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A Compact Wide-Band Circular Slot Quad-Port MIMO Antenna for 5G Wireless Applications

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ABSTRACT: This paper introduces a 4-port antenna tailored for 5G, operating in the 4.4 to 7.25 GHz (Fractional Bandwidth is 48.9%) range with a 10 dB impedance bandwidth. The operating bandwidth includes the n79 band (4.4–5 GHz), 5G WLAN band (5.125–5.825 GHz), and Wi-Fi 6E band (5.925 to 7.125 GHz). Constructed on a compact FR4 substrate ($0.057\lambda \times 0.057\lambda \times 0.0018\lambda$ (where λ is the wavelength at 4.4 GHz), it exhibits robust performance in fabrication and measurements. The single antenna covers a total area as small as $20 \times 17.6\ \mathrm{mm}^2$, which enables the compactness of the MIMO antenna with a gain of up to 6 dBi and 85% radiation efficiency; it supports MIMO with a low correlation coefficient (< 0.02), high diversity gain (up to 9.98 dB), and minimal channel capacity loss (0.25 bps/Hz). The Total Active Reflective Coefficient (TARC) is computed to validate MIMO performance over the operating bandwidth. Featuring bidirectional radiation patterns in both E-plane and H-plane, the antenna is well suited for 5G applications, demonstrating potential for future wireless systems.

1. INTRODUCTION

The exponential growth of wireless demands propelled by the advent of 5G and the Internet of Things (IoT) underscores the imperative for substantial data exchange capabilities [1]. While single-element antennas have been conventionally employed, their inherent limitations in gain and bandwidth have spurred the development of Multiple Input Multiple Output (MIMO) antennas, integrating multiple elements on a single substrate [2, 3]. A plethora of MIMO antenna designs have emerged, varying in element counts from two to well over six [4–15]. Among these, four-element MIMO system stands out for its versatility, offering configurations in both linear and rectangular setups [5, 12–14]. While certain designs cater to lower frequency bands such as sub-1 GHz, there has been a significant shift in focus towards the sub-6 GHz bands, aligning with the burgeoning requirements of contemporary wireless networks [15]. Moreover, researchers have delved into the realm of multiband MIMO antennas [17], with a particular emphasis on techniques aimed at minimizing mutual coupling between ports [18]. Exploring flexible substrates has emerged as a promising avenue for compact MIMO systems, leveraging advantages such as enhanced conformability and manufacturability. However, implementing flexible substrates necessitates meticulous attention to ensure performance optimization and reliability. Despite the proliferation of MIMO antenna designs, there remains a dearth of discussions surrounding the utilization of flexible substrates and the determination of optimal operating frequencies. Consequently, there is a pressing need for further research to delve into the intricacies of design considerations and performance implications associated with flexible MIMO antennas across diverse frequency spectrums. Such endeavors are indispensable for addressing the evolving demands of wireless communication systems, ensuring their efficacy and resilience in the face of escalating data requirements. By bridging these gaps in knowledge, researchers can pave the way for developing next-generation MIMO antenna systems that are both agile and robust, catering to the dynamic landscape of wireless communication technologies.

The significance of the work is to design a compact 4-port antenna tailored for 5G, operating between 4.4 and 7.25 GHz. Its

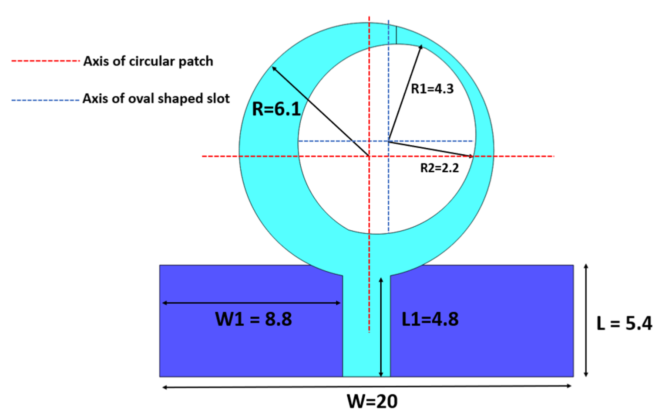

FIGURE 1. Structure and dimension of single element antenna.

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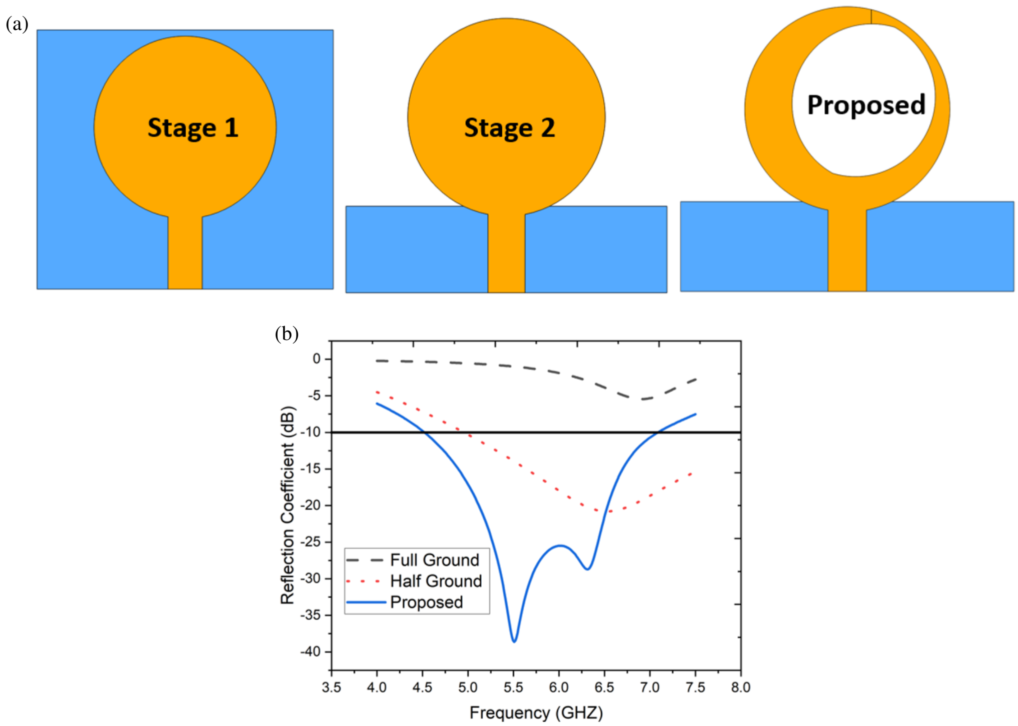

FIGURE 2. (a) Design evolution of proposed antenna. (b) Reflection coefficient of various stages of design evolution.

$20 \times 17.6\,\text{mm}^2$ size supports MIMO configurations with minimal interference and high diversity gain. The antenna boasts a gain up to 6 dBi and an 85% radiation efficiency, ensuring robust signal coverage. Its low Envelope Correlation Coefficient (ECC) (< 0.02) and high diversity gain (up to 9.98 dB) minimize channel capacity loss, enhancing system efficiency. Bidirectional radiation patterns and validation through Total Active Reflective Coefficient (TARC) analysis further confirm its suitability for various 5G applications, making it a promising candidate for future wireless systems.

The article is divided into three sections. Section 1 covers antenna design and analysis, followed by results and discussions in Section 2. Section 3 focuses on the implementation of the MIMO antenna, and Section 4 deals with MIMO parameters.

2. ANTENNA DESIGN AND ANALYSIS

A slotted circular radiator is connected to a feeding strip measuring $2.4\,\text{mm} \times 4.8\,\text{mm}$, printed on the front side of a 1.6 mm thick FR4 substrate. The substrate's back side hosts a partial ground. The configuration and measurements of the proposed antenna are illustrated in Figure 1. It comprises three primary components: a slotted circular radiating element, a feeding strip, and a partial ground plane. The radiating element consists of a circular structure with a radius of 6.1 mm and an oval-shaped slot with a radius of 4.3 mm (major axis) and 2.2 mm (minor axis), as depicted in Figure 1. The ground plane measures $20\,\text{mm} \times 5.4\,\text{mm}$, which enhances the proposed antenna's overall bandwidth and other radiation characteristics.

3. RESULTS AND DISCUSSION

The simulation process was facilitated by Advanced Design System (ADS) software, and the antenna design steps are outlined in Figure 2(a). Initially, Stage 1 utilized a full ground plane without an oval-shaped slot on the radiating element. However, as depicted in Figure 2(b), the antenna at Stage 1 failed to achieve the intended resonance. Consequently, the size of the ground plane was reduced in Stage 2, as illustrated in Figure 2(a). Although this configuration operated within the required band, it exhibited poor impedance matching across the spectrum. To address this issue, an oval-shaped slot was introduced on the circular radiating element of the proposed antenna. This adjustment resulted in a significant bandwidth ranging from 4.4 to 7.25 GHz, with $S_{11} \leq -40$ at 5.5 GHz, as demonstrated in Figure 2(b).

A parametric analysis was conducted on a specific parameter of the proposed antenna and is depicted in Figure 3. Initially, the length of the ground plane (L) was varied from 4.4 mm to 7.4 mm with a step size of 1 mm, and corresponding changes in the reflection coefficient were observed and plotted in Figure 3(a). Varying L from 4.4 mm notably improved impedance matching, especially at $L = 5.4$ mm, where bandwidth significantly increased with $S_{11} \leq -40$ dB at 5.5 GHz. Conversely, adjusting $L1$ from 3.8 mm to 6.8 mm shifted frequency operation and altered impedance matching, as shown in Figure 3(b). Other parameter studies are not presented here for brevity.

4. IMPLEMENTATION OF MIMO ANTENNA

The suggested single antenna element is transformed into a four-element MIMO antenna system, as depicted in Fig-

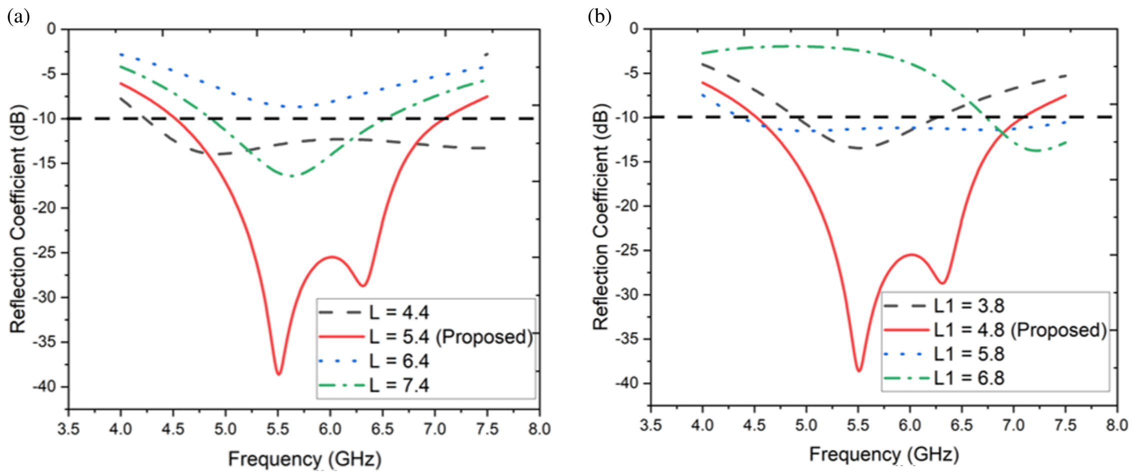

FIGURE 3. Parametric analysis of proposed antenna when altering (a) L, (b) $L1$.

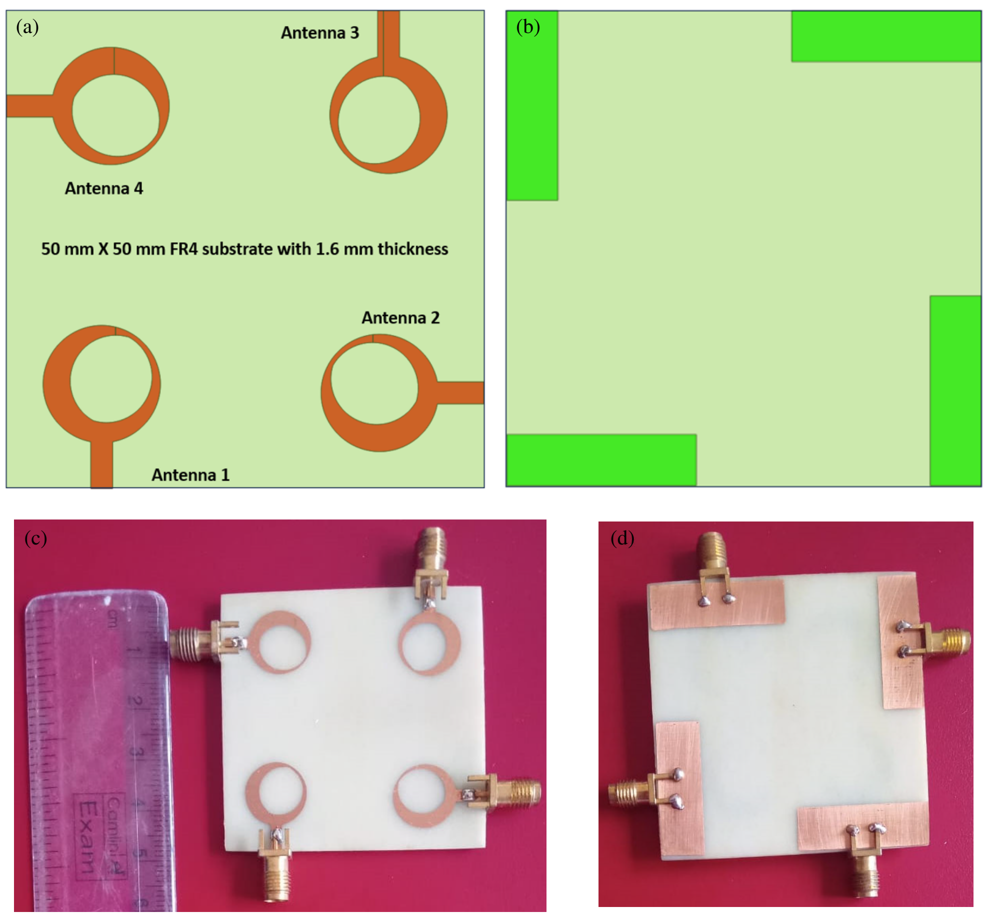

FIGURE 4. Simulated antenna, (a) front view, (b) back view. Fabricated prototype, (c) front view, (d) back view.

ures 4(a) and (b). Each antenna component within the MIMO system is strategically positioned to ensure that electromagnetic waves emanating from all radiating elements that propagate orthogonally. This orthogonal arrangement of antenna elements leads to a significant improvement in isolation, thereby enhancing the overall performance of the MIMO antenna systems. The proposed four-port MIMO antenna is constructed and practically evaluated, as depicted in Figures 4(c) and (d). The fabricated antenna's S-parameters are measured using Keysight's vector network analyzer (VNA). During the measurement of S_{11}, all other antennas are terminated by 50-ohm terminators. Figure 5(a) and (b) show simulated and measured reflection coefficients of the designed MIMO antenna, highlighting observed discrepancies possibly

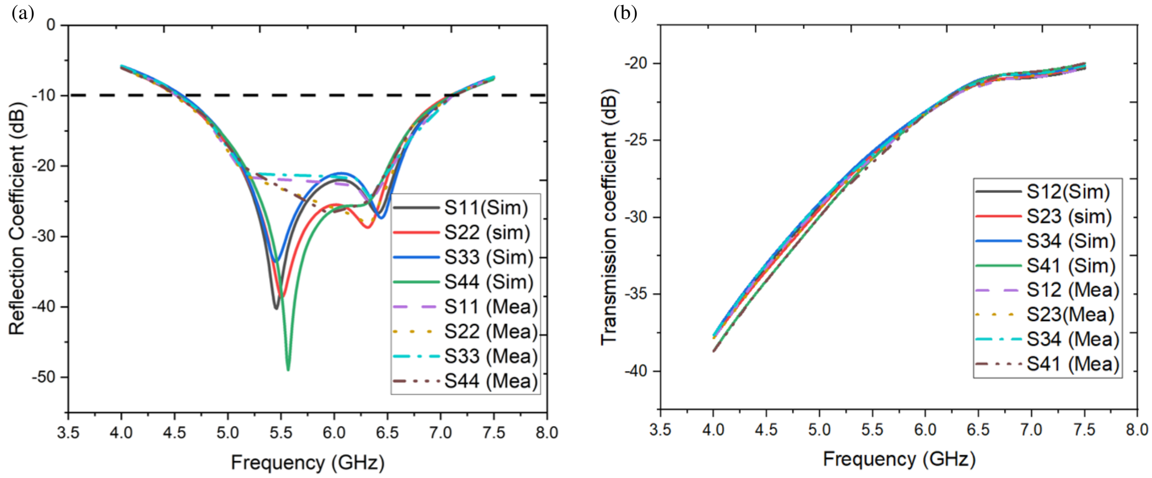

FIGURE 5. Simulated and measured (a) reflection coefficient, (b) transmission coefficient.

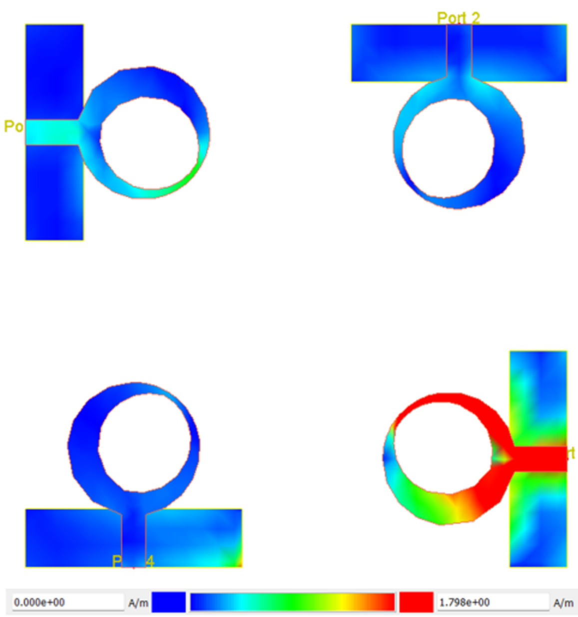

FIGURE 6. Surface current distribution of the proposed MIMO antenna at 5.5 GHz.

due to substrate changes, soldering effects, and environmental variations.

Figure 6 illustrates the simulated current distribution of the proposed MIMO antenna when only one port is excited. It is observed that the influence of feeding port 1 of the antenna is demonstrated, revealing induced currents in neighbouring elements that signify power coupling and isolation between these elements. It is evident that upon exciting antenna 1, all other radiating components become completely detached, ensuring a noteworthy improvement in isolation exceeding 20 dB.

Figures 7(a) and (b) illustrate the two-dimensional far-field radiation pattern of antenna 1 at 5.5 GHz when $\varphi = 0°$ and $90°$ (E and H-plane). At 5.5 GHz, the antenna demonstrates a bi-directional radiation pattern, as depicted. Likewise, Figures 7(c) and (d) illustrate the far-field pattern of antenna 1 at 6.5 GHz on both planes. It is evident that the designed antenna showcases distinctive radiation characteristics across the entire spectrum of operation.

Figure 8(a) displays simulated and measured gains of the antenna, ranging from 2 to 6 dBi within the desired operational band. Simulation and measurement curves exhibit similar trends, with slight deviations attributable to the measurement setup.

The antenna achieves radiation efficiency ranging from 50% to 88% across the operating spectrum, as depicted in Figure 8(b), affirming its suitability for mid-range 5G wireless communication.

5. MIMO RESULT VALIDATIONS

ECC serves as a critical parameter for assessing MIMO antenna performance, which can be computed using S-parameters or radiation patterns. Figure 9(a) shows simulated and measured ECCs for the flat MIMO antenna, staying below 0.03 within the desired band, indicating excellent performance. As a result of the discoveries, one can deduce that the proposed array of antennas with four elements contributes to the improvement of various functionalities.

Figure 9(b) validates the diversity gain of the proposed four-element antenna, with a maximum value up to 9.9 dB in the desired spectrum band. Additionally, researchers analyzed the Channel Capacity Loss (CCL) of the MIMO antenna, often denoted as CCL. They used Equations (1) and (2) to compute the CCL, crucial for determining the MIMO system's data transmission rate.

$$\text{Channel Loss (CL)} = -\log_2 \det\left(\varphi^R\right) \tag{1}$$

$$\varphi^R = \begin{bmatrix} \text{ECC}_{ii} & \cdots & \text{ECC}_{ij} \\ \vdots & \ddots & \vdots \\ \text{ECC}_{ji} & \cdots & \text{ECC}_{jj} \end{bmatrix} \tag{2}$$

where,

$$\text{ECC}_{ii} = 1 - \left(\left(S_{ii}^2\right) + \left(S_{ij}^2\right)\right)$$

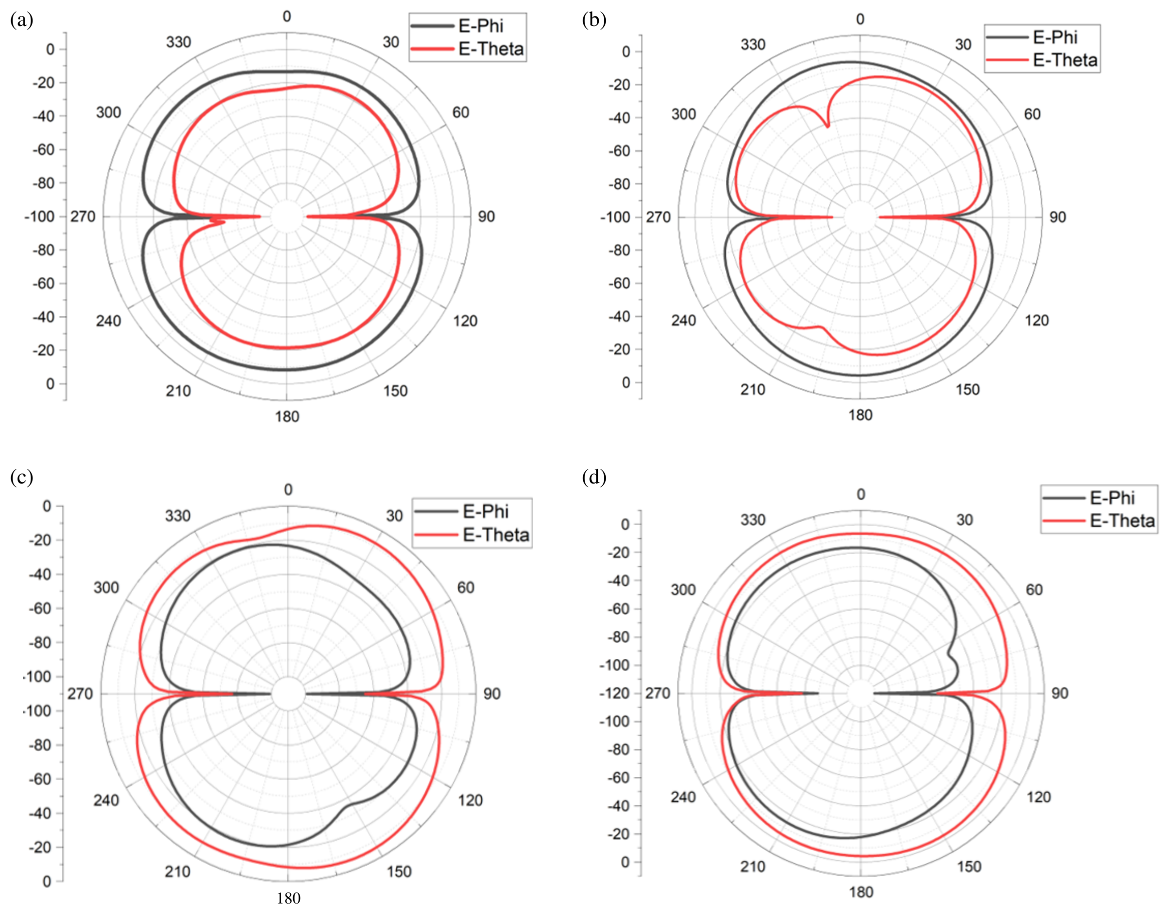

FIGURE 7. Measured far-field pattern of antenna 1 for E-plane at (a) 5.5 GHz, (b) 6.5 GHz, H-plane at (c) 5.5 GHz, (d) 6.5 GHz.

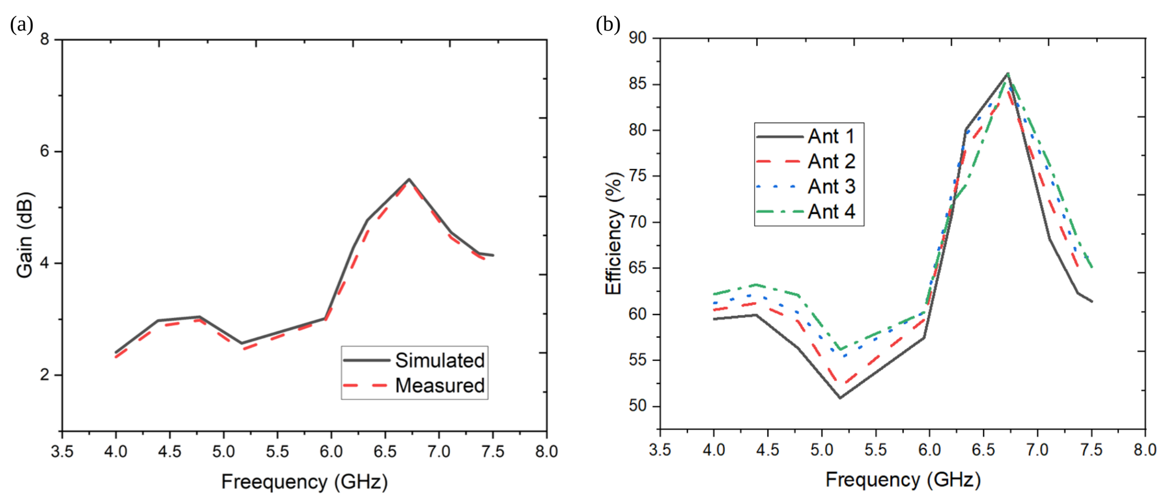

FIGURE 8. (a) Simulated and measured gain. (b) Radiation efficiency of the proposed MIMO antenna.

$$\mathrm{ECC}_{ij} = -\left(S_{ii}^{*}S_{ij} + S_{ji}^{*}S_{jj}\right) \quad \text{for } i, j = 1, 2...4$$

Figure 9(c) shows calculated CCL with the four-element antenna. CCL values are below 0.3 bits/sec/Hz over the operating resonance, indicating satisfactory data rates across the bandwidth for the wide-band MIMO antenna proposed. The CCL simulation outcomes corroborate these values, confirming the antenna's effectiveness. The TARC of the antenna is calculated and presented in Figure 9(d). TARC is computed for port 1 while altering the phase values of all other ports. It is observed that the alteration of phase values does not affect the overall bandwidth of antenna 1, ensuring the robustness of the antenna system in terms of its performance.

The proposed MIMO antenna is smaller and has a broader operating bandwidth than the referenced antennas listed in Ta-

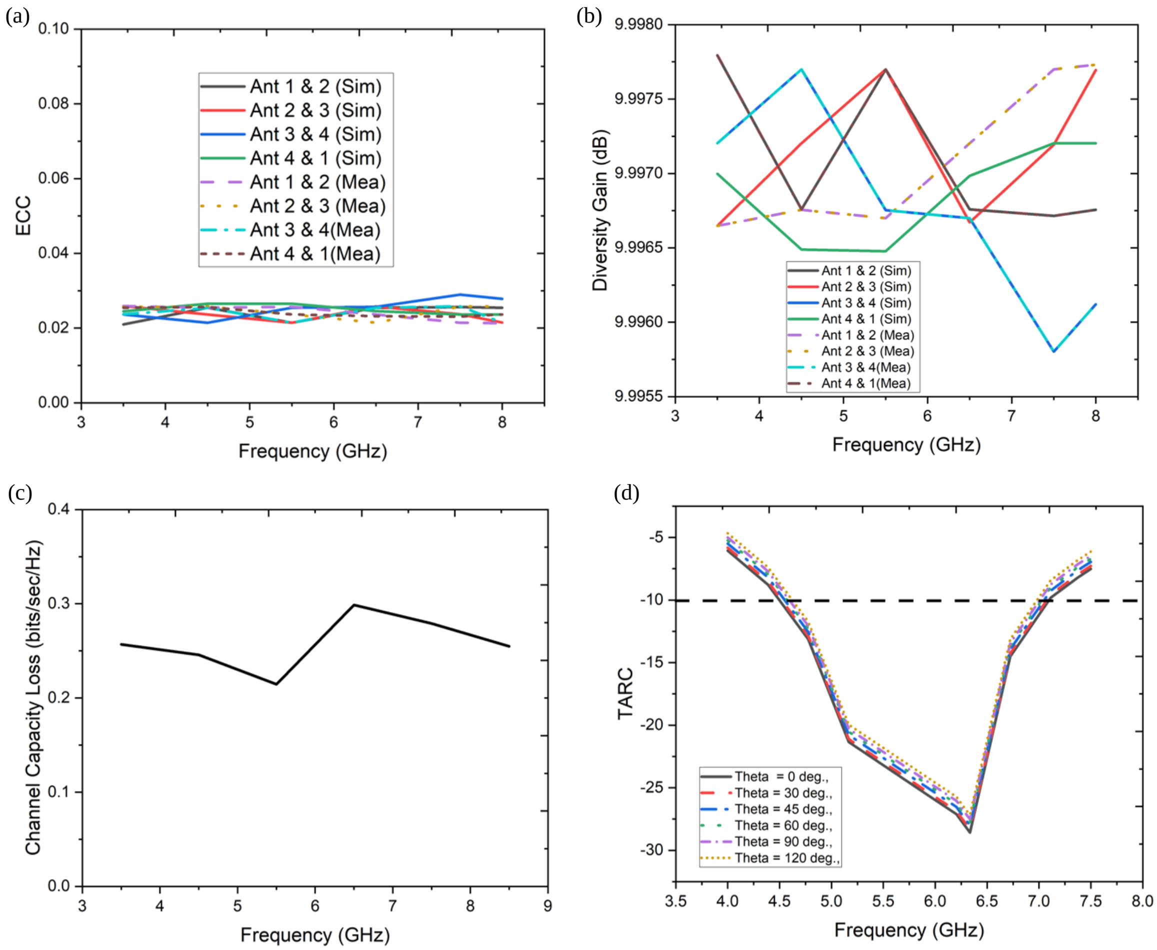

FIGURE 9. MIMO parameters (a) ECC, (b) diversity gain, (c) channel capacity loss (CCL), (d) total active reflection coefficient.

TABLE 1. Performance comparison of the proposed MIMO antenna with other antennas in the literature.

Reference	Size of the antenna (mm^2)	Electrical dimension of the antenna (mm^2)	Operating bandwidth (GHz)	No of ports	Gain (dBi)	Isolation (dB)	ECC
[9]	50×100	$0.0306\lambda \times 0.061\lambda$	2.7–3.6	4	3	25	NA
[12]	180×180	$2.86\lambda \times 2.86\lambda$	0.7–1, 2.6–7.2	4	5	13	< 0.5
[14]	120×65	$0.09\lambda \times 0.048\lambda$	3.3–5	4	2–4	18.8	< 0.018
[15]	70×145	$0.0377\lambda \times 0.072\lambda$	2.37–5.85	4	5	17.5	< 0.05
[16]	150×73	$0.115\lambda \times 0.056\lambda$	3.4–3.6	4	NA	20	< 0.06
[17]	88×88	$0.046\lambda \times 0.046\lambda$	2.32–2.524	4	4	> 15	NA
[18]	71×49	$0.037\lambda \times 0.0256\lambda$	2.3–2.6	1	1.4	NA	NA
This work	50×50	$0.057\lambda \times 0.057\lambda$	4.4–7.25	4	2–6	> 20	< 0.02

ble 1. It maintains similar ports but achieves notably higher isolation and lower ECC. Overall, it appears to provide improved performance in terms of size, bandwidth, isolation, and MIMO characteristics.

6. CONCLUSION

In conclusion, this research introduced a novel 4-port antenna designed for 5G applications, which operated in the 4.4 to 7.25 GHz range with a significant fractional bandwidth of 48.9%. Key frequency bands, including n79, 5G WLAN, and Wi-Fi 6E, were covered by the antenna, which was constructed on a compact FR4 substrate, ensuring robust performance in fabrication and measurements. Its compact size of $20 \times 17.6\,mm^2$ facilitated the integration of multiple-input-multiple-output (MIMO) systems, boasting a gain of up to 6 dBi and an impressive radiation efficiency of 85%. With a low correlation coefficient (< 0.02) and high diversity gain (up to 9.98 dB), the antenna minimized channel capacity loss (0.25 bps/Hz), validated by the Total Active Reflective Coefficient (TARC) computation across the operating bandwidth. Moreover, its bidirectional radiation patterns in both E-plane and H-plane made it highly suitable for 5G applications, showcasing considerable promise for future wireless systems.

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