High-Isolation and High Diversity Performance Two Element Mushroom-Shaped Electromagnetic Band Gap Based Slotted MIMO Antenna for C-Band (4–8 GHz) Wireless Applications

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***Abstract*— In this article, the design of a circular with L shaped slotted MIMO antenna designed for C-band applications (4.0–8.0 GHz), incorporating an Electromagnetic Band-Gap (EBG) mushroom shaped structure and appropriate decoupling structure to achieve an isolation of 20 dB between antenna elements. Fabricated on an FR-4 substrate with dimensions of $55 \times 45 \times 1.6$ mm³, the antenna exhibits a return loss better than –10 dB across the operating band. Key diversity parameters, such as the envelope correlation coefficient (ECC) and diversity gain, are observed to be 0.0015 and 9.99 dB, respectively. Furthermore, the radiation characteristics are favorable, with radiation efficiency exceeding 0.5, a total active reflection coefficient (TARC) below –35 dB, and a channel capacity loss (CCL) under 0.30 bits/s/Hz. These results indicate that the proposed MIMO antenna is well-suited for applications including weapon detection systems and wind profiler radar platforms.**

Keywords*— *Electromagnetic Band-Gap, Channel Capacity Loss, Envelope Correlation Co-efficient, Total Active Reflection Co-efficient, Multiple-Input Multiple-Output.

I. INTRODUCTION

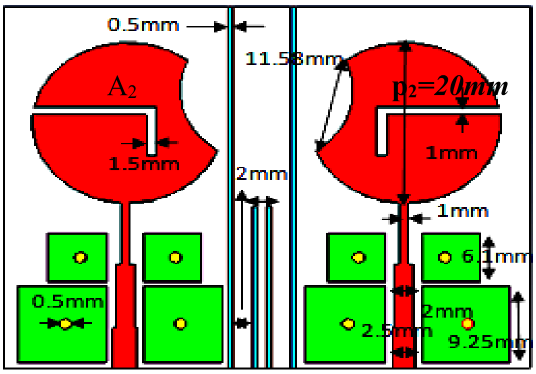
Wireless communication networks have evolved significantly, encompassing various architectures such as single-input single-output (SISO), multiple-input single-output (MISO), and multiple-input multiple-output (MIMO) systems. Among these, bandwidth remains a crucial factor influencing overall system performance. High-speed data transmission is essential in modern wireless applications—including voice, video, and data services—where system efficiency is heavily influenced by parameters like channel capacity at the receiver end. MIMO technology enhances these parameters by offering higher data rates, reduced channel capacity loss (CCL), and improved signal-to-noise ratio (SNR), making it highly suitable for complex and dynamic wireless environments.

Compared to SISO systems, MIMO antennas are preferred in advanced RF communication systems due to their superior diversity and multiplexing capabilities. These features contribute to enhanced data throughput and system reliability. Incorporating an appropriate feed network within an antenna array can further improve critical performance metrics such as bandwidth, gain, radiation characteristics, and circular polarization diversity [1]. A feed structure with two inputs and four outputs facilitates polarization diversity, contributing to wider impedance bandwidth, better axial ratio bandwidth, and higher peak gain in the C-band frequency range [2]. MIMO designs utilizing decoupling strategies, such as artificial magnetic conductors (AMCs) and T-shaped slots on the ground plane, demonstrate notable improvements in isolation and diversity performance [3–4]. Furthermore, integrating electromagnetic band-gap (EBG) structures helps suppress surface wave propagation, thereby enhancing isolation between antenna elements and enabling compact antenna designs suitable for military and industrial applications [5–9]. Incorporating slow-wave structures with EBG elements has also been shown to boost isolation, reduce antenna size, and enhance overall diversity performance [10]. Additional improvements in isolation and impedance bandwidth have been reported in MIMO configurations employing orthogonally placed Bow-Tie antenna elements [11].

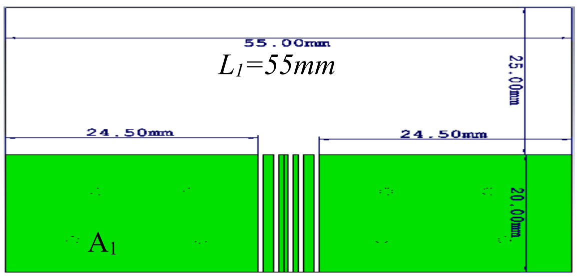
In this work, a C-band MIMO antenna with enhanced isolation is developed using an EBG structure on a cost-effective FR-4 substrate (εr = 4.4) with a thickness of 1.6 mm. Section II presents the detailed electromagnetic behaviour and simulation outcomes of the proposed design. Section III highlights the antenna's diversity performance through key metrics such as envelope correlation coefficient (ECC), diversity gain (DG), mean effective gain (MEG), total active reflection coefficient (TARC), and channel capacity loss (CCL). Finally, Section IV summarizes the findings and confirms the suitability of the proposed antenna design for efficient C-band wireless applications.

II. MIMO ANTENNA ANALYSIS AND RESULTS

Figure 1 (a)-(b) depicts an EBG MIMO antenna. This antenna is planned for C-band RADAR applications. Equation (1) [12] gives the fundamental resonant frequency of a MIMO antenna. Where A_1 and A_2 are the area of ground plane and radiating MIMO antenna and L_1 and p_2 are the total length of ground plane and diameter of the proposed circular MIMO antenna. The thickness of the substrate is denoted by h, and all dimensions are measured in millimeters.



(a)



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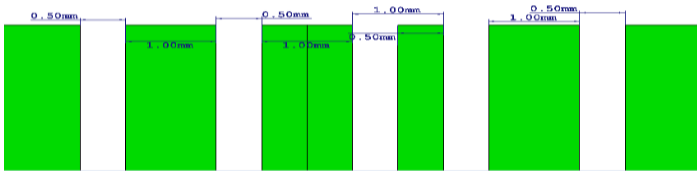
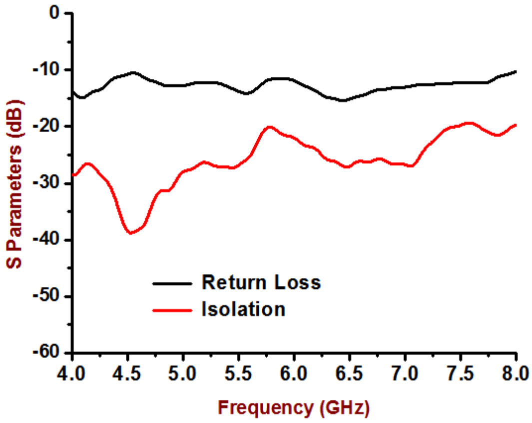
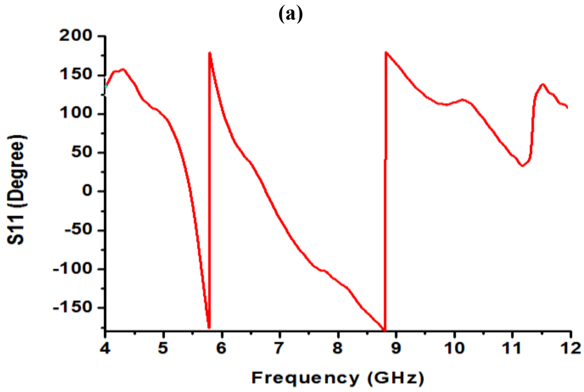


(b)

Fig. 1 Illustrates the design of the proposed MIMO antenna operating in the C-band (4–8 GHz): (a) front view and (b) bottom view.



(a)



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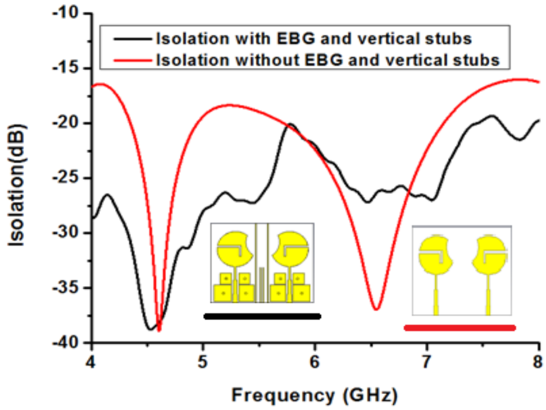


(c)

Fig. 2. (a) Simulated S-parameters obtained using CST Microwave Studio, (b) Phase of the return loss versus frequency, and (c) Isolation performance of the proposed MIMO antenna with and without the inclusion of EBG structures and vertical stubs

$$f_r(\text{GHz}) = \frac{144}{L_1 + p_2 + h + \frac{A_1}{2\pi\sqrt{\epsilon_r + 1}} + \frac{A_2}{2\pi\sqrt{\epsilon_r + 1}}} \quad (1)$$

The proposed MIMO antenna design features a circular radiating patch with a diameter of 20 mm and integrates four Electromagnetic Band-Gap (EBG) slots, effectively enhancing element isolation within the desired C-band frequency range. An I-shaped stub is introduced on the ground plane to further improve isolation and enhance the overall diversity performance. EBG structures, characterized by their periodic configuration, inhibit electromagnetic wave propagation within specific frequency ranges, thereby serving as effective tools for suppressing surface waves. When implemented with conducting rods connected to the ground, EBGs significantly improve isolation between adjacent radiating elements.

In addition to improving isolation, the EBG configuration also influences the antenna's quality factor (Q). The inclusion of EBG elements confines more electromagnetic energy, resulting in a higher Q-factor and a narrower operational bandwidth. While this increased energy confinement leads to greater conductor losses, it simultaneously contributes to stronger isolation and better return loss across the operating band. Moreover, the compactness of the EBG structures enables the overall antenna design to remain relatively small.

Figure 2(a) illustrates the simulated S-parameters of the proposed MIMO antenna, showing that the return loss remains below –10 dB across the entire C-band (4–8 GHz), while the mutual coupling between the two antenna elements is maintained below –20 dB, indicating excellent isolation. Figure 2(b) highlights the EBG response in the intended frequency range, showing a phase swing in the S11 parameter approaching 180°, a typical indicator of stopband behaviour. Figure 2(c) demonstrates the enhanced isolation performance attributed to the use of EBG elements and vertically oriented stubs positioned near the circular radiating patches.

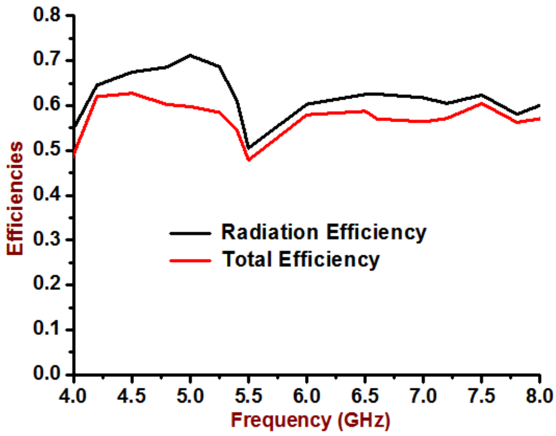


Fig. 3. Simulated radiation efficiency and total efficiency of the proposed MIMO antenna using CST Microwave Studio

Radiation efficiency is defined as the ratio of the radiated power (associated with the radiation resistance of the antenna) to the total power effectively delivered to the MIMO antenna through ports 1 and 2. As illustrated in Figure 3, the proposed MIMO antenna achieves both radiated and total efficiency values exceeding 0.5, indicating satisfactory performance across the C-band for applications such as RADAR systems. Additionally, the antenna exhibits a directive gain of more than 2.2 dBi throughout the 4–8 GHz frequency range.

The gain-bandwidth product for the antenna remains relatively stable, implying that as the bandwidth increases, a corresponding reduction in gain is observed. Despite this trade-off, the proposed antenna achieves a wide impedance bandwidth of 53.33%, which supports efficient signal transmission across the designated frequency band. Moreover, Figure 4 demonstrates that the group delay response remains nearly constant over the C-band, ensuring minimal signal distortion and making the design well-suited for time-sensitive and wideband communication systems.

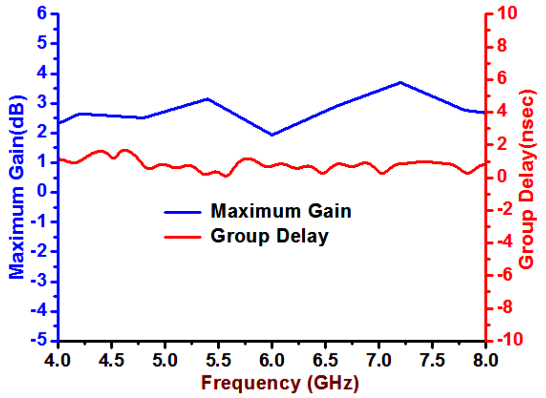
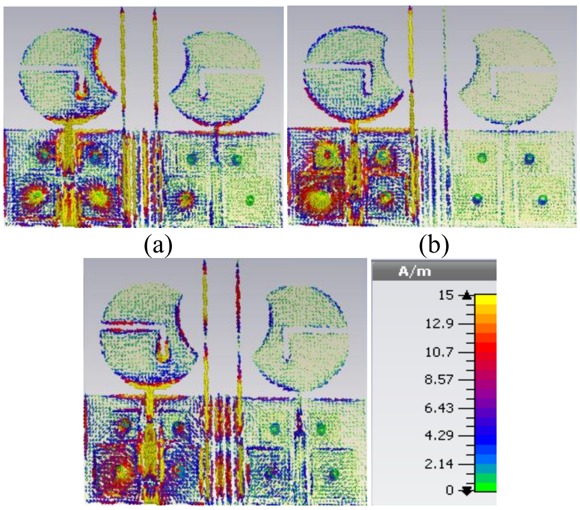
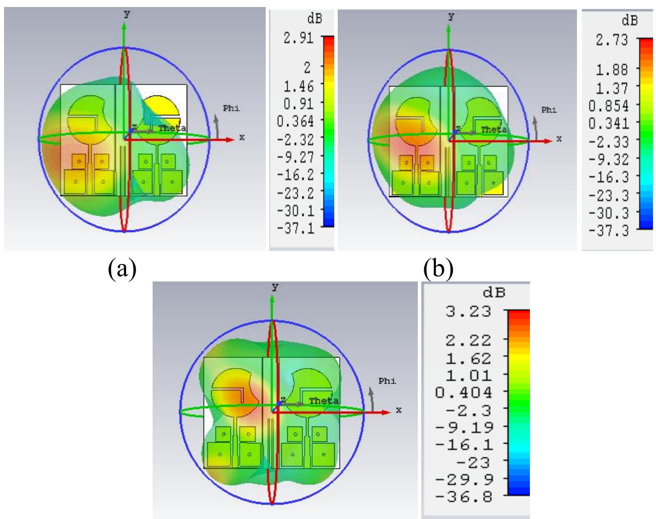


Fig. 4. Simulated maximum gain and group delay characteristics of the proposed MIMO antenna.



(c)

Fig. 5. Simulated surface current density distribution of the proposed MIMO antenna using CST Microwave Studio at (a) 4.5 GHz, (b) 5.5 GHz, and (c) 7.5 GHz, with Port 1 excited and Port 2 terminated with a 50 Ω load



(c)

Fig. 6. Simulated 3D radiation patterns of the proposed MIMO antenna using CST Microwave Studio at (a) 4.5 GHz, (b) 5.5 GHz, and (c) 7.5 GHz, with Port 1 excited by an external source and Port 2 terminated with a 50 Ω load.

Figure 5 presents the surface current distribution of the proposed MIMO antenna at three key operating frequencies: 4.5 GHz, 5.5 GHz, and 7.5 GHz. The observed current density patterns indicate the absence of localized charge accumulation, signifying a uniform distribution of surface currents across the radiating elements. This uniformity leads to relatively low surface current density, implying that minimal power is lost in the form of ohmic or reactive losses. As a result, a substantial portion of the input power is efficiently radiated into free space at the designated frequencies. This efficient power radiation confirms the antenna's effectiveness for high-performance C-band applications, such as those requiring stable gain, low loss, and strong isolation—key criteria for advanced MIMO systems.

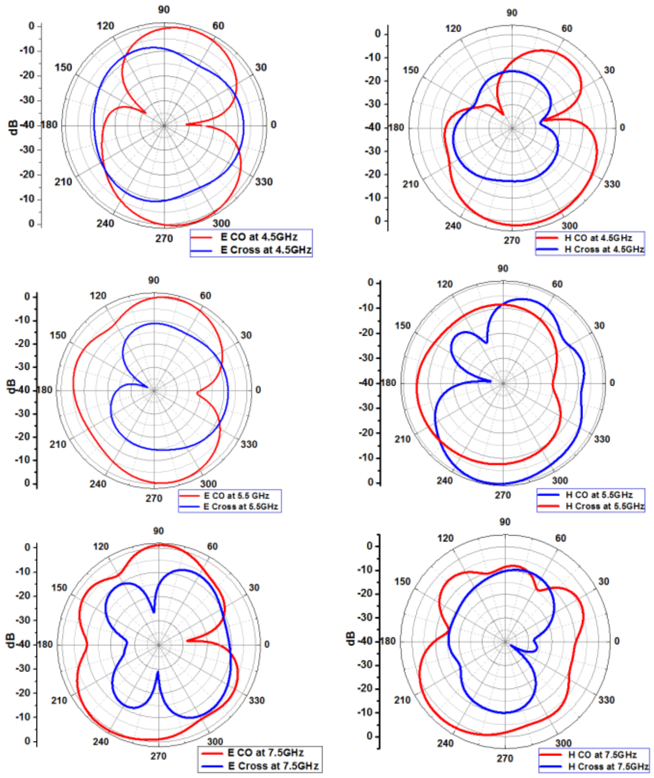


Fig. 7. Simulated 2D polar radiation patterns of the proposed antenna at 4.5 GHz, 5.5 GHz, and 7.5 GHz within the operating band, with Port 1 excited and Port 2 terminated with a 50 Ω impedance, using CST Microwave Studio.

Figure 6 presents the 3D radiation patterns of the proposed MIMO antenna at three representative frequencies: 4.5 GHz, 5.5 GHz, and 7.5 GHz. A peak gain of 3.23 dB is observed at 7.5 GHz. Based on the Poynting vector theorem, the radiated power predominantly propagates in the az (x–y) plane, while the electric field (E-field) is oriented in the ax (y–z) plane and the magnetic field (H-field) resides in the ay (x–z) plane. Thus, the radiated power component along the az direction can be expressed as Prad(az) = E(ax) × H(ay).

Figure 7 illustrates the E-plane and H-plane radiation patterns at 4.5 GHz, 5.5 GHz, and 7.5 GHz. The co-polarized radiation exhibits an almost omnidirectional pattern, distributing power uniformly in all directions. In contrast, the cross-polarized radiation—orthogonal to the co-polarized field—shows significantly lower radiated power, as also evident in Figure 6. This consistent and stable radiation behaviour across the band affirms the antenna's suitability for MIMO applications.

Additionally, Table I provides a comparative analysis between the proposed MIMO antenna and existing designs reported in the literature. Key performance metrics such as physical dimensions, inter-element isolation (decoupling), envelope correlation coefficient (ECC), and operating frequency range are used to highlight the advancements achieved in the proposed design.

TABLE I: PERFORMANCE COMPARISON OF THE PROPOSED ANTENNA WITH PREVIOUSLY REPORTED DESIGNS BASED ON VARIOUS KEY PARAMETERS

Size $(\lambda_0 * \lambda_0)^2$	Isolation (dB)	ECC	Frequency Range (GHz)	References
$0.92\lambda_0 \times 3.02\lambda_0$	28.2	0.0022	2.4-2.6GHz	[4]
$0.12\lambda_0 \times 0.12\lambda_0$	16	0.0056	2.1-2.5GHz	[8]
$0.92\lambda_0 \times 0.26\lambda_0$	16	0.0052	2.0-7.1GHz	[9]
$0.47\lambda_0 \times 0.47\lambda_0$	29	0.0022	2.4-2.5GHz	[11]
$1.10\lambda_0 \times 0.96\lambda_0$	**21**	**0.00153**	**4.0-8.0GHz)**	***[P]**

III. MIMO ANTENNA DIVERSITY PERFORMANCE

The diversity performance of the proposed MIMO antenna is initially assessed using the Envelope Correlation Coefficient (ECC), which quantifies the mutual coupling and correlation between the radiation patterns of the two antenna elements. It measures how independently the antenna elements operate in a multipath environment. The ECC is calculated using equation (2), as referenced in [12,13], and for optimal MIMO performance, its value should remain below 0.1. As shown in Figure 8, the ECC for the proposed antenna remains as low as 0.002 within the desired frequency band, indicating excellent isolation and low correlation between the elements. Additionally, the corresponding diversity gain (DG) is observed to be 9.99 dB, further confirming the antenna's strong diversity performance across the operating bandwidth.

$$ECC = \frac{\left|s^*_{11}s_{12} + s^*_{21}s_{22}\right|^2}{\left(1-\left|s_{11}\right|^2-\left|s_{21}\right|^2\right)\left(1-\left|s_{22}\right|^2-\left|s_{12}\right|^2\right)} \qquad 2(a)$$

$$ECC = \frac{\left|\iint_{4\pi}\left[E_i(\theta,\phi)\times E_j(\theta,\phi)\right]d\Omega\right|^2}{\iint_{4\pi}\left|E_i(\theta,\phi)\right|^2 d\Omega \times \iint_{4\pi}\left|E_j(\theta,\phi)\right|^2 d\Omega} \qquad 2(b)$$

In this context, XPR refers to the cross-polarization ratio, while Gθi(Ω), GΦi(Ω), and PΦ(Ω) represent the gain components and power density function of the incident electromagnetic wave over the beam solid angle Ω.

For an isotropic propagation environment with XPR = 0 dB, the Mean Effective Gain (MEG) remains relatively stable around –3 dB across the C-band. However, with XPR = 6 dB, MEG decreases and falls within the range of –3.5 dB to –4.9 dB. In a Gaussian propagation environment, the MEG exhibits slightly lower values. Specifically, with XPR = 0 dB, MEG ranges from –3 dB to –4.5 dB, while for XPR = 6 dB, it further drops to a range between –4.9 dB and –6.8 dB.

The simulated MEG performance under both isotropic and Gaussian conditions, considering distinct XPR values for typical indoor (XPR = 6 dB) and outdoor (XPR = 0 dB) environments, is illustrated in Figure 9, highlighting the antenna's suitability for varying propagation scenarios.

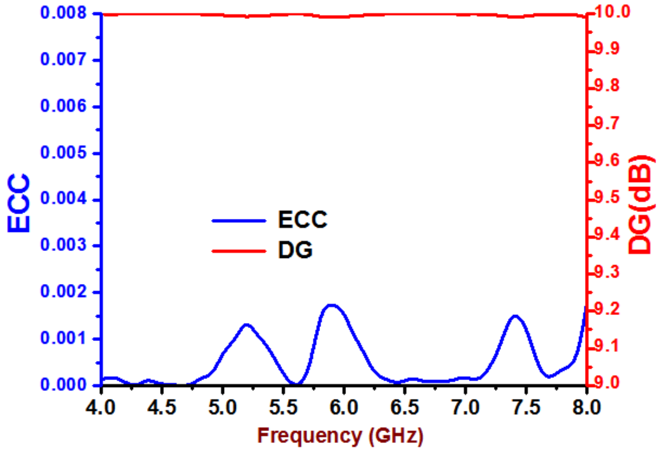


Fig. 8. Simulated Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) of the proposed MIMO antenna using CST Microwave Studio.

DG(dB) = 10√1-(ECC)^2, where ECC should preferably be 0 and the DG value should be 10dB. The Mean effective gain- ratio for a predicted antenna is in the range of ±3dB. MEG is defined as the ratio of mean effective received power to mean effective transmitted power to the antenna along a similar random path.

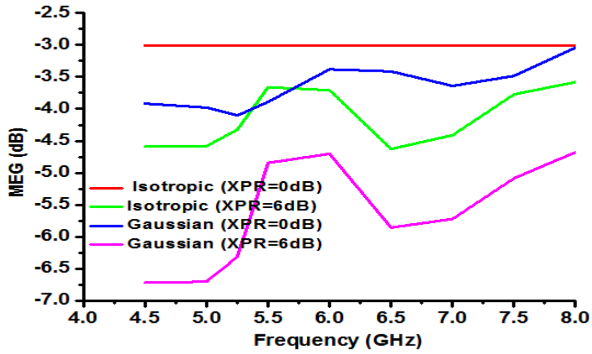


Fig. 9. Simulated Mean Effective Gain (MEG) versus frequency plot for the proposed antenna under different Cross-Polarization Ratios (XPR) and propagation media, using CST Microwave Studio.

The Mean Effective Gain (MEG) is defined as the ratio of an antenna's average received power in a given propagation environment to the average incident power along the same propagation path. Mathematically, for the *i*th antenna, it is given as:

$MEG_i = \varepsilon\_total^i / 2$,

where ε_total^i is the total efficiency of the *i*th antenna, calculated as:

$\varepsilon\_total^i = \varepsilon\_mis^i \times \varepsilon\_rad^i$

Here:

ε_mis^i is the mismatch efficiency and is expressed as:

$\varepsilon\_mis^i = 1 - \sum_{j=1}^{n} |S_{ij}|^2$

ε_rad^i represents the radiation efficiency, given by:

$\varepsilon\_rad^i = \sum_{j=1}^{n} |S_{ij}|^2$

MEG values under various Cross-Polarization Ratios (XPR) can be computed using Equation (3), as discussed in references [10], [12], and [13].

$$MEG_i = \frac{P_{rec.}}{P_{inc.}} = \oint\left[\frac{XPR\times G_{\theta i}(\Omega)+G_{\phi i}(\Omega)\times P_{\phi}(\Omega)}{1+XPR}\right]d\Omega \qquad (3)$$

$$TARC = \sqrt{\frac{\left(S_{11}+S_{12}\right)^2+\left(S_{22}+S_{21}\right)^2}{2}} \qquad (4)$$

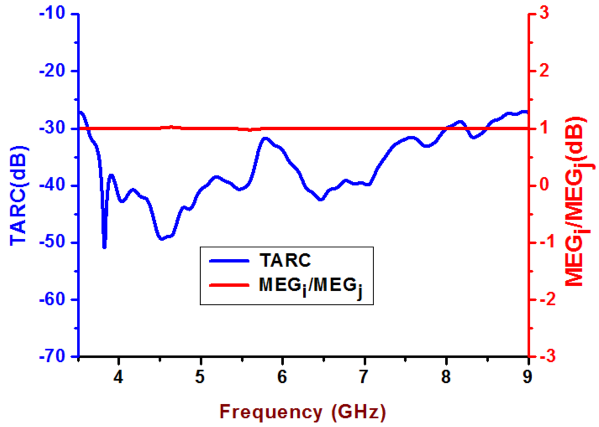


Fig. 10. Simulated Total Active Reflection Coefficient (TARC) and Mean Effective Gain (MEG) of the proposed MIMO antenna using CST Microwave Studio.

The Total Active Reflection Coefficient (TARC) is another important parameter used to assess the diversity performance of MIMO antennas and is derived from the S-parameters. It is defined as the square root of the ratio between the total reflected power and the total incident power when all ports are excited simultaneously with varying phases. TARC effectively represents the apparent return loss of a MIMO system under active excitation conditions. For an efficient MIMO antenna, the TARC value should ideally be less than 0 dB, indicating minimal reflection and better matching. The TARC is calculated using Equation (4), as referenced in [12,13]. In the case of the proposed design, the TARC is observed to be less than –35 dB within the desired frequency band, as shown in Figure 10, confirming excellent performance in terms of active reflection and diversity efficiency.

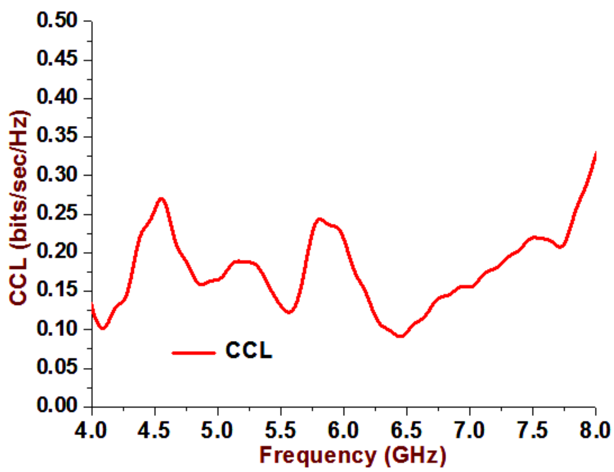


Fig. 11. Simulated Channel Capacity Loss (CCL) of the proposed MIMO antenna in the C-band using CST Microwave Studio.

$$CCL\ (dB) = -\log_2 Det\ (\phi^s) \quad (5)$$

Where, ϕ^s show a 2×2 correlation matrix to be evaluated using S-parameters, $\phi_{ii} = 1 - |S_{ii}|^2 - |S_{ij}|^2, \phi_{ij} = -(S_{ii} \times S_{ij} + S_{ji} \times S_{jj})$. Equation (5) can be used to calculate channel capacity loss. Channel bandwidth for MIMO antennas should be improved, but channel capacity loss should be reduced and should be less than 0.30bits/sec/Hz for 2×2 antenna system. Figure-11 shows the proposed antenna with CCL of less than 0.30bits/sec/Hz.

IV. CONCLUSION

The proposed MIMO antenna has been designed and its performance thoroughly evaluated through simulation for C-band applications. It achieves excellent isolation exceeding 20 dB and demonstrates strong diversity performance, with key parameters such as ECC, DG, TARC, CCL, and MEG remaining well within acceptable limits. These results validate its effectiveness for wireless communication systems, offering improved data throughput and signal-to-noise ratio (SNR) compared to conventional SISO antennas. Based on the comparative analysis presented in Table I and the overall diversity metrics, the proposed antenna design proves to be a strong candidate for advanced C-band RADAR applications, including weapon tracking systems and wind profiler technologies.

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