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Double Bow-Tie Slot Antenna Based on Metamaterial Enhanced Cavity Backed Substrate Integrated Waveguide

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ABSTRACT: This research delves into the intricate functionality of a fully planar double bow-tie antenna with orthogonal feeding and is innovatively constructed on a substrate-integrated cavity inspired by metamaterial designs. The architecture of the antenna includes Complementary Split Ring Resonators (CSRRs) and a double bow-tie patch, intricately etched onto the metal surfaces positioned on both the top and bottom of the substrate. The antenna is meticulously designed and fine-tuned for superior performance specifically in the K- and Ka-band frequencies. The incorporation of the double bow-tie patch in this antenna configuration brings forth several advantageous attributes such as improved impedance matching, exceptional high gain, and unidirectional radiation pattern. In a notable feature of this design, the antenna supports multiband operation which is achieved through the strategic integration of slots within the Substrate Integrated Waveguide (SIW) cavity, allowing the antenna to resonate at multiple frequencies. The antenna's superior performance and its ability to function effectively across multiple frequency bands have been rigorously validated through extensive simulation studies and thorough experimental testing.

1. INTRODUCTION

The evolution of planar slot antennas has led to their growing popularity, particularly due to their low-profile design and unidirectional radiation characteristics. These antennas also feature a high impedance bandwidth and substantial gain, making them an excellent choice for integrating into a variety of communication systems operating in the millimeter and microwave frequency ranges. Among the most noteworthy configurations is microstrip-line slot antenna, which boasts a straightforward structure accented by a variety of slot aperture shapes [1]. While these antennas offer compelling advantages — such as miniaturization, conformance to surfaces, and seamless integration with other planar components — they often grapple with the drawbacks of bi-directional radiation and limited gain [2–4]. In recent decades, a substantial body of research has focused on the design of compact multi-band and broadband antennas, exploring novel methods to enhance performance. Despite their unique benefits, these designs are generally more suited for lower frequency applications (below 10 GHz) and retain bi-directional characteristics that can limit their effectiveness [5]. To achieve the unidirectional radiation and high gain desired in modern applications, it is essential to incorporate a metallic (electrically conducting) cavity positioned behind slot antennas. Specifically, optimizing this arrangement requires the cavity to be placed at an ideal distance of approximately one-quarter of the free-space wavelength from the slot, thus effectively minimizing backside radiation. In recent years, cavity-backed slot antennas (CBSAs) have garnered attention in the literature, particularly for their impressive gain, potential for miniaturization, and wide bandwidth capabilities [6]. However, traditional CBSAs face significant challenges, primarily due to their considerable volume arising from the integration of metallic cavities with irregularly shaped surfaces. Moreover, the fabrication process for CBSAs complicates the design, as it necessitates the combination of two disparate technologies: printed circuit board (PCB) fabrication and metallic waveguide assembly. This complexity poses obstacles to the implementation of such antennas in today's compact wireless systems [7–9]. In response to these challenges, a groundbreaking technology called substrate integrated waveguide (SIW) has emerged, capturing the attention of the microwave engineering community in recent years. This innovative approach promises to mitigate the limitations associated with conventional CBSA designs, paving the way for more efficient and versatile antenna solutions [10, 11]. Its structure bears a close resemblance to the traditional dielectric-filled waveguide, yet it ingeniously employs a series of metallized via holes along its sides [12]. These holes serve as the controlling mechanism for electromagnetic propagation, effectively confining the waves within a well-defined channel.

One of the standout features of the SIW is its remarkable ability to maintain low propagation losses across both microwave and millimeter-wave frequency ranges [13]. This characteristic makes it a superior alternative to conventional planar transmission lines, such as microstrips or coplanar waveguides, which tend to exhibit higher levels of signal loss. By providing a more efficient conduit for signal transmission, the SIW paves the way for advanced applications in modern telecommunications and radar systems [14]. Researchers have extensively explored the realm of traditional substrate integrated waveguide (SIW) based antennas, leading to significant advancements in

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this field. In study [15], they introduce a novel broadband SIW bow-tie slot antenna that operates at a center frequency of 9.81 GHz, showcasing an impressive relative bandwidth of 8.9%. This design emphasizes not only efficiency but also the potential for dual polarizations, making it suitable for various applications. Furthermore, in [16], the authors demonstrate a broadband and high-gain antenna array that is fed by an SIW, specifically designed to meet the demands of 5G technology. This innovative array aims to provide enhanced performance and reliability for next-generation communication systems, highlighting the continued evolution of antenna design. Kumar and fancyhdr in [17] introduce a novel bandwidth broadening approach for SIW cavity-backed antennas, utilizing a shorted-via technique. This innovative method significantly enhances the impedance bandwidth of planar cavity-backed slotted antennas while maintaining their original dimensions, ensuring that the overall size of the antenna remains unaltered. The design showcases impressive performance, achieving an impedance bandwidth of 15.71%, which spans the frequency range from 12.02 GHz to 14.07 GHz. In [18], a detailed study presents a compact dual-band bow-tie slot antenna specifically designed to operate at two important frequency ranges: 900 MHz and 2400 MHz, both of which are part of the Industrial, Scientific, and Medical (ISM) bands. This paper describes innovative techniques aimed at effectively lowering the operating frequencies of the dual-band bow-tie slot antenna, enhancing its performance for various applications in wireless communication. A metamaterial-based double-sided bow-tie antenna for intelligent transport system communications operating in public safety band is presented in [19]. The proposed antenna demonstrates an impressive simulated gain of 5.64 dBi at the frequency of 3.5 GHz and 4.0 dBi at 4.9 GHz. In comparison, the measured gains reflected values of 5 dBi and 3.7 dBi, respectively, showcasing the antenna's effectiveness across these critical frequency ranges. In this paper, the concept of wave confinement is extended using broadside coupled complementary split ring resonators (BC-CSRRs) to propose a novel fully planar metamaterial-inspired cavity for the millimeter-wave regime. A novel design technique is proposed in [20] that allows for the implementation of dual-band and dual-polarized performance in the SIW cavity-backed slot antenna. Each cavity has a long bow-tie shaped slot with different sizes. This design excites four different hybrid modes within the target frequency range. Extensive efforts and substantial research have been dedicated to making advancements in this specific field.

In current paper, innovative approach inspired by Metamaterial (MTM) Theory Method and Substrate Integrated Waveguide (SIW) techniques are introduced to design a slotted bow-tie antenna. This antenna is characterized by its compact dimensions, wide bandwidth, and superior radiation properties. The first approach employs the principles of metamaterials along with substrate integrated waveguide technologies to enhance the bow-tie antenna's design. By integrating trapezoidal slots into its structure and utilizing metallic via holes that create connections between the top surface and ground plane, the antenna's effective aperture area is significantly increased. This strategic design not only maximizes the antenna's performance but also minimizes surface wave propagation and reduces substrate losses, resulting in an antenna that is more efficient and reliable in its operational capabilities. Following the application of the proposed methods, results indicate that the designed antenna successfully covers a wide frequency band while exhibiting high radiation properties. To further enhance performance parameters of the antenna, an orthogonal feeding technique has been incorporated into the structure. The findings detailed in this paper validate the effectiveness of the proposed approaches. The subsequent section delves into a comprehensive discussion of the antenna's design process, outlining the specific techniques and considerations implemented to achieve these improvements.

2. DESIGN OF DOUBLE BOW-TIE ANTENNA

Figure 1 presents a detailed illustration of the geometry of the proposed antenna, specifically highlighting the intricacies of the designed bow-tie antenna. This antenna has been meticulously constructed using a high-performance Rogers RT5880 substrate, which boasts a thickness of 0.8 mm, a dielectric constant of 2.2, and an extremely low loss tangent of 0.0009. These material properties are essential for achieving optimal performance, as they influence the antenna's efficiency and overall effectiveness. In the visual representation in Figure 1, trapezoidal slots have been purposefully etched into the top surface of the antenna to create the bow-tie configuration. This specific design modification serves a significant functional purpose: it effectively enlarges the antenna's effective aperture area, which is crucial for enhancing its radiation capabilities. Importantly, this enhancement is accomplished without expanding the antenna's physical dimensions, thus preserving its compact form factor.

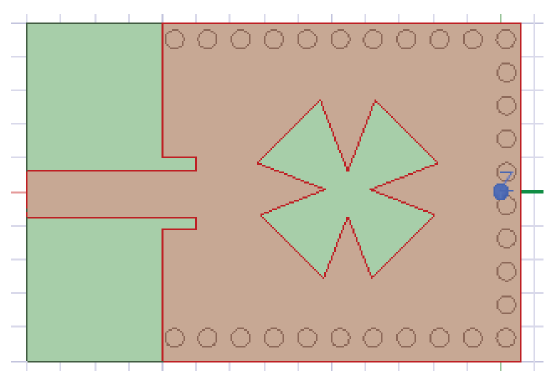

FIGURE 1. SIW structure with double bow-tie configuration.

The design of the antenna incorporates metallic via holes that are strategically modeled throughout the Rogers RT5880 dielectric substrate layer. These via holes serve to create a direct electrical connection between the top surface of the antenna and its ground plane situated on the backside. This design element is critical, as it helps to establish a more cohesive structure by ensuring that the top and bottom components of the antenna work effectively together. One of the key benefits of employing the Substrate Integrated Waveguide (SIW) approach in this antenna design is its remarkable capability to minimize substrate losses while simultaneously suppressing surface waves [21].

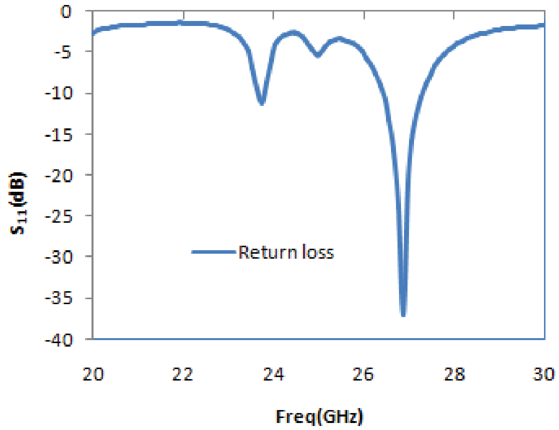

FIGURE 2. S parameter graph for SIW structure with double bow-tie configuration.

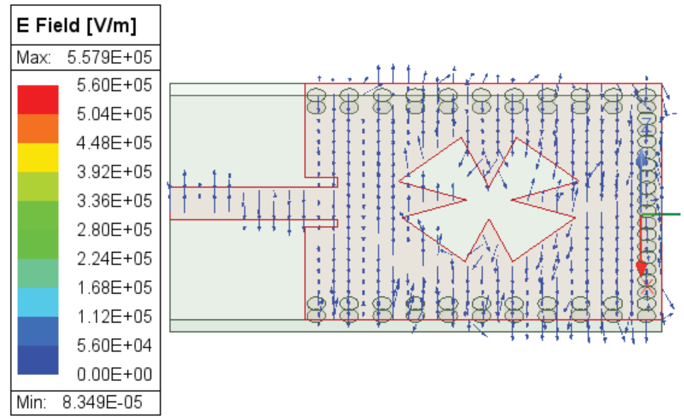

FIGURE 3. Electric field distribution of the structure.

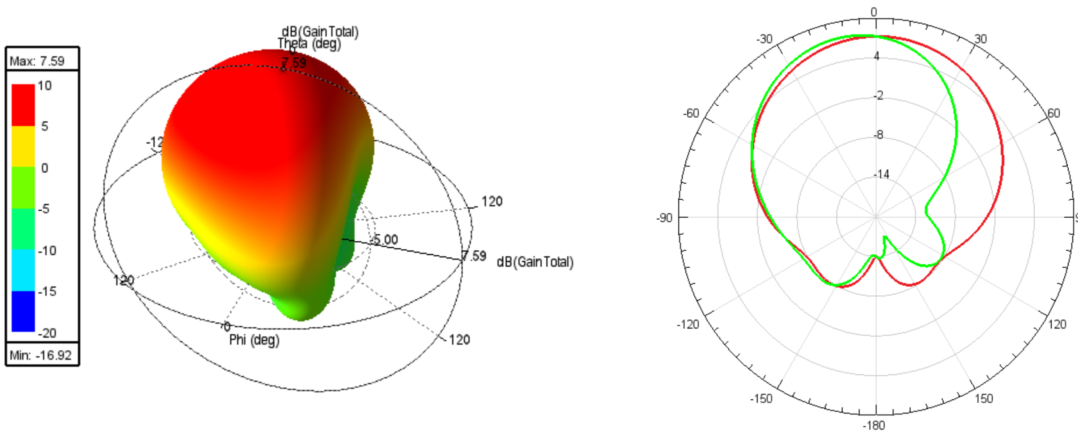

FIGURE 4. 2D and 3D gain plots of SIW structure with double bow-tie configuration.

Notably, this is achieved without necessitating an increase in the antenna's physical dimensions. The reduction of substrate losses is particularly vital as it enhances energy efficiency, ensuring that more of the transmitted power contributes to effective radiation [22]. Moreover, the suppression of surface waves plays a crucial role in maintaining the integrity of the antenna's performance. Surface waves can lead to unwanted radiation patterns and interference, diminishing the overall efficiency of the antenna [23]. By effectively controlling these phenomena, the SIW approach has led to significant improvements in several key performance metrics, including impedance matching — ensuring optimal power transfer, an increased impedance bandwidth — allowing the antenna to operate efficiently over a broader range of frequencies.

The proposed bow-tie antenna, inspired by substrate integrated waveguide (SIW) concepts, features simulated layouts with dimensions of $30 \times 13\,\text{mm}^2$ as illustrated in Figure 1. These dimensions are meticulously designed to optimize performance. The simulated reflection coefficient responses, indicated by S_{11} values lower than -10 dB, for the SIW based double bow-tie antenna are illustrated in Figure 2. Specifically, the antenna operates within the range of 26.43 GHz to 27.30 GHz, demonstrating remarkable efficiency that is conducive to various high-frequency applications. The results suggest that the antenna could be well-suited for the use in advanced communication systems that require reliable performance in this frequency range. This frequency span is crucial for applications that require versatile operational capabilities. Figure 3 clearly illustrates the simulated electric field distribution at the designated operating frequency. The electric field demonstrates a powerful presence along the bow-tie slot, peaking sharply at this frequency. This robust field is predominantly concentrated on the design's patches, which are critical to its overall efficacy. Furthermore, significant electromagnetic radiation extends across the ground plane, underscoring its vital role in the system's performance. The detailed distribution pattern unequivocally identifies regions of enhanced electromagnetic interaction, which are essential for optimizing functionality in the specified operational environment.

In terms of performance, Figure 4 reveals the antenna's impressive radiation characteristics, exhibiting a gain of 7.59 dBi. Additionally, as demonstrated in the accompanying figures, the principal lobe of the antenna is strategically positioned to focus in the broadside direction. This orientation is primarily attributed to the integration of a cavity-backed structure, which serves to significantly amplify the radiated energy directed to-

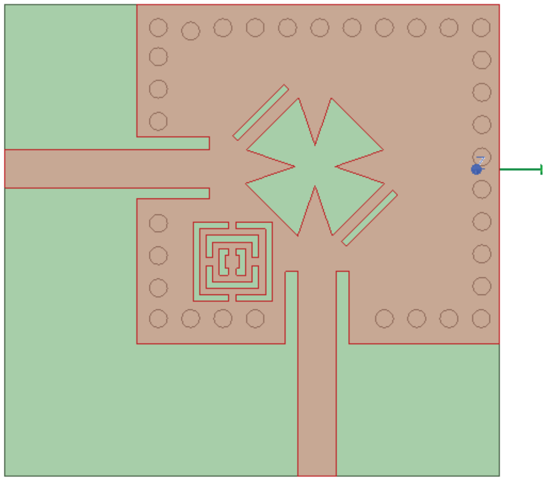

FIGURE 5. SIW structure with 2 slots, MTM and orthogonal feeding.

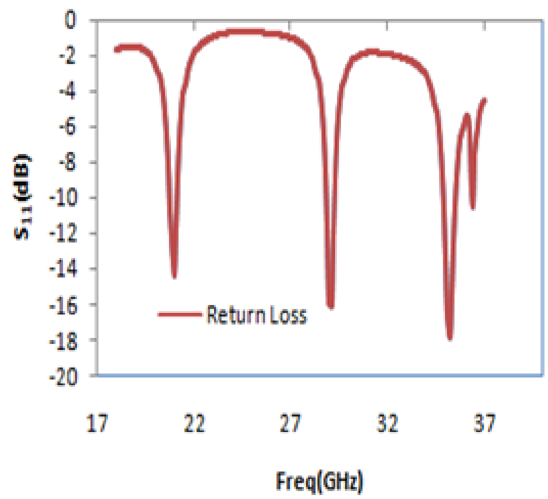

FIGURE 6. S parameter graph of SIW structure with 2 slots, MTM and orthogonal feeding.

ward the broadside while effectively suppressing any radiation that may occur in the rearward direction. As a result of these design considerations, the proposed antenna successfully achieves a unidirectional radiation pattern, characterized by enhanced performance and efficiency in the desired direction of emission. The excitation of the proposed antenna is accomplished through a straightforward microstrip line configuration, which is integrated with a waveguide port to ensure effective signal transmission. The entire design process is carried out using HFSS (High-Frequency Structure Simulator) software, known for its advanced electromagnetic simulations, facilitating an accurate representation of the antenna's performance parameters. The antenna's structural parameters are carefully fine-tuned to achieve optimal performance, encompassing factors such as dimension, material composition, and design geometry. These enhanced specifications are detailed comprehensively in Table 1, showcasing each parameter's influence on the antenna's efficiency and signal quality.

TABLE 1. Double bow-tie antenna's structural parameters.

Bowtie slant length	1.57 mm
Ground plane dimensions	14.6 mm × 14.6 mm
Bowtie Slant width	2.2 mm
Length of the rectangular slots	2.5 mm
Maximum width of the rectangular slots	0.7 mm
Radius of via holes	0.55/2 mm or 0.275 mm
Pitch	0.98 mm
Feed line length	5 mm
Feed line width	1.35 mm
Substrate height	0.508 mm
Substrate length	14.6 mm
Substrate width	14.6 mm
Metamaterial outermost dimensions	1.2 mm × 1.2 mm
Metamaterial innermost dimensions	0.8 mm × 0.8 mm

2.1. SIW Antenna Design with 2 Slots and MTM

This section presents three innovative and effective design methodologies inspired by Metamaterials (MTMs), Substrate Integrated Waveguide (SIW) technology, and orthogonal feeding techniques. These methodologies are employed to develop a slotted double bow-tie antenna that possesses a compact form factor while delivering multibands, wide bandwidth, and superior radiation characteristics. The antenna is specifically tailored for the use in 5G wireless communication systems, functioning efficiently within the millimeter-wave frequency band. The design process begins by selecting key parameters for simulations, which include the dimensions of the slotted bow-tie structure, dielectric substrate material, and the configuration of the feeding network. The methodologies integrate a strategic implementation of metamaterials to achieve improved performance metrics. By using a unit cell analysis, we tailored the effective permittivity to manipulate wave propagation characteristics, aiding in the design of radiating elements. The addition of orthogonal feeding techniques ensures that the antenna maintains a low return loss across the intended frequency bands. Specifically, a microstrip feed with a characteristic impedance of 50 Ω was designed, allowing for precise control of the feeding mechanism and thus maintaining the integrity of the broadband performance. The layout of the SIW was optimized for minimal loss and better integration within a compact form factor. Moreover, the addition of slots in Figure 5 significantly enhances the design flexibility, allowing for more precise control over the operating frequency bands of the cavity-backed antenna. The graph in Figure 6 illustrates the simulated reflection coefficient of the proposed design. The comprehensive simulated analysis of the proposed antenna structure highlights the incorporation of slot elements, which contributes to its ability to resonate at three distinct frequencies: 20.88 GHz, 28.98 GHz, and 35.12 GHz. This innovative design not only

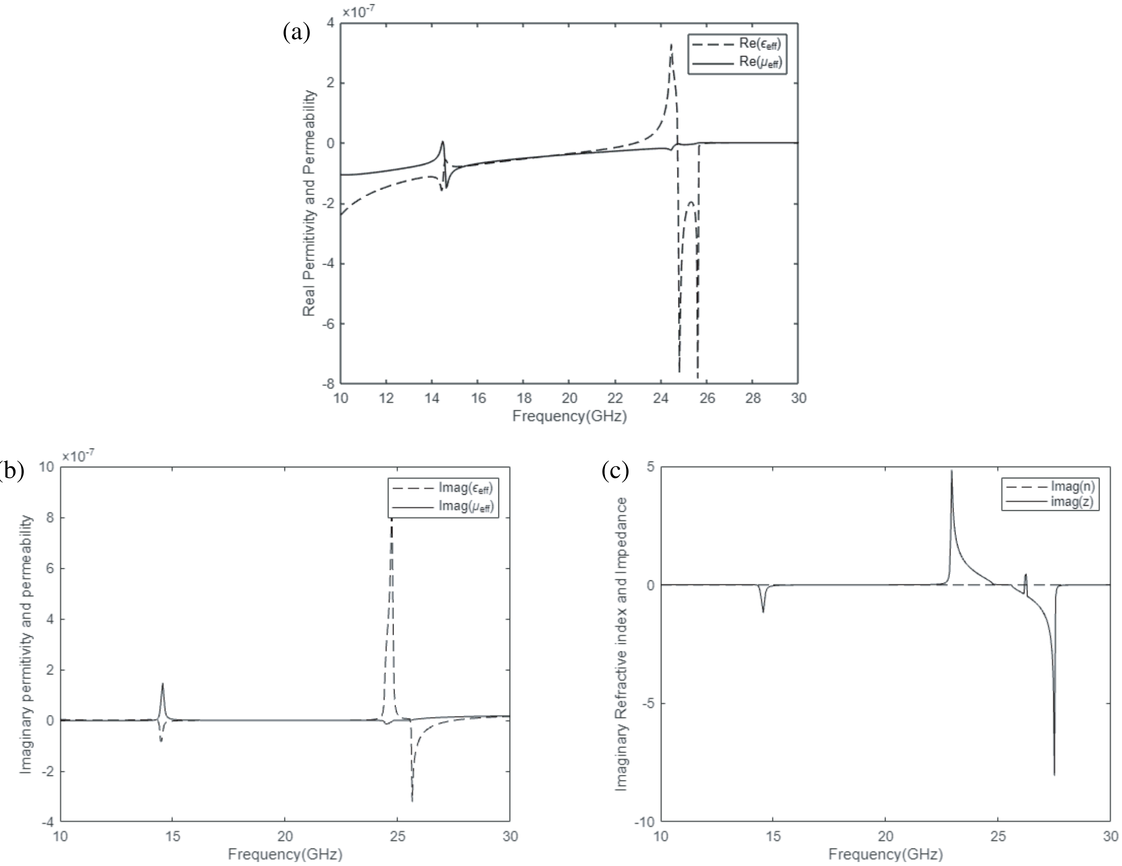

FIGURE 7. (a) Real permittivity and permeability of MTM. (b) Imaginary permittivity and permeability of MTM. (c) Refractive index and impedance of MTM.

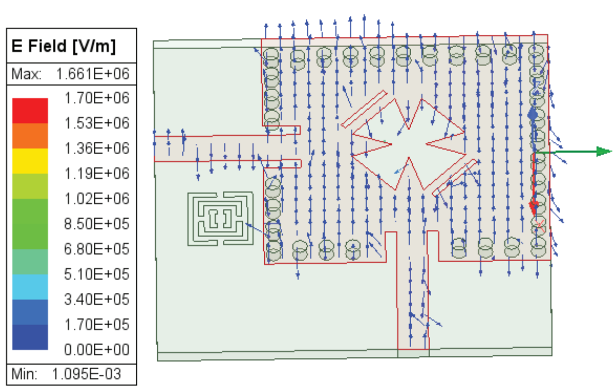

FIGURE 8. Electric field distribution of the structure.

improves resonance but also enhances performance characteristics. The structure achieves an impressive impedance bandwidth of 350 MHz at the first resonance frequency, 400 MHz at the second resonance frequency, and 670 MHz at the third resonance frequency with all defined at a -10 dB level. Figures 7(a) and 7(b) display the real and imaginary parts of the effective dielectric constant and magnetic permeability. The metamaterial has very low effective permeability, which leads to a low effective normalized intrinsic impedance near that frequency. Figure 7(a) shows that above 25 GHz, the relative effective electric permittivity and magnetic permeability are both negative, strongly supporting the metamaterial behavior of the MTM element being studied. In Figure 7(b), the imaginary parts of the relative effective electric permittivity and magnetic permeability are close to zero, indicating that the MTM structure has minimal loss, and additionally Figure 7(c) shows unit cell refractive index changes. Figure 8 clearly illustrates the simulated electric field distribution of the structure at the designated operating frequency. Furthermore, the simulated antenna gain results are visually represented in Figures 9, 10, and 11, demonstrating gains of 4.37 dBi, 3.60 dBi, and 6.67 dBi respectively at each of the resonant frequencies. This showcases the antenna's effectiveness in converting input power into radio waves. Also these visualizations clearly indicate that the antenna exhibits a unidirectional radiation pattern, suggesting its capacity to focus energy in a specific direction, which is advantageous in numerous applications such as communications and radar systems.

3. PARAMETRIC STUDIES

3.1. Effect of Bowtie Slot Position

A detailed parametric analysis is meticulously performed to dissect the influence of various positions of the bow-tie slot on the overarching behavior of the system. The simulation outcomes compellingly demonstrate that modifying the slot's position instigates significant shifts in return loss values at the critical first and third resonant frequencies, as clearly illustrated

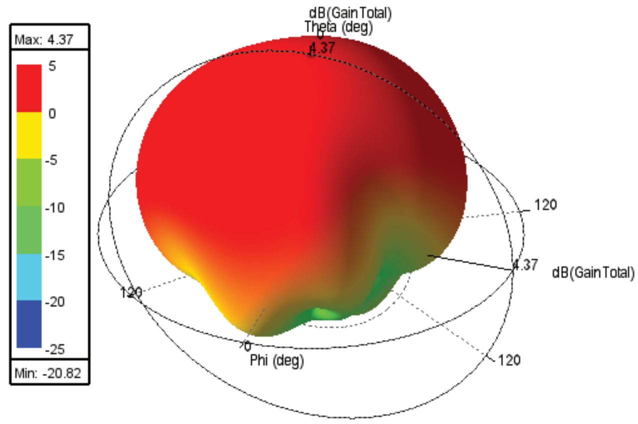

FIGURE 9. 4.37 dBi gain at 20.88 GHz frequency of SIW antenna structure with 2 slots, MTM and orthogonal feeding.

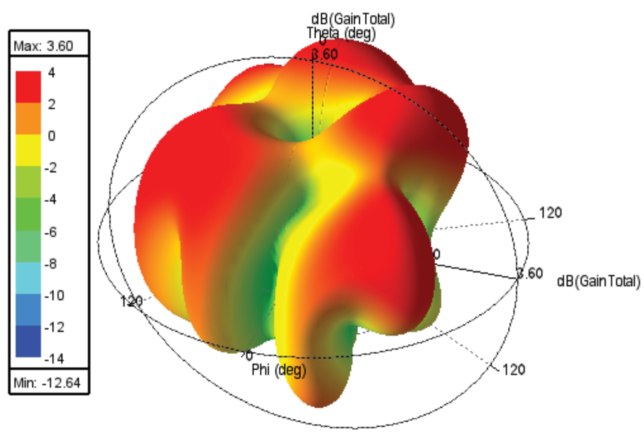

FIGURE 10. 3.60 dBi gain at 28.98 GHz frequency of SIW antenna structure with 2 slots, MTM and orthogonal feeding.

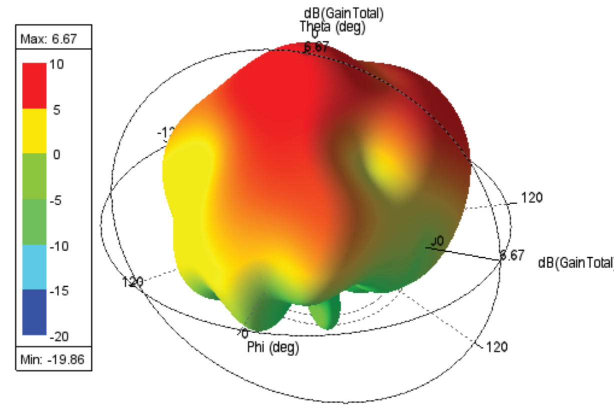

FIGURE 11. 6.67 dBi gain at 35.12 GHz frequency of SIW antenna structure with 2 slots, MTM and orthogonal feeding.

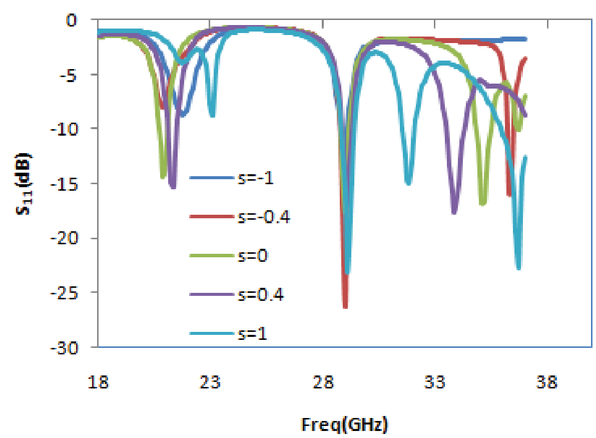

FIGURE 12. Parametric analysis on position of bow-tie slot.

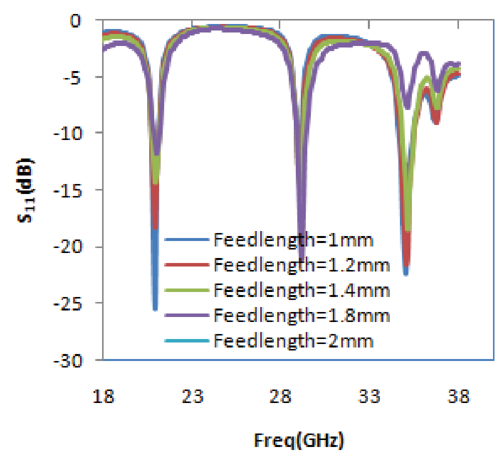

FIGURE 13. Parametric analysis on feed-length.

in Figure 12. Specifically, as the slot is adjusted incrementally from -1 mm to 1 mm, an observable increase in the return loss value emerges. This shift points to a potential degradation in impedance matching, which is crucial for effective energy transfer. Moreover, a slight yet noteworthy shift in the upper resonating frequency is detected, highlighting how essential precise slot positioning is for achieving optimal operational characteristics in the system. Intriguingly, throughout these adjustments, the central resonating frequency remains steadfast, showing no signs of fluctuation. However, the escalating return loss values hint at an underlying deterioration in impedance matching, potentially leading to diminished energy transmission efficiency across the affected frequency range. This behavior accentuates the intricate balance that must be struck between slot placement and system performance, illuminating the necessity for meticulous calibration in design protocols.

3.2. Feedline Length

As the length of the feedline is varied from 1 mm to 2 mm in Figure 13, results show that there is no discernible shift in either of the resonating frequencies of the antenna. This stability is crucial as it indicates that the fundamental operational characteristics of the antenna remain unaffected by minor adjustments in the feedline length. However, a notable increase in the return loss value of the designed antenna has been measured at all three resonating frequencies. This increase suggests a deterioration in impedance matching, which implies that the variations in feedline length, despite leaving resonating frequencies unchanged, impact the antenna's efficiency in energy transmission. Such findings highlight how fine-tuning the feedline

TABLE 2. Comparison of the performance between the designed and previously reported works.

Ref.	Size (mm^2)	RF (GHz)	RL (dB)	Gain (dBi)	IBW	WS	TYPE	MTM
[17]	25.5×24	12.15 GHz, 12.59 GHz, and 13.86 GHz	> 30 dB	3.80 dBi, 4.03 dBi, and 4.90 dBi	2.03 GHz	Ku Band	SIW cavity backed Bow-tie complementary ring slot antenna	CSRR
[20]	20×16	8.28 GHz and 10.164 GHz	> 20 dB at 8.28 GHz and > 30 dB at 10.164 GHz	5.3 dBi and 4.4 dBi	600 MHz and 888 MHz	X band radar and satellite communications	SIW cavity backed Bow-tie slot antenna	NO
[24]	17.8×16	9.98 and 10.6 GHz	> 30	3.53 and 5.4 dBi	1.03 GHz	X Band	SIW cavity backed Bow-tie slot antenna	NO
[25]	36×36	3.5 GHz and 4.9 GHz	> 15 dB at 3.5 GHz and > 20 dB at 4.9 GHz	5 dBi and 3.7 dBi	400 MHz and 750 MHz	5G and public safety bands	Metamaterial-Based Double-Sided Bowtie Antenna	CSRR
[26]	33×28	7.56 GHz and 9.88 GHz	> 30 dB at 7.56 GHz and > 40 dB at 9.88 GHz	5.2 dBi to 6.1 dBi	3 GHz	C-bandand X-band	SIW enhanced Bow-Tie Antenna Based on CSRR	CSRR
[27]	30×16	33 GHz	> 25 dB	6 dBi	2.6 GHz	Ka Band	MTM and SIW-Inspired Bowtie Antenna Loaded with AMC	CSRR, SRR
Proposed	30×13	20.88 GHz, 28.98 GHz, 35.12 GHz	> 14 dB at 20.88 GHz and > 16 dB at 28.98 GHz > 18 dB at 35.12 GHz	4.37 dBi and 3.60 dBi and 6.67 dBi	350 MHz, 400 MHz, 670 MHz	K and Ka band	SIW cavity backed Double Bow-tie slot antenna based on CSRR	CSRR

Ref — Reference, RF — Radio Frequency, IBW — Impedance Bandwidth, IL — Insertion Loss, RL — Return Loss, NR — Not Reported, NA — Not applicable, RE — Radiation Efficiency, WS — Wireless Standard

length can significantly influence antenna performance. Optimizing this parameter is essential for achieving the best possible efficiency, ensuring that the antenna effectively transmits and receives radio waves with minimal energy loss. This underscores the importance of meticulous feedline adjustment as part of the overall antenna design and optimization process.

4. EXPERIMENTAL VALIDATION

The proposed antenna is meticulously crafted on a Rogers RT Duroid 5880 substrate, characterized by its dielectric constant (ε_r) of 2.2 and a precise thickness of 0.787 mm. The tangible prototype of the antenna, along with the testing setup within an anechoic chamber, is presented in Figure 14. The simulated performance reveals an impressive tripleband response, spanning frequencies 20.88 GHz, 28.98 GHz, and 35.12 GHz resulting in noteworthy bandwidths of 350 MHz , 400 MHz, and 670 MHz, respectively. The measured reflection coefficient, depicted in Figure 15, aligns remarkably well with the simulated results, further validating the design's efficacy. At the heart of its capabilities, the antenna boasts simulated gains of 4.37 dBi, 3.60 dBi, and an exceptional 6.67 dBi at its three resonant frequencies, visually represented in Figure 16. The measured gain of the antenna closely aligns with the simulated results, across the operational frequency bands as shown in Figure 17. This accuracy demonstrates the antenna's effec-

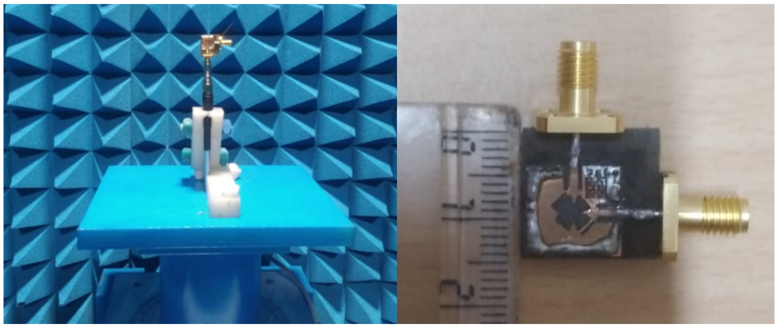

FIGURE 14. Anechoic chamber setup for measurement.

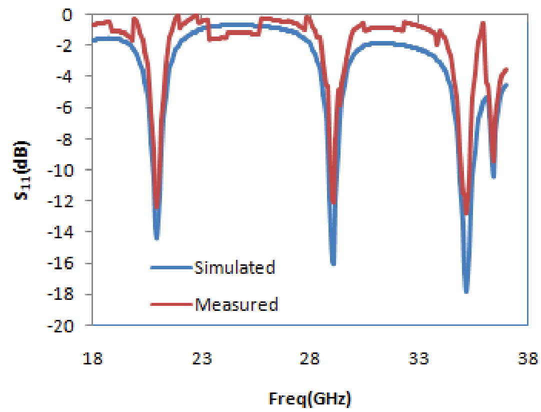

FIGURE 15. S parameter graph of the SIW structure.

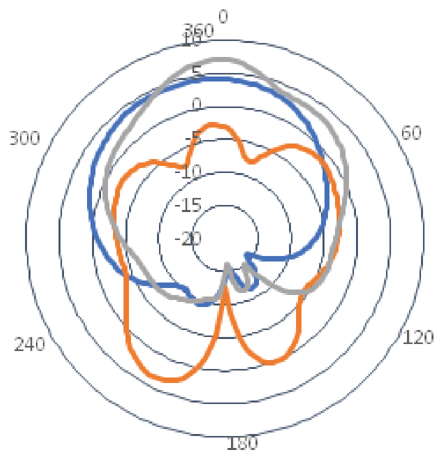

FIGURE 16. Simulated gain plot at all three frequencies.

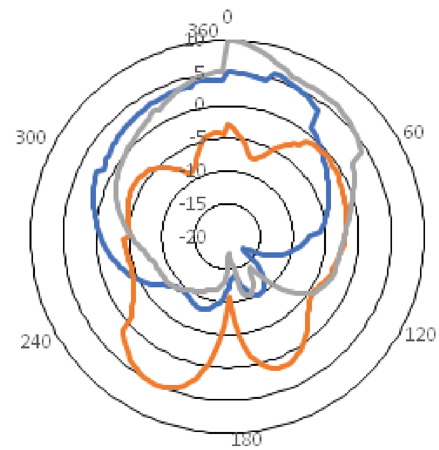

FIGURE 17. Measured gain plot at all the three frequencies.

tive design and performance; however, minor discrepancies can be attributed to limitations in the fabrication process, resulting in slight deviations between the simulated and measured outcomes. The choice of Rogers RT Duroid 5880, while being advantageous for its low loss and high-frequency performance, can also present challenges such as cost and mechanical fragility, which may complicate mass production. Additionally, the complexity of achieving precise fabrication tolerances for bow-tie slots and feeding techniques might introduce inconsistencies in real-world applications, impacting overall performance. Enhancing the reproducibility and consistency of manufacturing processes will be crucial for minimizing deviations between simulated and measured outcomes. In Table 2, a performance comparison between the designed antenna and relevant previously reported research studies is provided.

5. CONCLUSION

This paper presents a cutting-edge Double Bow-tie antenna, ingeniously engineered using a metamaterial-enhanced cavity-backed Substrate Integrated Waveguide (SIW). The antenna design prominently features a bow-tie shaped slot that is meticulously crafted to optimize electromagnetic performance. It is energized through a straightforward yet effective microstrip line feeding technique, which not only achieves superior impedance matching but also significantly amplifies the antenna's gain, resulting in enhanced signal clarity and strength. The innovative architecture incorporates precisely designed slots within the antenna structure, enabling it to operate across three distinct frequency bands. To amplify its performance further, an orthogonal feeding technique has been intricately applied, coupled with the integration of advanced metamaterials (MTMs). This combination leads to remarkable improvements in bandwidth across all three operational bands, showcasing the antenna's potential to meet demanding communication standards. The fabrication of this state-of-the-art antenna is accomplished using a single substrate, employing standard PCB technologies that ensure reliability and cost-effectiveness. Furthermore, the applications of this advanced double bow-tie antenna extend beyond traditional wireless communications as it holds promise for the use in next-generation 5G and 6G technologies and satellite communication systems where compact and efficient design is crucial. Future research could explore the integration of this antenna within dynamic environments, adaptive communications, and multi-frequency operations, potentially leading to breakthroughs in smart city technologies and autonomous vehicle communications.

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