

A Miniaturized 2×2 Orthogonal MIMO Antenna for 5G NR Mid-Band Applications (n77/n78/n79)

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ABSTRACT: The proposed prototype miniaturizes a two-port wideband multi-input multi-output (MIMO) antenna structure to operate over a specified frequency spectrum from 2.6 to 5.1 GHz and exhibits an impedance bandwidth of 64.93% to support 5G mid-band (n77/n78/n79) applications. The antenna design incorporates a pair of spoon-shaped radiating units configured orthogonally to achieve polarization diversity. To improve inter-port isolation (S_{21}), T-shaped slots along with a diagonally oriented rectangular slot are employed in the ground plane, while the isolation value remains better than -15 dB within the prescribed limit. The developed MIMO antenna was implemented in a compact configuration on an FR4 substrate, with physical dimensions of 30×30 mm². The antenna exhibits a gain ranging from 3.5 to 3.9 dB with radiation efficiency varying from 94% to 96% and a stable radiation pattern within the targeted frequency band. The diversity performance metrics across the operating frequency range were validated by the envelope correlation coefficient ($ECC < 0.01$), diversity gain ($DG < 9.99$ dB), and mean effective gain (MEG) close to -3 dB. Experimental findings show close correlation with simulated data, confirming the effectiveness of the developed MIMO antenna structure for 5G New Radio (NR) mid-band operation.

1. INTRODUCTION

There is a demand to boost the signal quality and channel capacity of the system. The fifth generation of communication technology aims to provide an appropriate solution to achieve a higher peak data rate, minimal latency, increased network capacity, and efficient quality of service. To meet the goal of the 5G mobile communication system, multi-input multi-output (MIMO) technology has been introduced. MIMO has become widely adopted due to increasing the channel capacity of the communication system, especially in complex scattering-rich environments. Additionally, it enables high throughput within the same bandwidth and improves link reliability. Designing a compact and efficient MIMO antenna is difficult to realize because of the restricted space within portable devices; they may be tightly coupled with each other [1–4]. However, when antenna elements are closely packed, it leads to strong mutual coupling, which restricts the extent of possible miniaturization. Therefore, several strategies have been reported by researchers to achieve high isolation by inhibiting the propagation of undesired surface waves, such as electromagnetic band gap and metasurface structures, which destroy the compactness of the antenna and make it very complex [5, 6]. An alternative solution to suppress surface waves is a defected ground structure (DGS), which is generally easier to achieve by reshaping its surface current distribution [7–9]. Subsequently, in order to mitigate electromagnetic coupling between antenna elements, decoupling methods are employed using a neutralization line (NL) and parasitic elements (PEs). NLs and PEs require additional space, which increases the overall footprint of the sys-

tem [10–12]. The techniques discussed above are suitable only for limited-bandwidth operation. Some researchers reported dual-band MIMO antennas by utilizing various antenna configurations. In [13], multiple slots loaded in the ground plane result in isolation that can be improved at 2.4 GHz and 3.4 GHz, while another design reported in [15] utilized the combination of a ladder-shaped slot and a neutralization technique for isolation enhancement in a WLAN application. In [16], high isolation is obtained by incorporating a DGS, ground branches, and a T-shaped parasitic element. A dual Y-shaped stub works as an isolating element in [17]. However, previously reported antenna designs suffer from large physical dimensions and exhibit narrow bandwidth, which increase their complexity to control mutual coupling and ensure that sufficient isolation is achieved at both resonating frequencies. To resolve these issues, researchers have focused on those approaches to achieve isolation for wideband or ultra-wideband (UWB) operation without requiring any external decoupling structure, such as self-decoupling methods, by employing asymmetric coplanar feed and polarization diversity, but these techniques are not very effective for isolation improvement [18]. After that, recent literature has explored techniques to achieve high isolation without compromising the compactness of the MIMO antenna. An I-shaped stub is used on the partial ground plane to achieve acceptable isolation [19–21] by inserting a comb-shaped isolating structure between antenna elements for wideband applications [22], by inserting a caterpillar-shaped decoupling structure for a UWB-MIMO antenna [23], and by using the characteristic mode theory for a wideband flower-shaped MIMO antenna [24]. Port isolation is obtained by employing polarization diversity [25]. A critical review of existing techniques reveals

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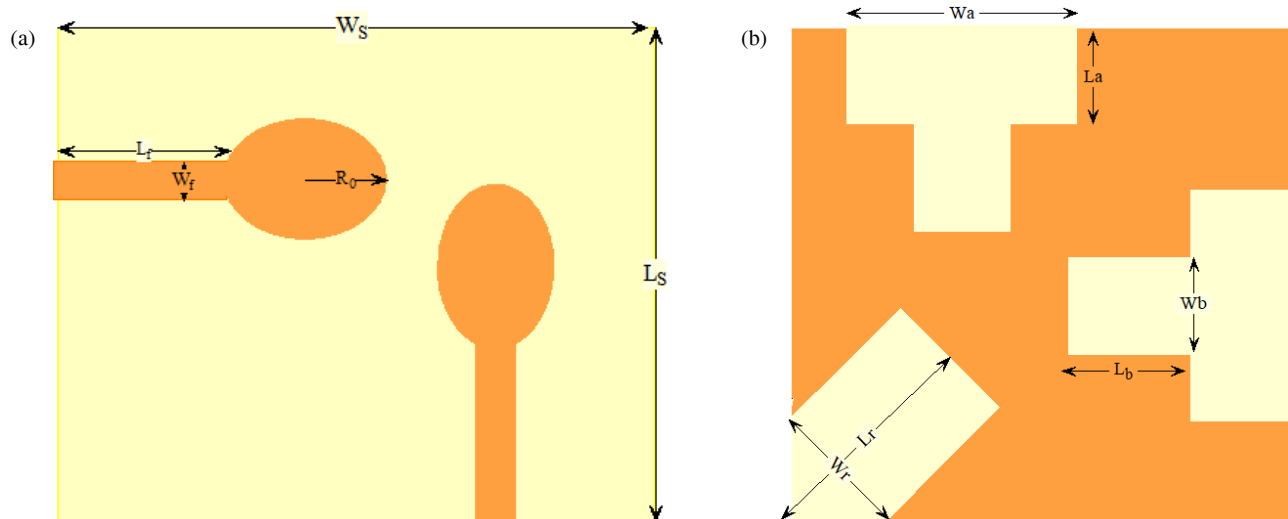


FIGURE 1. Schematic layout of the proposed antenna structure. (a) Front view and (b) back view.

that most of the previously reported MIMO antenna design configurations attain reduced mutual coupling by increasing their design complexity.

This work presents a compact wideband MIMO antenna incorporating a defected ground structure (DGS) that was developed for 5G NR mid-band operation. The key design objective of this study is to achieve a wideband with improved isolation, consistent gain, high efficiency, and enhanced MIMO performance within a compact footprint. The antenna maintains port isolation exceeding -15 dB across the operating range through the proper optimization of ground defects. The proposed MIMO antenna occupies an area of small footprint, $30 \times 30 \text{ mm}^2$. The spoon-shaped radiating elements are placed orthogonally, which inherently minimizes the mutual coupling. Owing to its small configuration, it is an appropriate choice for size-efficient design in future wireless applications.

2. PHYSICAL CONFIGURATION

The structural layout of the proposed design is shown in Fig. 1. The radiating element is implemented on the top of a 1.6 mm thick FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.02. The radiating component comprises two orthogonally arranged spoon-shaped elements that are energized through a 50Ω microstrip feed line. The ground plane is a conductive surface formed on the underside of the dielectric substrate. Two T-shaped slots and one diagonally oriented rectangular slot at an angle of 45° are formed on the ground plane to achieve an enhanced bandwidth and minimize the inter-element coupling between the radiating elements. The proposed MIMO antennas were analyzed and numerically optimized using the ANSYS HFSS simulation software suite version 2021. The final optimized dimensions are summarized as follows: $W_s = 30 \text{ mm}$, $L_s = 30 \text{ mm}$, $L_f = 8.75 \text{ mm}$, $W_f = 2.2 \text{ mm}$, $R_0 = 3.8 \text{ mm}$, $W_a = 16 \text{ mm}$, $W_b = 6 \text{ mm}$, $L_a = 6 \text{ mm}$, $L_b = 8 \text{ mm}$, $W_r = 10 \text{ mm}$, $L_r = 14.5 \text{ mm}$.

3. STRUCTURAL AND PERFORMANCE ANALYSIS OF MIMO ANTENNA

3.1. Influence of T-Shaped Slot on Antenna Response

Figure 2(a) illustrates the variation of the S -parameter response in terms of the T-slot dimensions. The ground plane is modified by a T-slot orthogonally etched on it. This study aimed to optimize the performance of the S -parameter ($S_{11} < -10 \text{ dB}$). These slots provide flexibility in tuning the antenna's resonant frequency. Subsequently, incorporating these slots on the ground plane provides a corresponding bandwidth from 2.3 to 5.2 GHz, exhibiting improved impedance matching and maintaining a reflection level below -10 dB . The isolation between ports is also improved by optimizing the slot length; however, the coupling is still high at lower frequencies.

3.2. Influence of Rectangular Slot on Antenna Response

When a diagonally oriented rectangular slot is inserted at the lower side of the ground layer at an angle of 45° , it mitigates the effect of electromagnetic coupling between antenna elements at the low-frequency band. Fig. 2(b) shows the simulated S -parameter characteristics before and after introducing a slot. With the inclusion of the slot, the mutual coupling minimized has a value lower than -16 dB .

Figure 3 shows the surface vector current distribution to analyze the behavior of the decoupling mechanism. In the absence of a rectangular slot, the continuous ground plane offers an uninterrupted coupling path between the closely spaced antennas. When one radiating element is excited, a high-density surface current is induced on the adjacent element, as shown in Fig. 3(a) at 2.4 GHz. This implies that the induced current is dominated by the reactive near-field coupling. Consequently, a second element acts as a parasitically excited radiator through mutual coupling, thereby degrading the port isolation.

After introducing a diagonally oriented rectangular slot in the ground plane, a DGS is incorporated to create an impedance

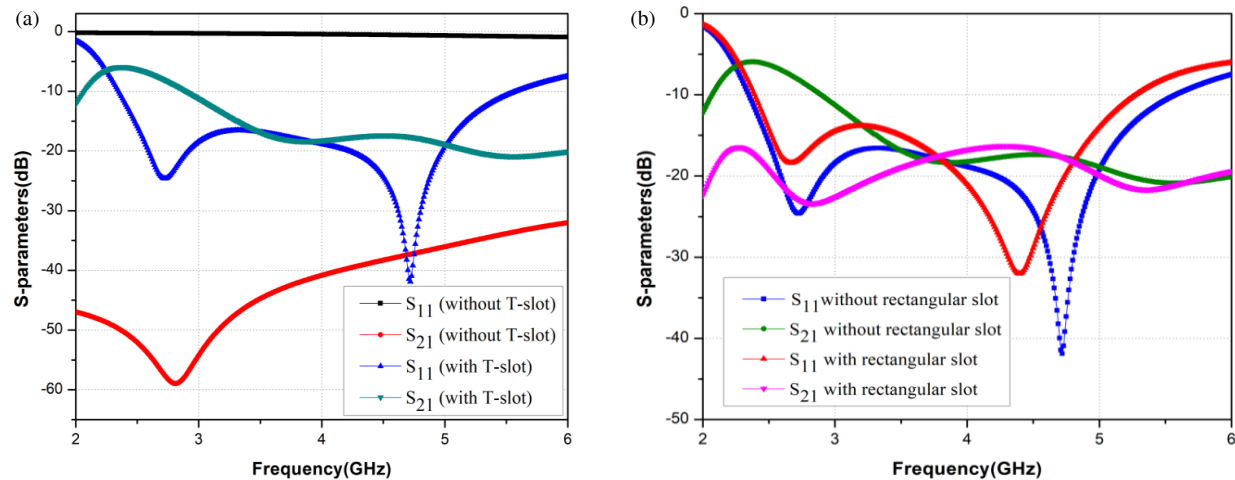


FIGURE 2. Simulation based S -parameter responses. (a) Effect of introducing the T-slot and (b) effect of introducing the rectangular slot.

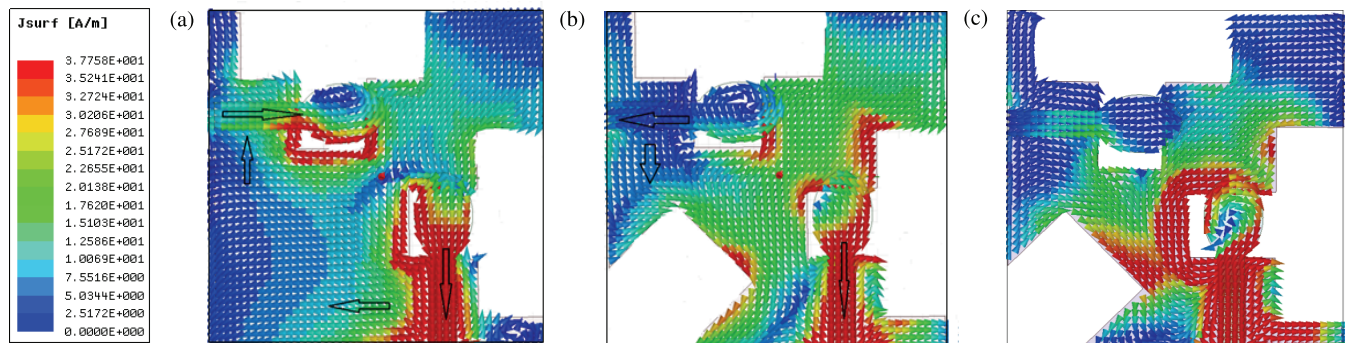


FIGURE 3. Surface current vector distribution of the proposed antenna, (a) 2.4 GHz, (b) 2.4 GHz, (c) 4.4 GHz.

discontinuity that effectively suppresses surface-wave propagation. This disruption of the current path confines the surface current to the excited element and significantly reduces the undesired induced current on the adjacent element. Fig. 3(a) and Fig. 3(b) show the surface vector current distribution at 2.4 GHz for the cases without and with a diagonally incorporated rectangular slot. So we can easily compare the analysis and observe the effect of isolation between the two antennas. A further significant reduction is observed in Fig. 3(c) at 4.4 GHz, confirming that each antenna radiates independently, thereby resulting in improved port isolation.

3.3. Analysis of Parameter Variation

This section presents a parametric study performed to analyze the impact of the modified slot structures of the DGS on the S parameters. The optimization can be carried out by adjusting a single parameter at a time while keeping the others unchanged. From Fig. 4, it is clear that when the T-shaped slot width (W_a) is varied from 8 to 16 mm with a step size of 2 mm, it significantly impacts both impedance matching and isolation characteristics. At $W_a = 8$ mm and 10 mm, the antenna exhibits only the n79 band, and the higher resonance is shifted towards the left side because the length of the current path becomes longer. Which does not meet the desired performance, and a port iso-

lation of nearly -14 dB is achieved. When the W_a parameter varies from 12 to 16 mm, it covers the n77, n78, and n79 bands with improved return loss at lower and higher resonating frequencies, and also significantly improves the isolation characteristics. Further, parametric analysis was performed on the rectangular slot length (L_r), which varied significantly from 10 to 16 mm. Each variation affects both the S_{11} and S_{21} responses, as illustrated in Fig. 5. The rectangular slot length (L_r) substantially improves the isolation at lower frequencies. The finding reveals that $L_r = 14.5$ mm produces the optimal value for the S -parameter characteristics.

4. RESULT AND DISCUSSION

4.1. Return Loss and Port-to-Port Isolation

A prototype of the spoon-shaped antenna, as described in Section 4, was fabricated and experimentally tested. The images of the antenna prototype after fabrication are depicted in Fig. 6(a). The S -parameters were experimentally tested with the help of N5224B PNA vector network analyzer (VNA) in the 43.5 GHz range. A comparative study between simulated and measured responses of the S -parameters is demonstrated in Fig. 7. Here, it is demonstrated that a small variation between the simulated and experimental results is mainly caused by the dielectric losses because all the simulators are basically based on the

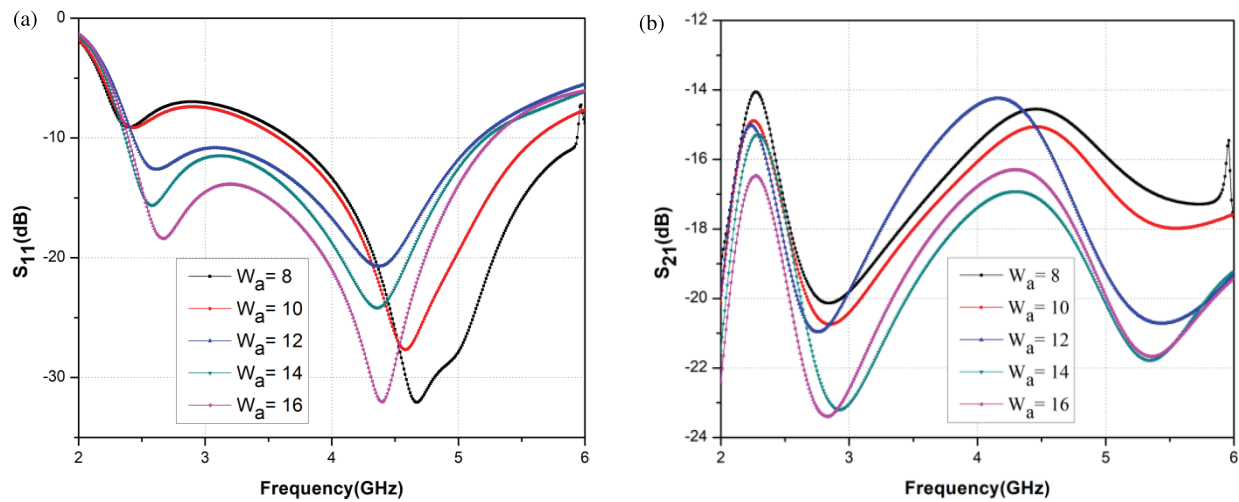


FIGURE 4. Variation of T-slot width (W_a): (a) Reflection coefficient and (b) isolation characteristics.

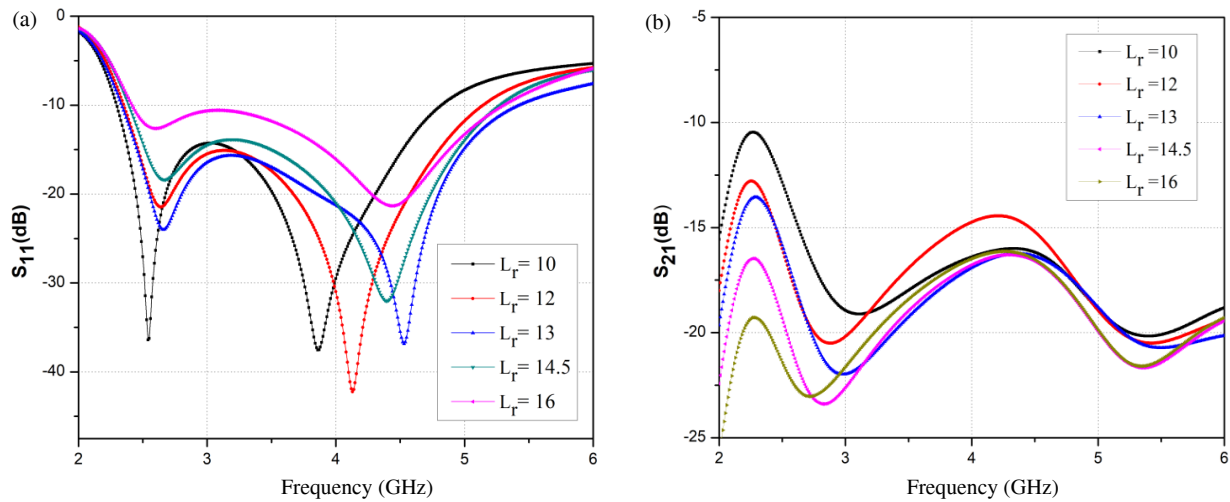


FIGURE 5. Variation of rectangular slot length (L_r): (a) Reflection coefficient and (b) isolation characteristics.

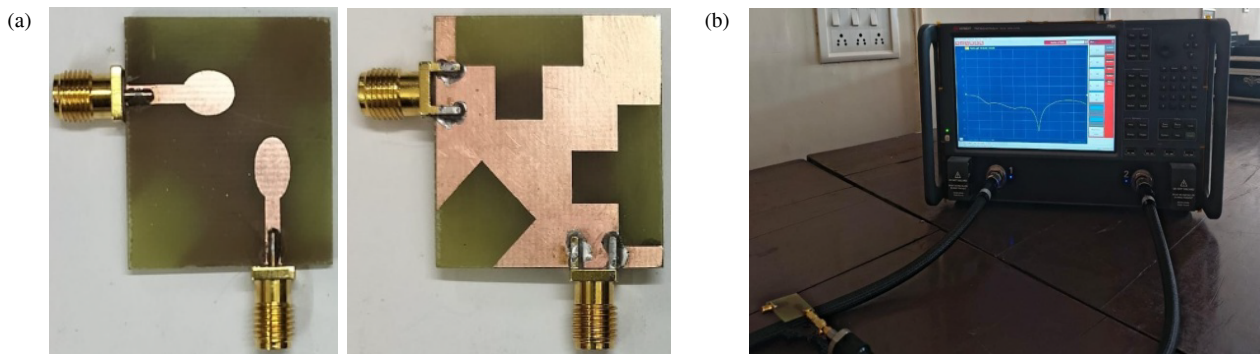


FIGURE 6. (a) Physical realization of the designed antenna and (b) VNA-based measurement system.

mathematical models in which they have taken some approximations and assumptions, which are responsible for the variations between the simulated and measured results, and minor deviations are obtained. Another type of error can also be considered, which is called a fabrication error, if the fab-

rication processes are not precise enough and a minor discrepancy exists between simulated and experimental results. The fabricated antenna achieved a bandwidth of 2.6–5.1 GHz with $S_{11} < -10$ dB and $S_{21} < -15$ dB. This antenna satisfies the

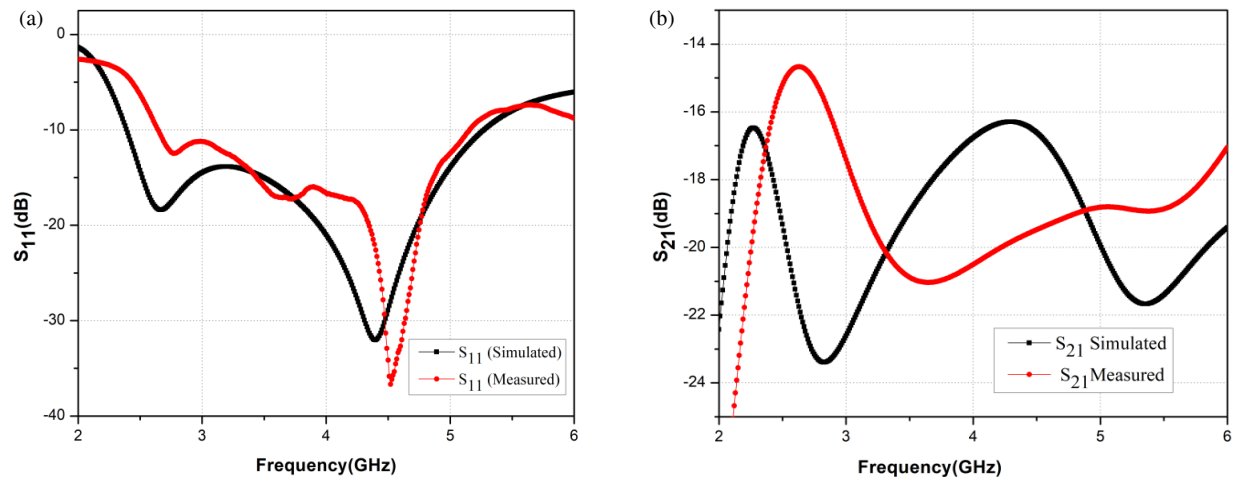


FIGURE 7. Comparative analysis between simulated and measured (a) return loss (S_{11}) and (b) inter-port isolation (S_{21}).

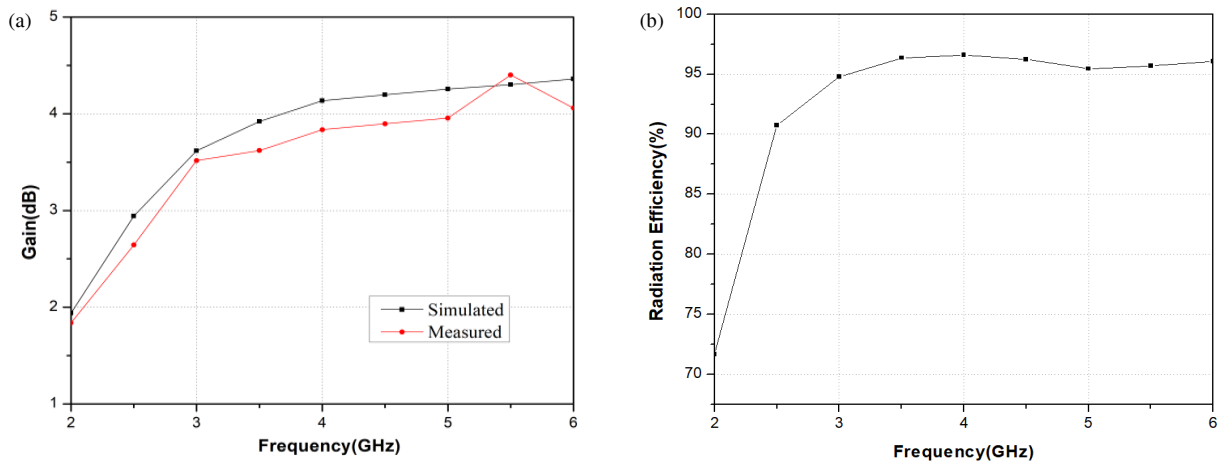


FIGURE 8. (a) Gain characteristic and (b) simulated radiation efficiency characteristic.

requirements for impedance matching and isolation; therefore, it is well-suited for MIMO applications.

4.2. Antenna Gain and Radiation Efficiency

The antenna gain quantifies the capability of the antenna to concentrate the power radiated in a specific direction compared to an isotropic radiator. Fig. 8(a) illustrates the simulated and measured gain performance of the designed dual-port MIMO antenna. The experimentally determined realized gain varies from 3.5 to 3.9 dB, which is approximately flat across the 3.3–5 GHz targeted frequency range. Radiation efficiency quantifies the amount of supplied power that is effectively emitted as radiation by the antenna. As shown in Fig. 8(b), it remains between 93% and 96% throughout the operating range.

4.3. Radiation Characteristics

To validate the radiation performance, the far-field radiation behaviour of the proposed dual-port MIMO antenna was experimentally examined inside an anechoic chamber, as shown in Fig. 9(c). In Figs. 9(a) and (b), the simulated and experimen-

tally obtained co-polarization far-field radiation patterns are obtained in the E -plane (XOZ) and H -plane (YOZ), showing good agreement at 3.5 and 4.5 GHz. In the E -plane ($\varphi = 0^\circ$), the radiation pattern exhibits bidirectional characteristics with two main lobes positioned approximately 180° apart, while maintaining approximately omnidirectional characteristics in the H -plane ($\varphi = 90^\circ$). This radiation behavior confirms the radiation stability over the 5G NR mid-band spectrum.

4.4. Analysis of MIMO Antenna Performance

The effectiveness of the proposed antenna is characterized through MIMO performance parameters, such as ECC, DG, CCL, TARC, and MEG, which were evaluated.

4.4.1. Envelope Correlation Coefficient (ECC)

ECC is employed to evaluate the inter-element correlation characteristics of the MIMO antenna system. A lower value of ECC indicates independent radiation behavior and strong diversity performance, whereas a high ECC value substantially degrades the diversity performance of the antenna elements. For

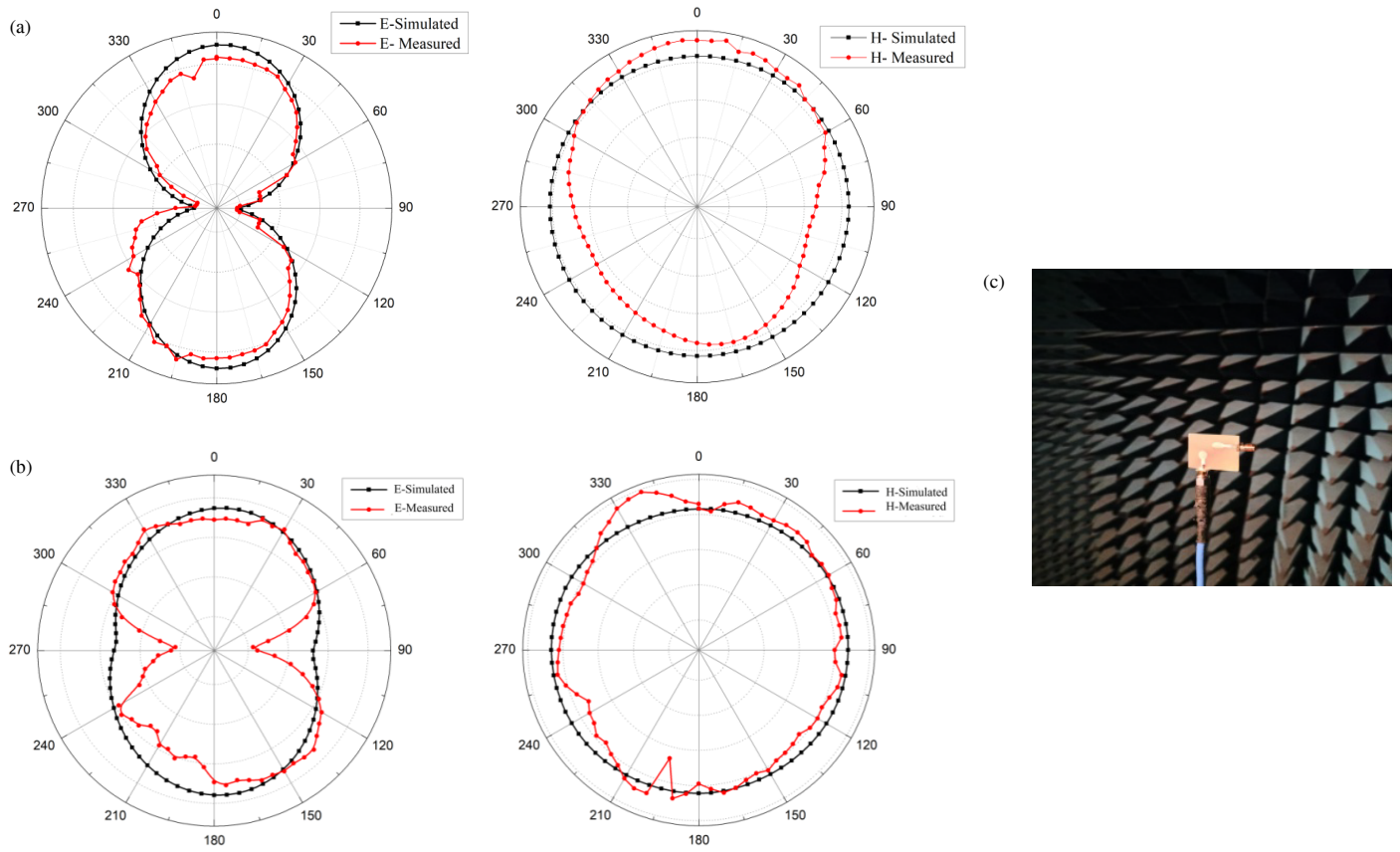


FIGURE 9. The co-polarized radiation characteristics, (a) at 3.5 GHz, (b) at 4.5 GHz, and (c) anechoic-chamber-based setup for radiation pattern measurement.

a two-port MIMO antenna, the ECC is calculated using the S -parameters according to (1) [26].

$$\text{ECC} = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \quad (1)$$

Figure 10(a) reveals a close agreement between the simulated and measured values, which are consistently below 0.01 across the operating band. The obtained values were far below the acceptable limit of 0.5. Thus, the proposed MIMO antenna is suitable for diversity performance.

4.4.2. Diversity Gain (DG)

In a MIMO antenna, DG refers to the improvement in the link quality by alleviating multipath fading effects. It improves the signal-to-noise ratio by aggregating uncorrelated faded signals and reducing the effect of multipath fading, resulting in improved link reliability.

The diversity gain can be obtained from the ECC using (2) [27].

$$\text{DG} = 10\sqrt{1 - (\text{ECC})^2} \quad (2)$$

Figure 10(b) depicts the simulated and measured diversity gain values, which approach 10 dB over the operating range, thereby confirming the strong diversity performance.

4.4.3. Channel Capacity Loss (CCL)

CCL is a performance metric of MIMO that represents the loss in the maximum attainable channel capacity owing to the correlation and low isolation between antenna elements. For 2×2 MIMO antenna systems, CCL is calculated using (3) [20].

$$C_{\text{loss}} = -\log_2 \det(A) \quad (3)$$

Here,

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad a_{ii} = 1 - |S_{ii}|^2 - |S_{ij}|^2$$

$$\text{and, } a_{ij} = -(S_{ij}^* S_{ij} + S_{ji}^* S_{jj}) \quad \text{for } i, j = 1 \text{ or } 2$$

Figure 10(c) shows that the CCL value of the realized MIMO antenna is maintained below 0.3 bits/sec/Hz over the entire operating range, which confirms minimal capacity degradation and efficient data transmission.

4.4.4. Total Active Reflection Coefficient (TARC)

TARC is employed as a comprehensive indicator for evaluating the combined reflection response of MIMO antennas under simultaneous excitation at all ports. A $\text{TARC} < -10$ dB signifies good impedance matching along with low reflection losses, thereby ensuring stable and reliable performance of the antenna under simultaneous multi-port excitation. The corresponding

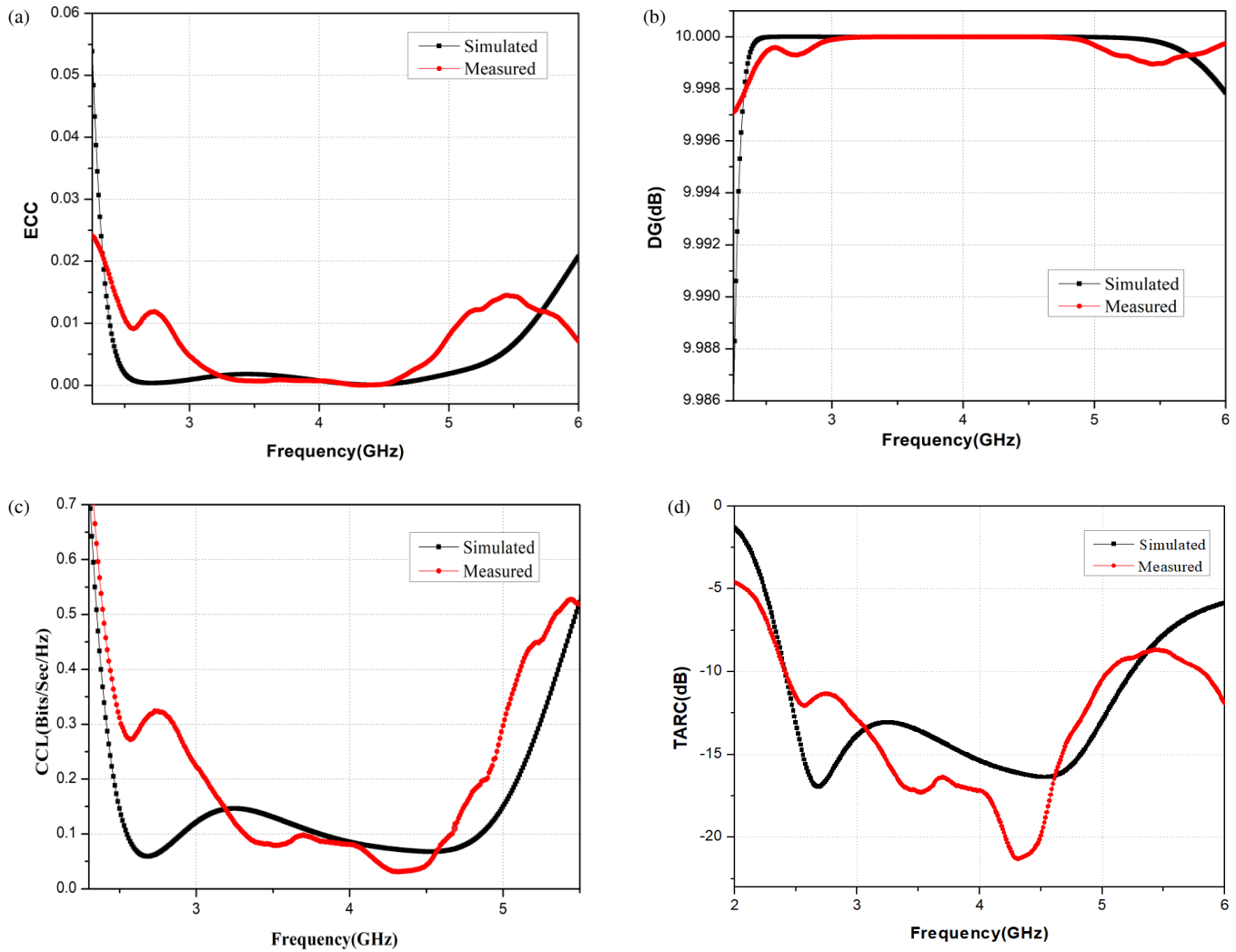


FIGURE 10. MIMO characteristics of the proposed MIMO antenna: (a) ECC, (b) DG, (c) CCL, and (d) TARC.

equation is given by (4). Fig. 10(d) presents the TARC responses obtained from both simulated and measured data [25].

$$\text{TARC} = \sqrt{\frac{(|S_{ii} + S_{ij}e^{j\theta}|^2) + (|S_{ji} + S_{jj}e^{j\theta}|^2)}{2}} \quad (4)$$

4.4.5. Mean Effective Gain (MEG)

MEG is utilized to assess the average received power of antenna elements by multipath propagation. It is commonly employed to evaluate the power distribution and maintain balance between antenna elements in an MIMO system. The calculation of MEG is carried out using Equation (5).

$$\text{MEGi} = 0.5 \left[1 - \sum_{j=1}^M |S_{ij}|^2 \right] \quad (5)$$

where M refers to the selected antenna element; ‘ i ’ corresponds to the port index; and S_{ij} denotes scattering parameters.

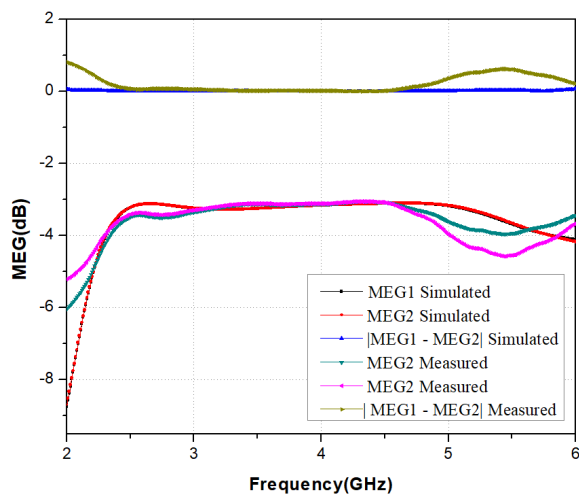
From Fig. 11, it is clearly shown that the MEG values of the two elements range from -3.4 dB to -4.1 dB within the operating band. The maximum difference between the elements is less than 1 dB, indicating balanced signal reception and satisfactory diversity performance.

After evaluating the diversity parameters, a comparative study between the proposed design and recently reported wide-band antenna designs, based on physical size, operating bandwidth, isolation, gain, and diversity parameters, while using the same substrate material (FR4) and two feeding ports, is presented in Table 1.

The comparative analysis demonstrates that, despite the compact antenna configuration, the proposed design achieves isolation better than -15 dB while retaining stable bandwidth, which is acceptable for a practical MIMO system. In addition, the gain is maintained within the required limits for the intended application. Moreover, the obtained MIMO performance metrics indicate the reliable and efficient overall MIMO performance of the antenna systems.

TABLE 1. Comparative performance analysis of the proposed MIMO antenna relative to previously reported works.

Ref	Year	Size (mm ³)	Bandwidth (GHz)	Minimum Isolation (dB)	Peak Gain (dB)	ECC	DG (dB)	CCL (bits/s/Hz)
[8]	2025	44 × 22 × 1.6	3–6.5	−53	11.5	0.0006	9.99	< 0.2
[10]	2024	42 × 30 × 1.6	3–7	< −15.5	5.6	0.025	NR	0.22
[15]	2025	38 × 25 × 1.6	5–6	< −21.5	3.5	< 0.004	> 9.95	< 0.4
[18]	2023	34 × 20 × 1.6	2.92–5.72	< −15	3	< 0.02	> 9.99	0.2
[19]	2025	36 × 26 × 1.6	3.07–5.20	−21	4.5	< 0.005	> 9.99	< 0.3
[20]	2024	36 × 26 × 1.6	3.28–5.9	< −18	4.1	< 0.001	9.99	0.02
[21]	2021	47 × 32 × 0.8	3.0–7.7	< −20	4.13	0.04	9.98	0.3
[23]	2022	25 × 20 × 0.8	3.12–5.00	−18.5	2.5	< 0.01	NR	NR
[24]	2023	40 × 25 × 1.6	3.29–5.96	< −50	6.22	< 0.01	> 9.95	0.28
Current Work	2026	30 × 30 × 1.6	2.6–5.1	< −15	3.9	< 0.01	> 9.99	< 0.3

**FIGURE 11.** MEG characteristics.

5. CONCLUSION

This study reports a miniaturized dual-port (MIMO) antenna designed to achieve a wideband operation encompassing the 5G mid-band. The developed antenna prototype was implemented on a cost-effective FR4 substrate with a compact footprint of $30 \times 30 \text{ mm}^2$. Measurement results verify that the designed antenna provides a wide bandwidth of 2.6–5.1 GHz with satisfactory impedance matching while maintaining an isolation level better than -15 dB across 5G NR bands by employing an effective and properly configured DGS technique. The evaluated MIMO metrics, including ECC, DG, CCL, TARC, and MEG, are consistent with the simulated results, thereby validating the performance of the practical MIMO antenna measurements. The realized performance revealed that the antenna achieved uniform radiation characteristics with satisfactory gain over the designated frequency range.

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