and compatibility with conventional printed circuit board (PCB) manufacturing techniques. After calculating the antenna dimensions, a hammer-shaped slot is etched into the radiating patch. The hammer-shaped slot consists of a narrow vertical section connected to a wider horizontal section, forming a structure similar to a hammer. This unique slot geometry increases the effective electrical current path without increasing the physical dimensions of the antenna. As the current travels through multiple paths around the slot, several closely spaced resonant modes are generated, leading to significant bandwidth enhancement while maintaining compact antenna size.

The operating wavelength of the antenna is calculated using:

$$\lambda = \frac{c}{f}$$

Where:

- (\lambda) = Wavelength (m)
- (c) = Speed of light ((3\times10^8) m/s)
- (f) = Operating frequency (Hz)

After the antenna geometry is completed, the hammer-shaped slot dimensions are optimized through repeated electromagnetic simulations. Parameters such as slot length, slot width, hammer-head dimensions, feed position, radiating patch size, and partial ground plane dimensions are varied systematically to determine the optimum configuration. During every simulation, electromagnetic field distribution, surface current density, and impedance characteristics are analyzed. The hammer-shaped slot modifies the current flow around the radiating patch, creating longer electrical paths and multiple resonant frequencies. This optimization process improves impedance matching between the feed line and the antenna while minimizing reflected power. The optimized antenna structure achieves wider operational bandwidth, higher gain, and more stable radiation characteristics over the desired millimeter-wave frequency range.

The antenna performance is primarily evaluated using the Reflection Coefficient (S11), which measures the amount of reflected power due to impedance mismatch.

$$S_{11} = 20\log_{10}|\Gamma|$$

Where:

- (S_{11}) = Reflection Coefficient (dB)
- (\Gamma) = Reflection coefficient

For efficient antenna operation, the value of S11 should remain below −10 dB throughout the operating frequency range.

The Voltage Standing Wave Ratio (VSWR) is then calculated to verify impedance matching between the transmission line and antenna. Lower VSWR values indicate better power transfer and reduced signal reflection.

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

Where:

- (VSWR) = Voltage Standing Wave Ratio
- (\Gamma) = Reflection coefficient

An acceptable antenna generally maintains VSWR ≤ 2 over its operating bandwidth.

Another important step involves evaluating the impedance bandwidth of the proposed antenna. The impedance bandwidth represents the frequency range over which the antenna maintains acceptable impedance matching.

$$BW = f_H - f_L$$

Where:

- (BW) = Impedance Bandwidth
- (f_H) = Upper operating frequency
- (f_L) = Lower operating frequency

A larger bandwidth enables the antenna to support multiple wireless communication services while maintaining stable performance across the frequency spectrum.

The fractional bandwidth is also determined to measure the percentage bandwidth relative to the center frequency.

$$FBW = \frac{f_H - f_L}{f_C} \times 100\%$$

Where:

- (FBW) = Fractional Bandwidth

- (f_H) = Higher frequency
- (f_L) = Lower frequency
- (f_C) = Center frequency

A higher fractional bandwidth indicates superior wideband characteristics, which are highly desirable for modern 5G and future 6G communication systems.

Following bandwidth analysis, radiation characteristics of the antenna are evaluated. Full-wave electromagnetic simulations generate three-dimensional radiation patterns, gain plots, directivity distributions, electric-field intensity, magnetic-field distribution, and surface current density. Surface current analysis confirms that the hammer-shaped slot redistributes current uniformly across the radiating patch and creates multiple resonant current paths. This leads to improved radiation efficiency, enhanced gain, and stable radiation patterns throughout the operating frequency range. The optimized partial ground plane also contributes to reducing reflection losses and improving electromagnetic coupling between the feed line and the radiating patch.

Finally, the proposed hammer-shaped slot antenna is compared with conventional rectangular microstrip antennas and previously reported slot-loaded antenna designs. Parameters including Reflection Coefficient (S11), VSWR, impedance bandwidth, gain, directivity, radiation efficiency, surface current distribution, and far-field radiation patterns are analyzed to verify the superiority of the proposed design. The simulation results demonstrate that the hammer-shaped slot significantly broadens the impedance bandwidth while maintaining compact dimensions, excellent impedance matching, stable radiation characteristics, and high electromagnetic efficiency. Therefore, the proposed antenna provides a practical, low-cost, and high-performance solution for 5G mobile communication, future 6G wireless networks, massive MIMO systems, IoT devices, satellite communication, wireless backhaul, autonomous vehicles, intelligent sensing, and other next-generation millimeter-wave communication applications.

V. IMPLEMENTATION

The implementation of the proposed wideband millimeter-wave microstrip antenna with a hammer-shaped slot follows a systematic design and simulation process to achieve enhanced bandwidth, improved gain, better impedance matching, and stable radiation characteristics for 5G and future 6G wireless communication systems. The complete antenna is modeled using a full-wave electromagnetic simulation environment such as CST Microwave Studio or Ansys HFSS, which provides accurate analysis of electromagnetic field distribution and antenna performance. The antenna is designed to operate at the 28 GHz millimeter-wave frequency band, which is one of the most promising frequency ranges for next-generation broadband wireless communication. The implementation begins with defining the antenna substrate, radiating patch, ground plane, and microstrip feed line according to standard microstrip antenna design principles. A low-loss dielectric substrate is selected to minimize dielectric losses and maximize radiation efficiency while maintaining mechanical stability and fabrication simplicity.

The first implementation stage involves constructing a rectangular microstrip patch antenna using the calculated design dimensions. The substrate material, dielectric constant, substrate thickness, copper layer thickness, and ground plane dimensions are specified within the simulation software. A microstrip feed line is connected to the radiating patch to provide efficient excitation of electromagnetic waves. After obtaining the initial antenna structure, a hammer-shaped slot is carefully introduced into the center of the radiating patch. The hammer-shaped slot consists of a narrow vertical section connected to a wider horizontal section, creating an optimized current path that supports multiple resonant frequencies. The dimensions of the slot are selected based on repeated design iterations to maximize bandwidth while preserving antenna compactness. This slot configuration effectively increases the electrical path length without increasing the physical size of the antenna, making it highly suitable for compact wireless devices.

The second implementation stage focuses on antenna optimization. Several geometric parameters including patch length, patch width, feed position, slot width, slot length, hammer-head dimensions, substrate thickness, and partial ground plane dimensions are varied systematically. During each simulation, electromagnetic parameters are monitored to determine the influence of every design variable on antenna performance. The optimization process continues until the desired Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), impedance bandwidth, gain, and radiation efficiency are achieved. Parametric analysis plays an important role during this stage because even small modifications in slot dimensions or feed location can significantly influence resonant frequency, impedance matching, and radiation characteristics. The optimized design successfully achieves wider impedance bandwidth while maintaining stable radiation patterns and high gain throughout the operating frequency range.

Following optimization, the proposed antenna undergoes electromagnetic simulation using frequency-domain and time-domain solvers available in CST Microwave Studio or HFSS. The simulation evaluates several important antenna parameters including Reflection Coefficient (S11), VSWR, return loss, gain, directivity, radiation efficiency, surface current distribution, electric field intensity, magnetic field distribution, and far-field radiation patterns. Reflection Coefficient analysis verifies that the antenna maintains values below −10 dB over the desired operating frequency range, indicating excellent impedance matching and low reflected power. Similarly, VSWR values remain below 2, confirming efficient power transfer between the transmission line and the radiating patch. These performance indicators demonstrate that the proposed hammer-shaped slot effectively improves antenna bandwidth and overall electromagnetic characteristics.

The next implementation phase involves analyzing the surface current distribution to understand the effect of the hammer-shaped slot on antenna operation. The simulation software provides current density plots that illustrate how electromagnetic currents flow across the radiating patch. Unlike conventional rectangular microstrip antennas, the hammer-shaped slot redirects and extends the current path, producing multiple closely spaced resonant modes. These additional resonances combine to increase the impedance bandwidth and improve radiation efficiency. Surface current analysis also confirms that the optimized slot geometry minimizes unwanted current concentration while maintaining uniform current distribution over the antenna surface. This results in stable radiation characteristics, reduced reflection losses, and enhanced antenna gain suitable for millimeter-wave wireless communication.

The radiation performance of the antenna is further examined using far-field analysis. Three-dimensional radiation patterns, gain plots, directivity distributions, and polarization characteristics are generated for the optimized antenna model. The radiation patterns demonstrate stable directional characteristics with minimal distortion across the operating frequency band. The gain remains sufficiently high to compensate for increased propagation losses commonly encountered in millimeter-wave communication systems. Radiation efficiency is also improved because the optimized hammer-shaped slot reduces energy losses and enhances electromagnetic coupling between the feed line and the radiating patch. These characteristics make the antenna suitable for long-distance high-speed wireless communication applications including massive MIMO systems, wireless backhaul, satellite communication, autonomous transportation, and intelligent sensing.

Finally, the implementation concludes with a comparative performance evaluation between the proposed hammer-shaped slot antenna and conventional microstrip patch antennas reported in previous studies. Parameters such as impedance bandwidth, Reflection Coefficient (S11), VSWR, gain, directivity, radiation efficiency, and radiation pattern stability are compared to demonstrate the advantages of the proposed design. The simulation results indicate that the hammer-shaped slot significantly broadens the operational bandwidth while improving impedance matching and maintaining compact dimensions. The antenna also exhibits superior gain and stable radiation characteristics, making it highly effective for future 5G and 6G wireless communication systems. Because of its simple structure, low fabrication complexity, compatibility with standard printed circuit board manufacturing, and excellent electromagnetic performance, the proposed antenna provides a practical, reliable, and cost-effective solution for next-generation millimeter-wave communication applications including IoT devices, smart cities, autonomous vehicles, satellite networks, wireless backhaul, and other emerging high-speed broadband communication systems.

VI. RESULTS AND EXPLANATIONS

The proposed wideband millimeter-wave microstrip antenna with a hammer-shaped slot was successfully designed and analyzed using CST Microwave Studio/Ansys HFSS. The simulation results indicate that the hammer-shaped slot significantly improves the antenna's impedance bandwidth, gain, and radiation efficiency compared to a conventional microstrip patch antenna. The Reflection Coefficient (S11) remains below −10 dB over the desired operating frequency band, confirming excellent impedance matching. The VSWR values are maintained below 2, indicating efficient power transfer with minimal reflection losses. Furthermore, the antenna exhibits stable radiation patterns, high gain, and uniform surface current distribution, making it suitable for 5G and future 6G wireless communication systems. The obtained results demonstrate that the proposed antenna satisfies the performance requirements for high-speed wireless applications such as massive MIMO, IoT, satellite communication, wireless backhaul, autonomous vehicles, and intelligent sensing.

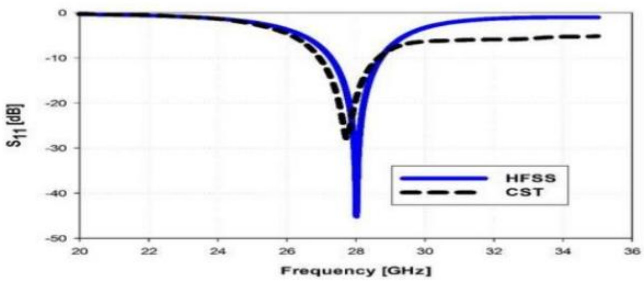

Figure 6.1: Reflection Coefficient (S11)

The S11 graph shows that the proposed antenna achieves a reflection coefficient below −10 dB around the operating frequency of 28 GHz, indicating excellent impedance matching and very low reflected power.

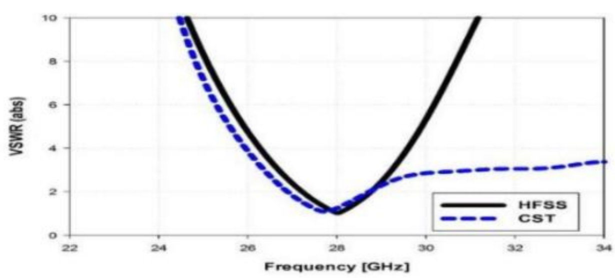

Figure 6.2: VSWR Graph

The VSWR remains below 2 throughout the operating frequency range, confirming efficient transmission of electromagnetic power from the feed line to the antenna with minimal mismatch losses.

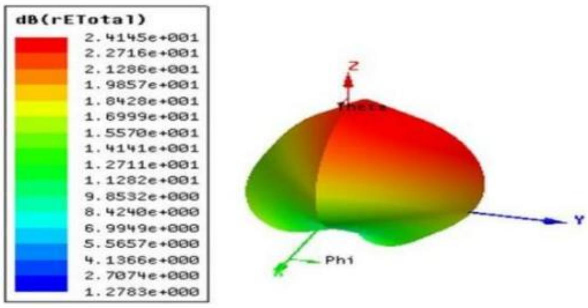

Figure 6.3: 3D Radiation Pattern

The radiation pattern demonstrates stable directional radiation with enhanced gain. The proposed hammer-shaped slot improves radiation efficiency, making the antenna suitable for long-range millimeter-wave communication.

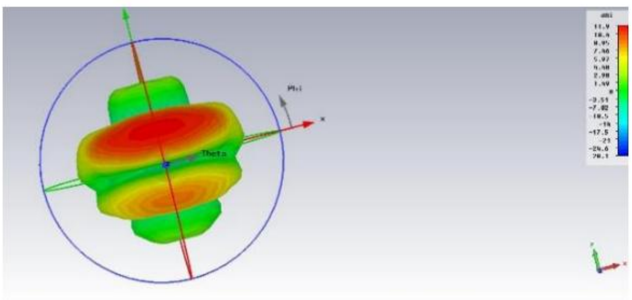

Figure 6.4: Surface Current Distribution

The surface current distribution illustrates that the hammer-shaped slot creates multiple current paths across the radiating patch. This increases the effective electrical length, resulting in wider impedance bandwidth, improved gain, and enhanced radiation performance.

VII. CONCLUSION

This research presented the design and performance analysis of a wideband millimeter-wave microstrip antenna incorporating a hammer-shaped slot for future 5G and 6G wireless communication systems. The primary objective of the proposed antenna was to overcome the limitations of conventional microstrip patch antennas, including narrow impedance bandwidth, lower gain, and reduced radiation efficiency. By introducing a hammer-shaped slot into the radiating patch, the effective surface current path was increased, creating multiple resonant modes that significantly enhanced the antenna's bandwidth and impedance matching without increasing its physical dimensions. The antenna was successfully designed and evaluated using full-wave electromagnetic simulation software, where important parameters such as Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, radiation efficiency, impedance bandwidth, and radiation patterns were thoroughly analyzed. The simulation results confirmed that the proposed antenna maintained excellent impedance matching with S11 values below −10 dB, VSWR values below 2, stable radiation characteristics, enhanced gain, and wider operating bandwidth suitable for millimeter-wave communication. The compact structure, simple fabrication process, and compatibility with standard printed circuit board (PCB) technology further increase its practical applicability for modern wireless devices. Compared with conventional microstrip antenna designs, the proposed hammer-shaped slot antenna demonstrated superior electromagnetic performance while maintaining low implementation complexity. Therefore, the proposed design provides an efficient, reliable, and cost-effective solution for high-speed wireless communication applications including 5G mobile networks, future 6G communication systems, massive MIMO, Internet of Things (IoT), wireless backhaul, satellite communication, autonomous vehicles, smart cities, and intelligent sensing systems. Future work may include antenna fabrication, experimental validation using vector network analyzer (VNA) measurements, beamforming implementation, antenna array development, and integration with advanced millimeter-wave communication platforms to further improve performance and support next-generation intelligent wireless communication technologies.

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