

High-Isolation SIW-Based MIMO Antenna for Mid X-Band Wireless Applications

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Abstract—This paper presents a substrate-integrated waveguide (SIW) based multiple-input multiple-output (MIMO) antenna operating in the X-band frequency range from 9.4 GHz to 10.5 GHz. The design excited by a coaxial cable feeding technique to achieve efficient feeding, wide impedance bandwidth around 12%, and compact planar integration. Simulation results demonstrate a high isolation level exceeding -25 dB between antenna elements, effectively minimizing mutual coupling. The antenna exhibits an average radiation efficiency of approximately 90%, highlighting the low-loss characteristic of the SIW configuration. Moreover, the gain remains above 6.66 dBi across the entire operational band, ensuring satisfactory radiation performance for high-frequency wireless applications. These characteristics make the proposed antenna as a strong candidate for many applications like radar, satellite communication, and advanced wireless systems requiring compactness, high isolation, and robust performance within the mid X-band spectrum.

Keywords—Antenna, SIW, MIMO, high isolation, X-Band.

I. INTRODUCTION

Due to the growing demand for high data rates, improved signal-to-noise ratio (SNR), and the increasing need for multimedia services in modern wireless communication networks, Multiple Input Multiple Output (MIMO) technology has emerged as a key solution to enhance traffic capacity and overall network performance [1]. Multiple-input multiple-output (MIMO) antenna technology has become essential in advancing modern wireless communication systems by improving channel capacity, data throughput, and link reliability [2]. The substrate-integrated waveguide (SIW) technique [3] presents a promising alternative. Unlike conventional microstrip designs, SIW technology is increasingly considered a future solution for planar transmission lines due to its planar configuration, low loss, and compact structure, which make it well suited for high-frequency antenna applications [4]. Efficient excitation using coaxial cables provides good impedance matching and

minimizes feeding losses. Several antenna designs have demonstrated the potential of SIW-based MIMO antennas to overcome the limitations of conventional microstrip and dielectric resonator antennas, such as narrow bandwidth and high mutual coupling. In [5] Kumar et al. presented a compact half-mode SIW cavity MIMO antenna at 3.51 GHz using slot etching and coaxial feeding, achieving enhanced bandwidth (160 MHz), isolation (19.5 dB), and high radiation efficiency more than 70%. Although their work focuses on lower frequencies, it validates the effectiveness of SIW cavity segmentation and slot techniques for improving isolation and bandwidth. In [6] a dual-band microstrip SIW antenna operating at approximately 10 GHz and 22 GHz, achieving gain values in the range of 6 to 7.2 dBi. This design effectively leverages SIW cavity resonators combined with coaxial feeding techniques to maintain low reflection coefficients and minimize losses. Although targeting dual-band operation, the antenna's performance in terms of gain and bandwidth is comparable to that expected in single-band SIW designs within the X-band frequency range, underscoring the versatility and robustness of SIW technology for multi-frequency high-performance antenna applications. The work on [7] introduces a compact, dual-band, eight-port Multiple Input Multiple Output (MIMO) stacking antenna integrated with Substrate Integrated Waveguide (SIW) and a common ground. The antenna operates in the 9.2-9.5 GHz and 11.5-12.25 GHz frequency bands, achieving The SIW-integrated MIMO antenna demonstrates excellent isolation (>15 dB), high gain (8 dB and 6.6 dB), and favourable diversity parameters. This work presents an SIW-based MIMO antenna design with high isolation of more than -25 dB and acceptable impedance matching in the whole frequency band. The proposed SIW MIMO antenna is designed to operate in the X band application from 9 GHz to 10.5 GHz range. By integrating SIW technology with MIMO and coaxial feeding, the proposed solution achieves compactness, acceptable gain, and high isolation, making it suitable for advanced wireless applications like satellite and radar. The metrics performance

such as ECC, diversity gain, CCL and TARC of the proposed SIW MIMO antenna are also evaluated, showing excellent results for MIMO applications.

II. ANTENNA DESIGN

This paper introduces a Substrate Integrated Waveguide (SIW) antenna engineered to deliver enhanced performance while preserving a compact and straightforward design, making it well-suited for X-band applications. The antenna is implemented on a single-layer Rogers Duroid 5880 substrate, which features a relative permittivity of 2.2, a loss tangent of 0.0009, and a thickness of 3 mm. The detailed geometry and configuration are illustrated in Figure 1.

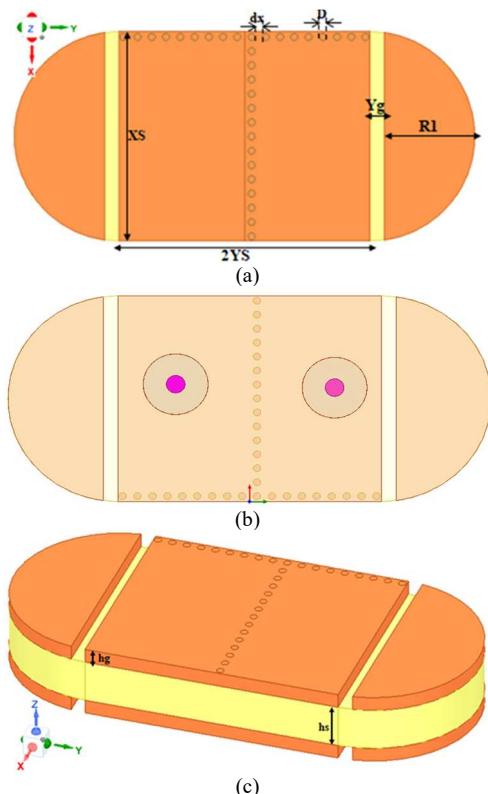


Fig. 1. Geometry of the proposed antenna (a) Top view (b) Bottom View and (C) 3D View

TABLE I. ANTENNA DIMENSION PARAMETERS IN MM

Para.	Value (mm)	Para.	Value (mm)	Para.	Value (mm)
XS	14.9	D	0.5	Yg	1
YS	8.9	dx	1	R1	6.45
hs	3	hg	1		

The SIW cavity's sidewalls are formed by metallic vias positioned along all four edges of the structure. Each via has a diameter denoted by D , and the spacing between adjacent vias is represented by dx . The complete set of geometric parameters for the proposed antenna is provided in Table I.

The proposed antenna incorporates a slot etched on both the upper and lower conductive surfaces. Waveguide-fed slot antennas are recognized for their low-profile configuration and ease of integration with planar microwave circuits, making them an attractive choice for X-band applications. To

take advantage of these characteristics, a 50-ohm feed line is employed to excite the structure.

The design and electromagnetic analysis of the slotted configuration, including the investigation of supported modes, are carried out using ANSYS HFSS. This full-wave simulation tool enables a comprehensive evaluation of the antenna's behavior and performance within the X-band frequency range.

A. Single Element Steps

To achieve wideband performance in the SIW antenna, this study emphasizes the optimization of the slot design. The antenna's characteristics are evaluated through a comparative analysis of three configurations: one without vias (Antenna 1), one incorporating vias (Antenna 2), and another integrating both vias and a slot (Antenna 3). As illustrated in Figure. 2, each design stage contributes progressively to performance enhancement. Notably, the incorporation of the slot in Antenna 3 significantly improves the impedance bandwidth, highlighting its critical role in bandwidth enhancement.

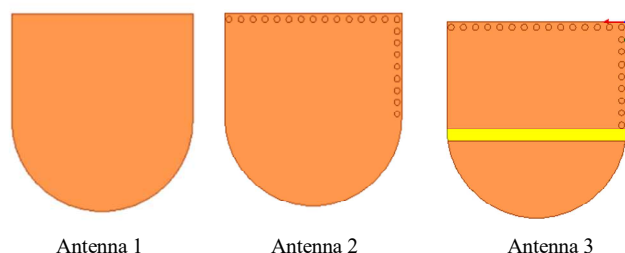


Fig. 2. Step-by-Step design of the proposed antenna.

As shown in Figure. 3, the results reveal that Antenna 1 and Antenna 2 both lacking a slot fail to exhibit any significant resonance, with their reflection coefficients remaining above -10 dB. In contrast, Antenna 3, which includes an integrated slot, demonstrates two distinct resonant frequencies at 9.24 GHz and 10.11 GHz. The inclusion of the slot markedly improves the antenna's performance, yielding an overall impedance bandwidth of 11.92%.

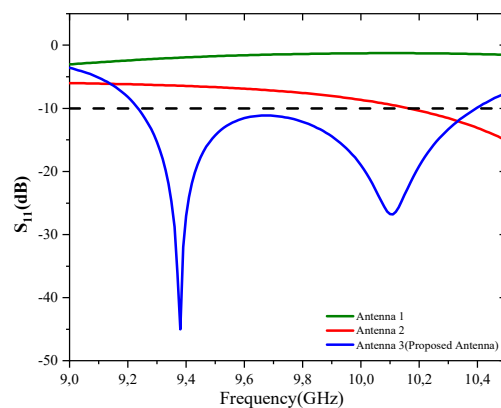


Fig. 3. Reflection coefficient (S_{11}) for three designs.

Figure 4 presents the radiation efficiency of the proposed antenna, which exceeds 90% throughout the entire operational frequency band. The simulated gain demonstrates strong performance, particularly at lower frequencies. Notably, the antenna achieves peak gains of 5.70 dBi at 9.24 GHz and 6.23 dBi at 10.11 GHz, confirming its suitability for high-efficiency X-band applications.

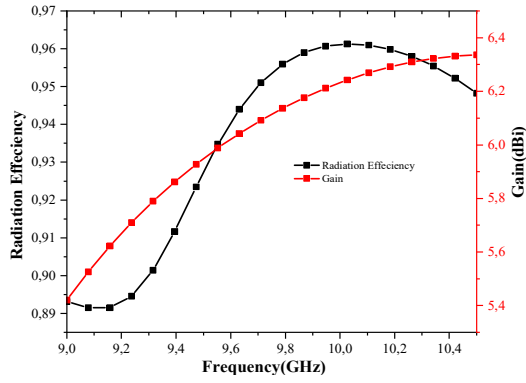


Fig. 4. Simulated gains and radiation efficiency of the proposed antenna.

III. RESULTS AND DISCUSSIONS

The figure 5 illustrates the simulated S-parameters of the proposed SIW MIMO antenna. From this figure we can observe that the reflection coefficient S_{11} and S_{22} well below the -10 dB indicating that the antenna operates wide band. The transmission coefficients S_{21} exhibit values below -25 dB over most of the operating bands, which demonstrates good port isolation and low coupling essential for MIMO designs. Overall, the antenna shows effective ultra-band operation with good isolation and impedance performance.

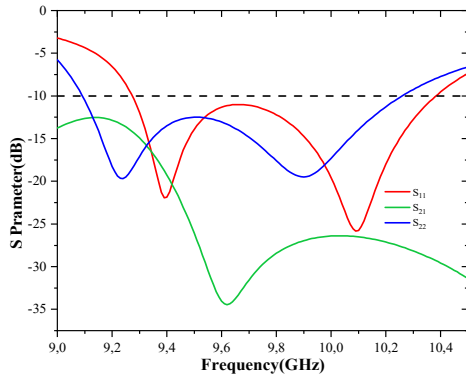


Fig. 5. Simulated S-parameters of the proposed SIW MIMO antenna.

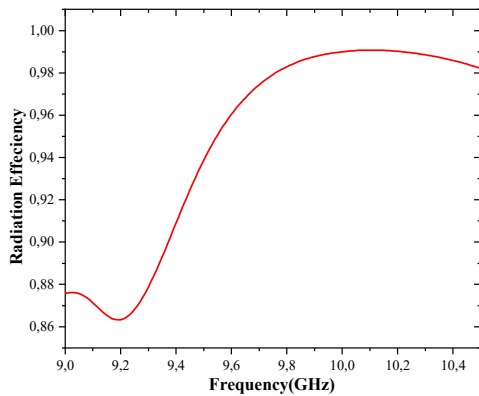


Fig. 6. Simulated Gain of the Proposed design.

Figure 6 illustrates the radiation efficiency of the proposed antenna as a function of frequency. The efficiency remains above 0.86 across the operating band (9.0–10.4 GHz) and approaches nearly 100% around 10 GHz, indicating minimal losses and excellent radiation performance over the intended frequency range.

Figure 7 presents the simulated gain of the proposed SIW MIMO antenna over the frequency band. The proposed antenna provides a gain changing between 5.2 dBi and 6.6 dBi, with noticeable peaks near 9.2 GHz and 10.4 GHz. These results confirm that our proposed antenna maintains a relatively acceptable and stable gain within the operational band, which is suitable for MIMO applications

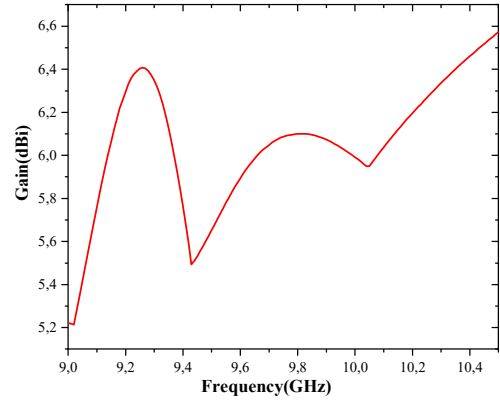


Fig. 7. Simulated Gain of the Proposed design.

Figure. 8 presents the axial ratio (AR) of the proposed antenna, showing that it remains well above 10 dB throughout the entire frequency range of 9.23–10.40 GHz. Since the AR exceeds 3 dB, this confirms that the antenna exhibits linear polarization.

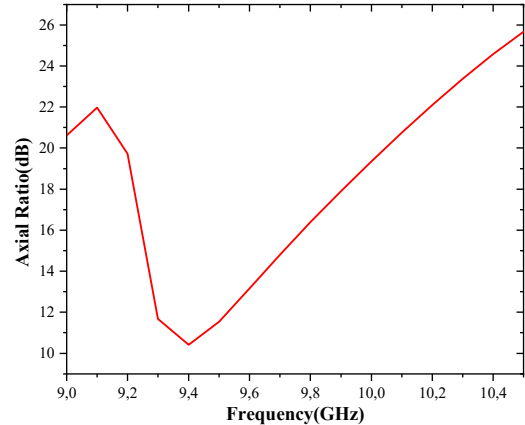
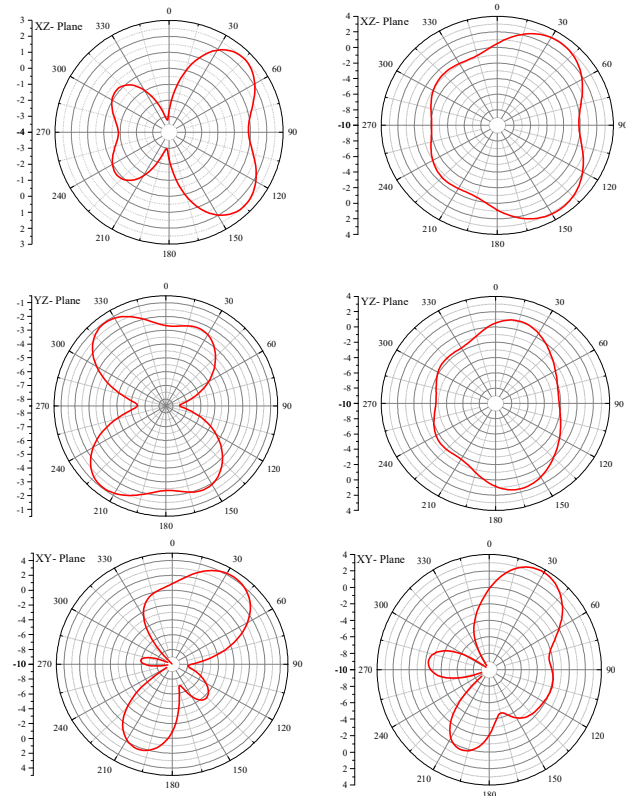


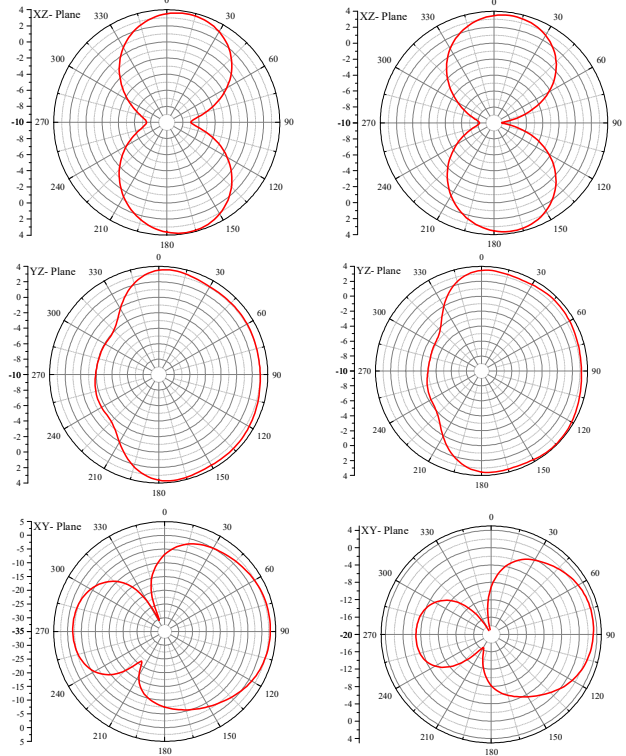
Fig. 8. Simulated Axial Ratio for the proposed SIW antenna.

The radiation patterns of the proposed antenna were analyzed at the resonance frequencies of 9.24 GHz, 9.40 GHz, 9.90 GHz and 10.11 GHz across the principal planes: XZ, YZ, and XY. At 9.24 GHz, the XZ plane exhibits an asymmetric pattern with stronger radiation in specific directions, highlighting the antenna's directional characteristics. In the YZ plane, the presence of multiple lobes suggests non-uniform energy distribution, likely influenced by polarization or resonance effects. The XY plane similarly displays a complex, multi-lobed pattern, indicating angle-dependent radiation behavior.

At 9.40 GHz, The XZ and YZ a plane becomes unidirectional, indicating higher directivity. The XY plane similarly displays a complex, multi-lobed pattern, indicating angle-dependent radiation behavior.



XZ-Plane, YZ-Plane and XY-Plane $f=9.24\text{GHz}$ XZ-Plane, YZ-Plane and XY-Plane $f=9.40\text{GHz}$



XZ-Plane, YZ-Plane and XY-Plane $f=9.90\text{GHz}$ XZ-Plane, YZ-Plane and XY-Plane $f=10.11\text{GHz}$

Fig. 9. Simulated radiation patterns of the proposed antenna at 9.24, 9.40, 9.90 and 10.11 GHz for different planes XZ, YZ, and XY.

At 9.90 and 10.11 GHz, the radiation pattern in the XZ plane resembles that of a dipole, suggesting a more balanced and uniform energy distribution. The YZ plane becomes predominantly unidirectional, indicating enhanced

directivity, whereas the XY plane continues to show multiple lobes, reflecting the frequency-sensitive nature of the radiation pattern. These observations demonstrate that the antenna exhibits dynamic radiation characteristics across different frequencies, making it a promising solution for multi-band applications where adaptable radiation performance is essential

IV. PERFORMANCE ANALYSIS PARAMETERS OF MIMO ANTENNAS

The proposed SIW MIMO antenna is evaluated in terms of various performance parameters, including Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), Mean Effective Gain (MEG), and Channel Capacity Loss (CCL). Within these condition limits : TARC < -10 dB, ECC < 0.5 , Diversity Gain ≈ 10 dB, MEG within ± 3 dB, and Channel Capacity Loss (CCL) < 0.4 bits/s/Hz [8], [9], [10], [11].

Figure 10 illustrates the simulated Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) of the proposed MIMO antenna, obtained from the S-parameters. The results reveal that the ECC remains very low across the operating frequency bands, demonstrating excellent isolation and low correlation between antenna elements. Consequently, the antenna achieves a high diversity gain, with a simulated value of approximately 10 dB across both operating frequency bands.

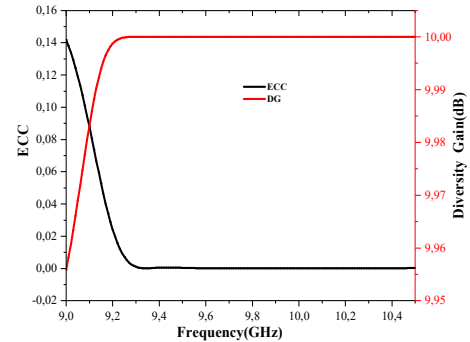


Fig. 10. Simulated Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) of the proposed MIMO antenna.

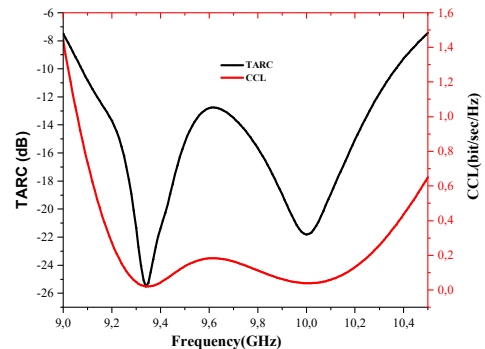


Fig. 11. Simulated TARC and CCL curves of the proposed SIW MIMO antenna.

The simulated TARC and CCL results, presented in Figure 11, indicate that the proposed MIMO antenna achieves a TARC lower than -10 dB and CCL less than 0.4 (< 0.4) bits/s/Hz in the operating frequency bands, fulfilling the requirement for good MIMO performance.

For good MIMO performance, the MEG difference between antenna elements should typically be within ± 3 dB. From figure 12, we can observe that our antenna satisfied this condition, which is a good sign for MIMO systems.

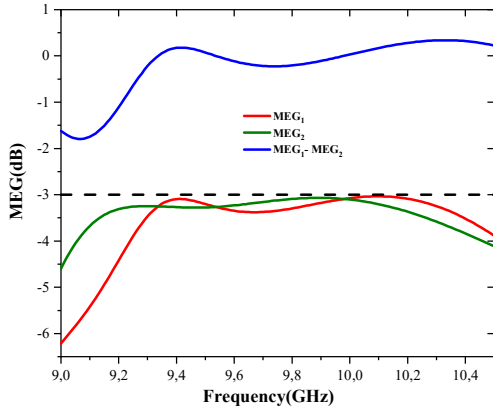


Fig. 12. Simulated MEG curve of the proposed SIW MIMO antenna.

TABLE II. COMPARISON OF THE PROPOSED ANTENNA WITH SOME OTHER WORKS

Ref	Size (mm ²)	Freq (GHz)	Isolation dB	Gain (dBi)	Effic. (%)
[12]	60x60	3-11	≥ 20	3.4	68
[13]	54x54	3.5-11	≥ 17	4.5	-
[14]	40x40	3.82-15.9	≥ 17	6.33	-
[15]	31.7x31.7	3-17	≥ 15.1	3.03	56.7
This work	17.8x14.9	9.00-10.5	≥ 25	6.66	90

V. CONCLUSION

In this article, a high-performance, compact SIW-based MIMO antenna with dimensions of only 17.8×14.9 mm² is proposed for X-band satellite communication applications. The antenna leverages the advantages of the Substrate Integrated Waveguide (SIW) technique to achieve superior performance while maintaining a reduced footprint. Notably, the design exhibits excellent isolation characteristics, exceeding 25 dB across the entire operating frequency range. Furthermore, critical MIMO performance metrics, including the Envelope Correlation Coefficient (ECC), radiation efficiency, Diversity Gain (DG), Channel Capacity Loss (CCL), Total Active Reflection Coefficient (TARC), and Mean Effective Gain (MEG), are thoroughly analyzed. The results demonstrate outstanding performance in all evaluated parameters, confirming the suitability of the proposed antenna for high-efficiency, compact MIMO systems in satellite communication applications.

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