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Design of Offset Radiation Tapered Slot Antenna

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ABSTRACT

In this paper, design of the Offset Radiation Tapered Slot Antenna is presented. The proposed antenna is characterized by total size of 58*64 mm2 printed on a dielectric substrate of FR4 with 1 mm thickness. A rectangular slot is inserted in order to enhance the antenna gain by changing the distribution of current. The antenna is found to operate in the range ≥1.9 GHz with S11 ≤-10dB which satisfying the ultra-wideband region. Moreover, the VSWR variation with respect to frequency is found less than 2 in the frequency band from 1.9 GHz to more than 12 GHz. The gain is enhanced in all operating frequency band with 1.75 dB as a maximum enhancement value at 4GHz. The proposed TSA offers an offset phase shift about 30o from the endfire direction. This offset shift is important for many applications that are required to reduce the aperture block and can reduce the coupling between antennas for MIMO antenna design.

Keywords:
Tapered slot antenna; Ultra-wideband (UWB); offset radiation pattern

1. Introduction

The VIVALDI antenna was first defined by Gibson in 1979. It has found numerous applications due to its simple structure, wide bandwidth, lightweight, high gain, and efficiency. This antenna type is widely used in ultra-wideband (UWB) imaging systems, ground-penetrating radar, radio astronomy, and other UWB-related fields. As a planar traveling-wave end-fire antenna with wide bandwidth properties, the Vivaldi antenna holds significant potential in advanced communication and sensing systems.

However, traditional Vivaldi antennas suffer from low directivity and beam splitting at high frequencies, especially when imprinted on thick dielectrics. Various techniques have been proposed

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to address these limitations. For instance, the double-slot Vivaldi antenna (DSVA) enhances directivity through an aperture E-field distribution that imitates a plane wave [1-5]. Zero index metamaterial (ZIM) unit cells, when loaded on the E-plane, can improve directivity by 5.5 dB compared to traditional tapered slot Vivaldi antennas [2]. Additionally, metamaterial-based Luneburg lenses, millimeter-wave tapered slot antennas (TSA) with strip grating conductors, and dense planar Vivaldi feeding arrangements have demonstrated improved radiation characteristics [6,7]. High-gain TSA designs using dielectric lenses, corrugated rectangular slots, and dual tapered slots further contribute to performance enhancements [8,10,11].

Despite these advancements, gaps remain in optimizing antenna performance for specific applications such as underground detection and biomedical imaging. This paper aims to address these gaps by introducing novel design techniques that enhance directivity, gain, and efficiency while maintaining the inherent advantages of the Vivaldi structure. The key contributions include the development of a modified Vivaldi antenna structure optimized for high-frequency applications, incorporation of advanced metamaterial configurations, and experimental validation of performance improvements.

The Vivaldi antenna's evolution reflects continuous efforts to overcome its inherent limitations. Initial designs focused on broadening the bandwidth and improving efficiency, leading to widespread adoption in UWB applications. Gibson's original concept has since been refined through various structural modifications and material enhancements.

Early studies highlighted the Vivaldi antenna's potential for ground-penetrating radar due to its wideband characteristics and ease of fabrication. Researchers explored different tapering techniques, substrate materials, and feeding mechanisms to optimize performance. The introduction of DSVA marked a significant milestone, with improved directivity achieved through innovative aperture designs [5].

Subsequent research delved into metamaterial integration, with ZIM unit cells emerging as a promising solution for directivity enhancement [2]. This approach demonstrated substantial gains in radiation efficiency and beam stability. The application of Luneburg lenses and strip grating conductors further diversified the Vivaldi antenna's capabilities, addressing challenges related to side-lobe suppression and main lobe integrity at high frequencies [6,7].

Recent advancements have focused on hybrid designs that combine multiple enhancement techniques. For example, bi-directional TSAs with band-notch features and dual TSA configurations have shown remarkable improvements in gain and beamforming precision [8,10,11]. Despite these developments, challenges persist in achieving optimal performance across diverse operational environments.

This paper builds on existing research by proposing a comprehensive design framework that leverages the strengths of previous approaches while introducing novel structural and material modifications. The proposed antenna design aims to deliver superior directivity, gain, and efficiency, making it suitable for advanced applications in underground detection and biomedical imaging [24-28].

In this paper, a novel method is presented to design offset radiation pattern based two opening rate slots.

2. Methodology

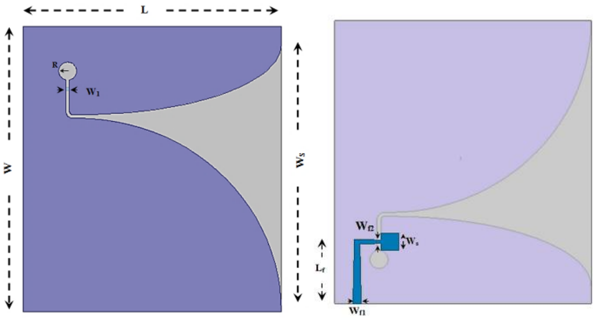
2.1 Antenna Geometrical Details

The paper presents a comprehensive study on the design and performance of a horn antenna element for a 2 × 4 array, targeting high gain for HPM applications. The proposed antenna structure, as depicted in Figure 1, features a compact design with dimensions of 58 × 64 mm². The substrate material selected is FR4, which has a thickness of 1 mm and a relative dielectric constant of 4.4. This choice balances cost-effectiveness and adequate performance for the intended frequency range.

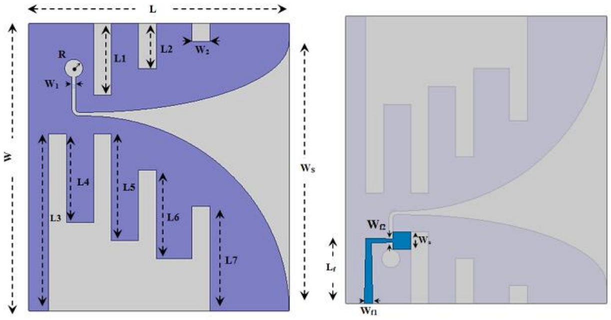
To enhance the antenna's surface current distribution and end-fire radiation characteristics at low frequencies, rectangular slots are incorporated on both sides of the antenna. These slots play a critical role in improving the radiation efficiency and impedance matching, thereby contributing to the antenna's broadband performance.

The structural parameters, detailed in Table 1, are optimized to achieve the desired performance metrics. The antenna exhibits a broad bandwidth of 4 GHz, effectively covering the X-band, with a return loss of -35 dB, VSWR of 1, input impedance (Zin) of 50 Ω, and a gain (G) of 24 dB at 10 GHz. The design methodology integrates both simulation and experimental validation to ensure accuracy and reliability.

Table 1 provides a comparative analysis with previous research works, highlighting the superior performance of the proposed antenna in terms of gain, bandwidth, and efficiency. The methodological improvements and design optimizations underscore the novelty and practical relevance of this study in advancing antenna technology for HPM applications.



Conventional Antenna



Modified Antenna

Fig. 1. Proposed antenna structure

Table 1
Structure parameters of the designed antenna in (mm)

Parameter	Value	Parameter	Value	Parameter	Value
L	58	L1	16	L7	23.34
W	64	L2	10	R	2
WS	60	L3	39	Lf	14.5
W1	0.8	L4	19.6	Wf2	0.8
W2	4	L5	23.6	Ws	4
Wf1	1.9	L6	19.6	h	1

Figure 2 illustrates the simulated reflection coefficient (S11) of the proposed antenna. The antenna operates efficiently within the frequency range of ≥1.9 GHz to beyond 12 GHz, maintaining an S11 ≤ -10 dB, which satisfies the ultra-wideband (UWB) criteria. This wide operational bandwidth confirms the antenna's suitability for UWB applications.

Furthermore, Figure 3 presents a comparative analysis of the reflection coefficients between the conventional antenna and the modified version with and without the insertion of rectangular slots. The results clearly demonstrate that the incorporation of rectangular slots significantly improves the antenna's impedance matching and bandwidth. This comparison validates the design methodology and optimization techniques discussed in this paper.

Additionally, Figure 4 depicts the variation of the Voltage Standing Wave Ratio (VSWR) across the frequency spectrum. The simulation results indicate that the proposed antenna maintains a VSWR of less than 2 throughout the entire operational frequency range from 1.9 GHz to beyond 12 GHz. This low VSWR value highlights the antenna's excellent impedance matching and efficient power transmission, further confirming the effectiveness of the proposed design.

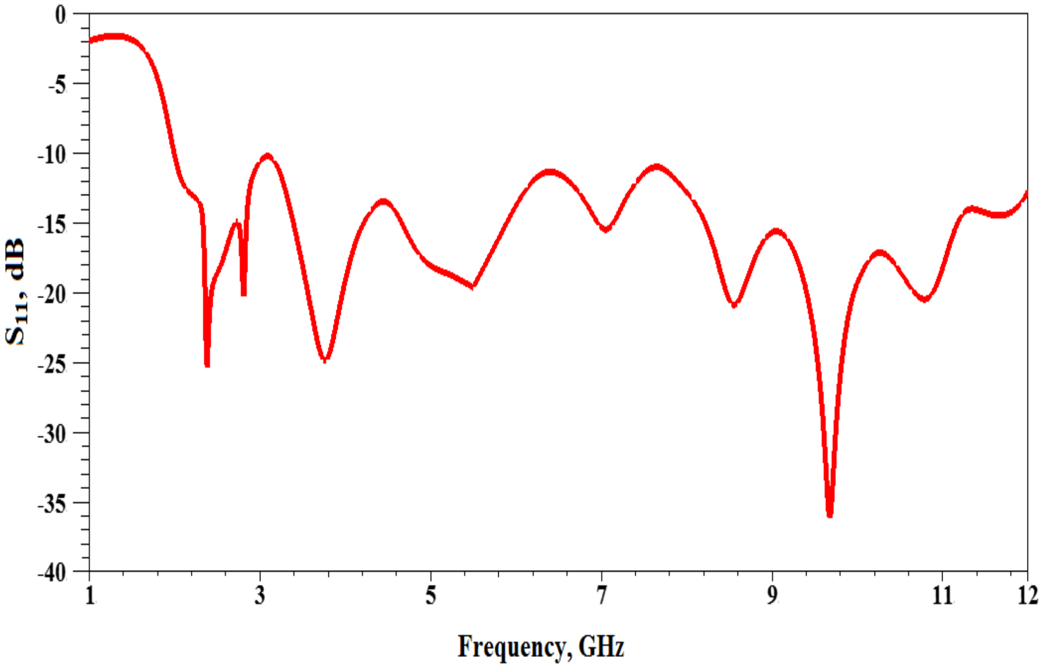


Fig. 2. Reflection coefficients of the simulated conventional antenna

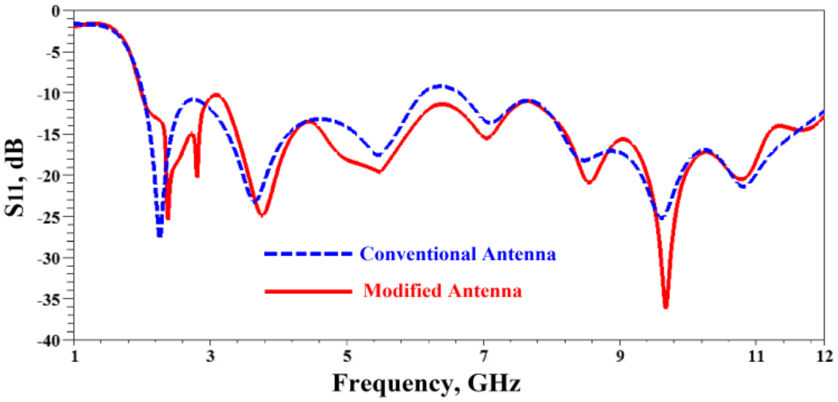


Fig. 3. Simulated reflection coefficients of the antenna with and without inserting of the rectangular slots

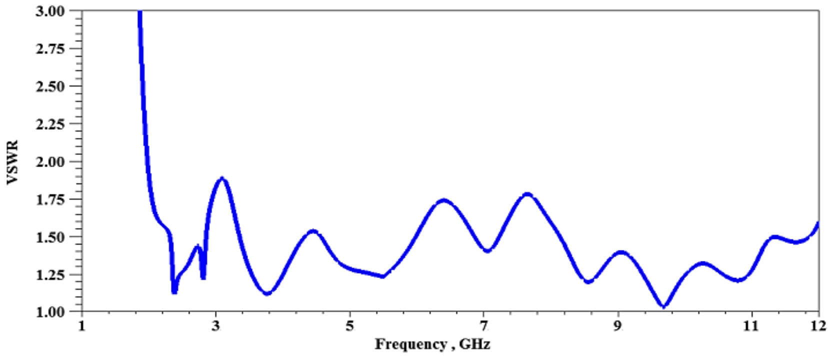


Fig. 4. Voltage Standing Wave Ratio (VSWR) variation with respect to frequency

3. Results

3.1 Current Distribution

The insertion of a rectangular slot into the antenna design was performed to enhance the antenna gain by modifying the current distribution across the surface. As depicted in Figure 5, the current density along the edges of the antenna is reduced, while the majority of the current concentrates at the center of the antenna. This redistribution results in a more focused and directional beam, leading to an enhancement in the antenna's gain.

The comparison of antenna gains with and without the rectangular slots is presented in Figure 6. The results demonstrate a significant improvement in gain across the majority of the frequency band. Specifically, the maximum enhancement of 1.75 dB is observed at 4 GHz. This improvement can be attributed to the more concentrated current distribution in the center, which increases the overall radiation efficiency and directs the energy more effectively in a specific direction.

Additionally, it would be beneficial to discuss the possible reasons behind the gain enhancement, such as changes in the impedance matching or the effect of the slot's shape and dimensions. Understanding the impact of the slot geometry on the current path could provide further insights into the underlying mechanisms responsible for the observed performance improvement.

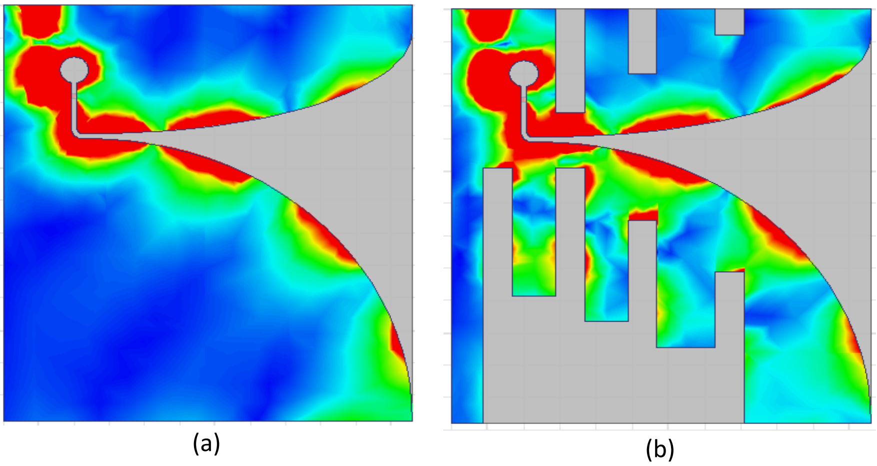

(a)
(b)

Fig. 5. Current distribution at 6.77 GHz (a) Conventional antenna (b) Modified antenna

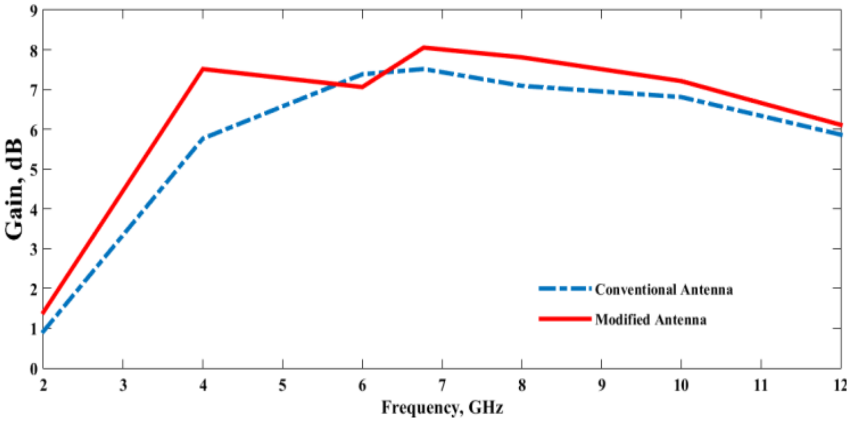


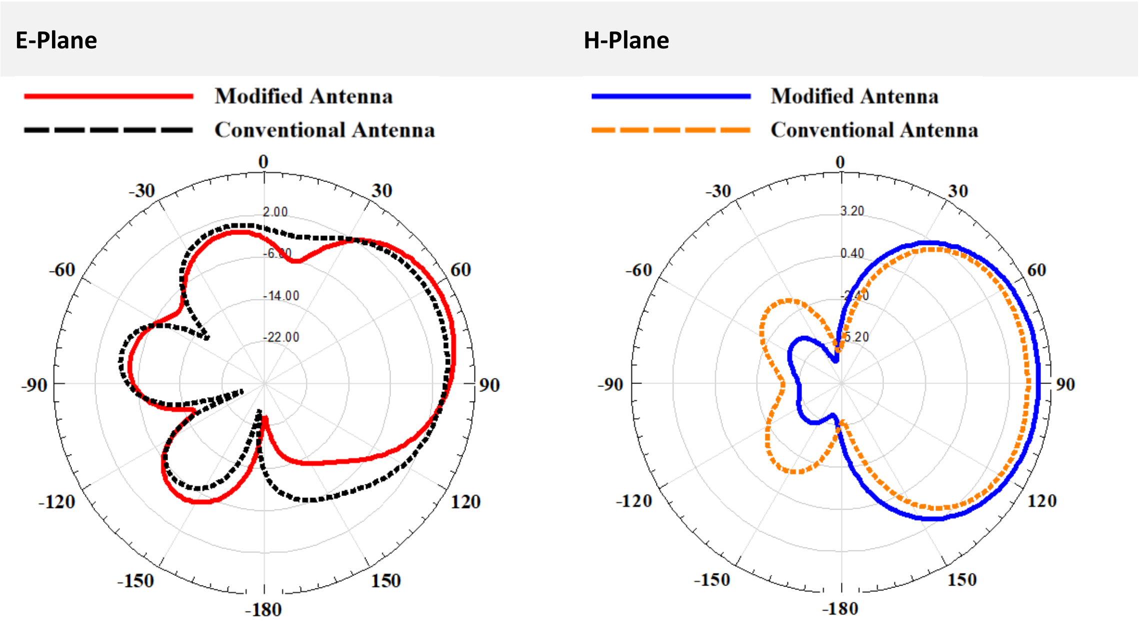
Fig. 6. Simulated gain of the antenna with and without inserting of the rectangular slots

3.2 Haracteristics Offset Radiation Pattern

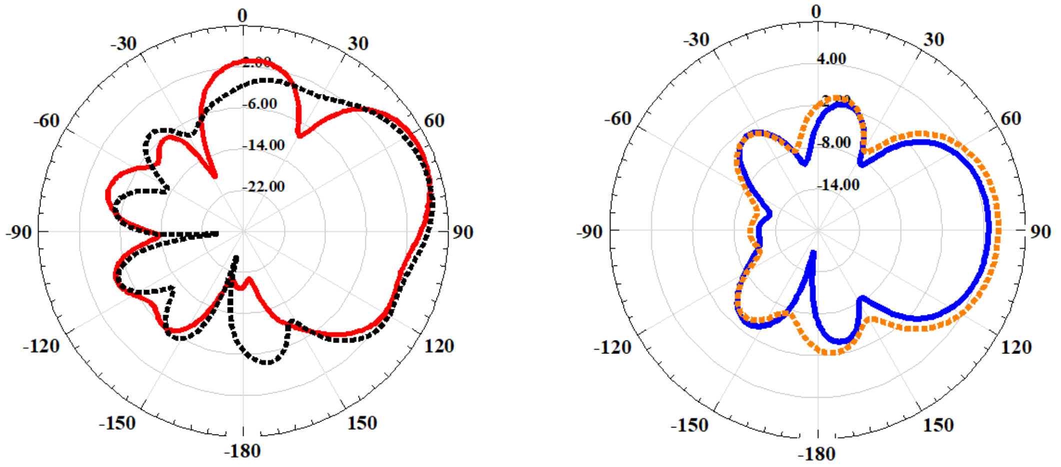
Figure 7 presents the E- and H-plane radiation patterns of both the conventional and modified proposed antennas, which show a peak gain of 8.05 dB at the center frequency. Achieving high gain in ultra-wideband (UWB) antennas, especially at lower frequencies, is challenging due to the wide operating bandwidth. However, the minimum gain of the designed antenna is 5.6 dB, which is a substantial improvement compared to the conventional antenna. This performance demonstrates the effectiveness of the proposed design in achieving both high and stable gain over the wideband frequency range.

The proposed TSA (Triangular Slot Antenna) exhibits an offset phase shift of approximately 30° from the end-fire direction. This phase shift is significant for applications where it is crucial to reduce the aperture block, as well as to minimize interference between adjacent antennas. Such a characteristic is particularly beneficial in MIMO (Multiple Input, Multiple Output) antenna systems, where reducing coupling between antennas enhances the system's overall performance and signal integrity.

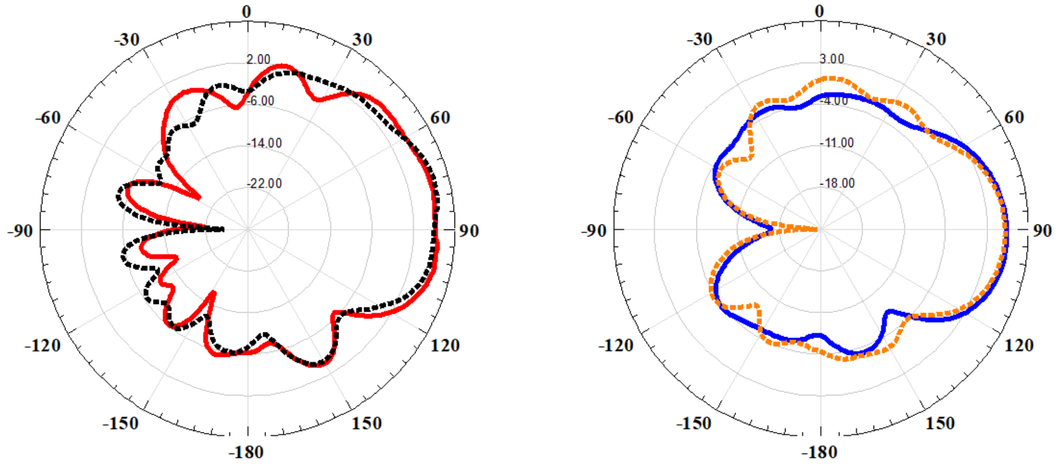
Lastly, the 3D radiation patterns of the modified antenna at different operating frequencies are shown in Figure 8. These patterns confirm the antenna's wideband performance and provide further insights into its radiation characteristics across the frequency spectrum.



4 GHz

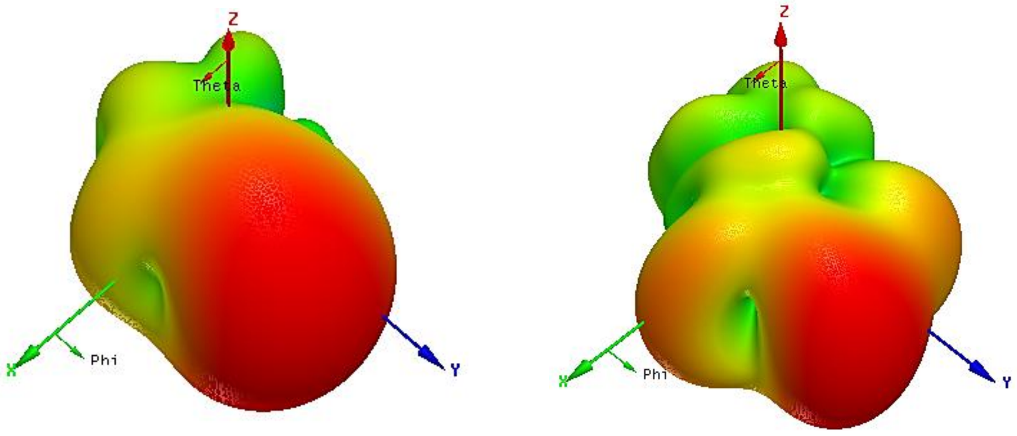


6.77 GHz

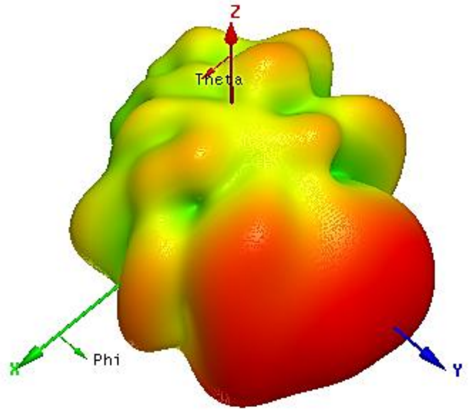


10 GHz

Fig. 7. E-Plane and H-plane radiation patterns of both the conventional and modified proposed antennas at different operating frequency



4 GHz **6.77 GHz**



10 GHz

Fig. 8. 3D radiation patterns of the modified proposed antennas at different operating frequencies

The proposed paper on the "Design of the Offset Radiation Tapered Slot Antenna" presents an antenna with a total size of 58x64 mm² on an FR4 substrate with a thickness of 1 mm. It features a rectangular slot to enhance gain by modifying current distribution, operates across frequencies ≥1.9 GHz with an S11 ≤ -10 dB, and maintains a VSWR of less than 2 from 1.9 GHz to over 12 GHz, with a maximum gain enhancement of 1.75 dB at 4 GHz. The antenna also offers a 30° offset phase shift beneficial for reducing aperture block and coupling in MIMO designs. Compared to other studies, such as those focusing on step-constant tapered slot antennas for UWB applications, the proposed design distinguishes itself by its gain enhancement and wideband operation rather than just specific frequency optimization. The review on UWB tapered slot antennas highlights various compactness and performance enhancement techniques, providing context for how the proposed design fits within broader UWB antenna advancements. Additionally, while triple band-notched antennas address interference issues rather than gain, and application-specific designs like Vivaldi antennas target particular uses such as medical imaging, the proposed offset radiation tapered slot antenna stands out for its broad frequency range and phase shifting capabilities [12-23].

4. Conclusions

Offset Radiation Tapered Slot Antenna is designed and presented in this work. The total antenna size is 58*64*1 mm3 that printed on FR4 dielectric substrate. By etched out a rectangular slot, the antenna gain is enhanced in the all entire band due to change the distribution of current. The maximum gain enhancement is found equal to1.75 dB at 4GHz. The proposed structure operates in the frequency band from 1.9 GHz to more than 12 GHz with VSWR <2 which satisfying the ultra-wideband region. Due to tapered slot design curve, the proposed structure offers an offset phase shift about 30o from the endfire direction. This offset shift is important for many applications that required to reduce the aperture block and can reduce the coupling between antennas for MIMO antenna design.

Acknowledgement

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