Received 28 September 2025; revised 24 October 2025; accepted 2 November 2025. Date of publication 10 November 2025;
date of current version 9 February 2026.

Digital Object Identifier 10.1109/OJAP.2025.3630824

A Miniaturized Quad-Port Circularly Polarized MIMO Antenna for mmWave Wireless Applications

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This work was supported in part by the National Key Research and Development Program of China under Grant 2023YFE0107900; in part by National Natural Science Foundation of China under Grant U2541208; in part by the Key Program of Shenzhen Natural Science Foundation under Grant JCYJ20241202124219023; and in part by the Program of Shenzhen Key Laboratory Evaluation under Grant SYSPG20241211173908022.

ABSTRACT This paper presents a miniaturized quad-port circularly polarized (CP) multiple-input multiple-output (MIMO) slot antenna with enhanced isolation, gain, and diversity performance for millimeter-wave (mmWave) applications. Each port excites an identical notched rectangular slot via a 50 Ω microstrip line. A simple “+”-shaped slot etched on the ground plane improves inter-element isolation. Additionally, a split ring resonator (SRR)-based reflector, designed at the antenna’s fundamental mode and placed above the array, improves the gain by 1 dBic and further reduces mutual coupling within a compact size of $14\times14\times0.508$ mm^3 ($1.31\lambda_0\times1.31\lambda_0\times0.047\lambda_0$), where λ_0 is free space wavelength at the operating frequency of 28 GHz. The proposed CP MIMO antenna has an impedance bandwidth (IBW) of 25.80–28.96 GHz, an axial ratio bandwidth (ARBW) of 26.56–28.96 GHz, a gain of 6.0 dBic, isolation of ≤ –22 dB, and a radiation efficiency exceeding 94%. Excellent diversity performance is demonstrated through a low envelope correlation coefficient (ECC), high diversity gain (DG), a mean effective gain (MEG), and low channel capacity loss (CCL). An equivalent circuit model of the MIMO antenna is analyzed. Measured and simulated results show strong agreement, confirming the antenna’s suitability for mmWave wireless communications and smart devices.

INDEX TERMS Axial ratio, circular polarization, mmWave, 5G network, MIMO antenna.

I. INTRODUCTION

THE research community is focusing on the rapid advancements in wireless communication technologies. The number of users is increasing rapidly, along with the demand for high data rates [1]. Multiple-input-multiple-output technology improves data rates, reliability, and channel capacity in multipath fading environments without requiring additional transmission power or bandwidth. MIMO systems enhance the communication performance by using multiple antenna elements at both the transmitter and receiver. Various MIMO antennas have been developed specifically for 5G applications in mmWave frequency bands [2]. MIMO antennas typically exhibit linear polarization (LP), which creates a multipath fading problem. Linear polarization limits the channel capacity of the multiple-input multiple-output antenna. To overcome this challenge, circularly polarized antennas have recently gained considerable attention in MIMO system design [3], [4]. Regardless of orientation independence, the circularly polarized antennas are preferred over LP antennas in terms of wireless connectivity due to their reliable connection between the sending and receiving device. In dynamic situations, the circularly polarized antennas, particularly left-handed circularly polarized (LHCP) and right-handed circularly polarized (RHCP), significantly reduce multipath interference, improve signal stability and MIMO system channel capacity [5], [6]. In MIMO antenna systems, isolation between closely spaced radiating elements is a critical design parameter that directly affects overall system performance. Poor isolation leads to mutual coupling, which causes signal distortion, impedance mismatch, and degradation of diversity characteristics, thereby reducing channel capacity and radiation efficiency. At mmWave frequency bands, achieving high isolation is particularly challenging due to short wavelengths and dense integration, which increase electromagnetic coupling between elements. Therefore, highly isolated and circularly polarized MIMO antennas within the limited space of modern wireless devices present a considerable challenge [7], [8]. Circular polarization in single microstrip patch element is obtained by generating two resonant orthogonal modes characterized by identical amplitudes with a phase difference of 90° [9]. Typically, circular polarization is achieved by adding a geometric structure called a stub to the patch's edge [10]. Moreover, CP can be achieved by incorporating slots into the radiating patch [11], cutting off the corners of a rectangular microstrip patch element, or truncating the corners [12]. The single patch CP antenna can be modified by incorporating a multi-element MIMO configuration to enhance its spatial diversity and link reliability [13]. Integrating circular polarization improves the performance in mobile and adverse weather conditions [14], [15]. In addition to ensuring polarization diversity, the MIMO systems should have multiple antenna elements closely spaced to maximize the compactness. However, MIMO performance gains scale with the number of antennas, presenting design challenges. Densely packed antenna arrays can lead to strong mutual coupling, potentially degrading channel capacity and diversity performance [16].

Several antenna designs have been proposed to reduce mutual coupling in MIMO systems, including 6-shaped and hexagonal nested neutralization line (HN-NL) [17], tapered slot antennas [18], [19], meander line antenna [20], slotted rectangular patches [21], and parasitic structures [22], [23], [24]. Additionally, MIMO antenna isolation can be enhanced using physically separated ground planes [25] and spatial diversity techniques [26]. Moreover, the split-ring resonators [27] and electromagnetic bandgap (EBG) [28] materials have been used to enhance the performance and isolation of MIMO systems. Recent research has introduced several innovative solutions, including a mmWave MIMO magnetoelectric (ME) dipole antenna array [29] and a four-port orthogonal circularly polarized MIMO antenna equipped with a polarization converter [30]. Additionally, a flexible MIMO antenna featuring E-shaped and rectangular slots has been proposed to improve isolation in the 26/31 GHz 5G bands [31]. Furthermore, a compact double-sided frequency selective surface (FSS) absorbing wall for decoupling 5G antenna arrays has demonstrated the ability to achieve over 20 dB of isolation [32]. Despite these advancements, several challenges remain, such as narrow bandwidth [19], [21], [26], [30], [32], inadequate isolation [19], [25], [28], [29], [32], large physical dimensions [9], [19], [21], [27], [32], and low gain performance [21], [22], [24], [27], [30], [32].

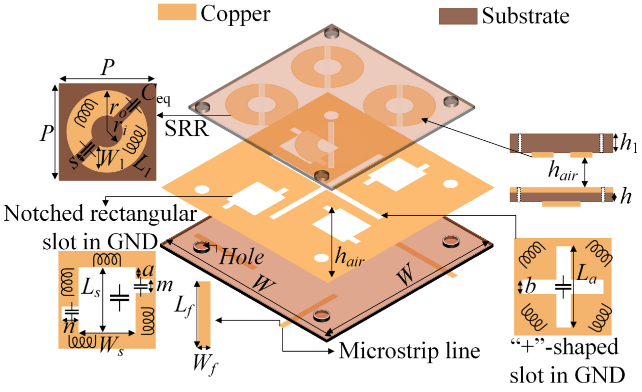


FIGURE 1. Deployed view of the proposed MIMO antenna with SRR superstrate.

This paper presents a quad-port circularly polarized MIMO slot antenna with enhanced isolation, using a simple "+"-shaped slot configuration, with following contributions.

- A "+"-shaped slot in the ground reduces the mutual coupling, and CP radiation minimizes polarization mismatch in 5G mmWave.
- An SRR-based reflector improves gain by 1 dBic, further reduces mutual coupling, and achieves high-efficiency suitable for low-power 5G devices (smartphones/IoT).
- The MIMO diversity performance, characterized by low ECC, high DG, favorable MEG, and low CCL, ensures robust signal quality in multipath mmWave applications.

The upcoming section of this paper includes the antenna design methodology of the proposed antenna in Section II, the SRR-reflector-based proposed MIMO antenna in Section III, an equivalent circuit model in Section IV, experimental results and discussion in Section V, an analysis of diversity performances in Section VI, and a comparison in Section VII. Finally, Section VIII concludes the paper.

II. ANTENNA DESIGN METHODOLOGY

A. ANTENNA CONFIGURATION

Fig. 1 illustrates the perspective view of the proposed MIMO antenna incorporating an SRR-based reflector superstrate. The overall MIMO antenna dimensions are $20\times20\times0.813$ mm^3 ($1.87\lambda_0\times1.87\lambda_0\times0.076\lambda_0$). A 50 Ω microstrip feed line is implemented on Rogers RO4003C substrate with a dielectric constant of 3.55 and a thickness of 0.305 mm. On the backside of the substrate, a rectangular notch and a "+"-shaped slot are etched on the ground plane to excite circular polarization. A 2×2 array of SRR reflectors, measuring 14×14 mm^2, is printed on a Rogers RT5880 substrate with a height of 0.508 mm (h_1) and placed above the antenna, with an air gap of 4.2 mm (h_{air}). Table 1 presents the optimized geometric parameters of the antenna, which are computed using the familiar transmission line theory of rectangular patch antenna [33].

TABLE 1. Dimensions of the proposed MIMO antenna.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
W	20	b	0.50	L_f	8.0
W_f	0.4	W_s	3.0	m	0.45
n	0.2	L_s	2.6	a	0.20
L_a	11.5	h_1	0.508	P	6.0
s	0.2	r_o	1.8	r_i	0.63

B. DESIGN EQUATIONS FOR SINGLE-ELEMENT ANTENNA

The proposed quad-port MIMO antenna consists of four radiators with simple microstrip feed lines, modeled using analytical formulas. The dimensions of a single-element for a rectangular microstrip patch antenna are determined using fundamental equations. The resonance frequency [34] can be calculated as

$$f_r = \frac{c}{2W\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

where ε_r represents the substrate's relative permittivity and c denotes the speed of light in meters per second (m/s). Based on the fundamental equation, the basic dimensions of the patch [34] antenna are given by

$$W = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2}$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{eff}-0.258\right)\left(\frac{W}{h}+0.8\right)}\right) \tag{3}$$

The effective length $L_{(eff)}$ of the patch is determined by

$$L(eff) = \frac{c}{2f_o\sqrt{\varepsilon_{(eff)}}} \tag{4}$$

where $\varepsilon_{(eff)}$ is the effective permittivity and h is the height of substrate. The length and width of the ground can be calculated as

$$L_g = 6h + L \tag{5}$$

$$W_g = 6h + W \tag{6}$$

The proposed quad-port MIMO antenna system is excited by a 50 Ω feed line with a width of 0.4 mm. For multiple antenna elements, the desired impedance matching is determined as

$$W_{Z_0} = \left(\frac{377}{Z_0\sqrt{\varepsilon_r}} - 2\right) \times h_s \tag{7}$$

where Z_0 represents the characteristics impedance of the feed line, h_s denotes the height of the substrate, W_{Z_0} indicates the width of a feed line for a specific impedance, and ε_r is the permittivity of the dielectric material. The width of feedlines is set to obtain 50, 70.7 and 100 Ω according to (7).

C. DESIGN EQUATIONS FOR SPLIT-RING RESONATOR

The simple microstrip line antenna is transformed into a quad-port MIMO antenna system using a split-ring resonator placed above the antenna array. The SRR is a crucial component of the MIMO antenna system, which operates as a reflector. Since the unit cell of SRR operates as an LC circuit, we can determine the resonant frequency as [35]:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{8}$$

where C represents the equivalent capacitance and L denotes the effective inductance of the ring.

$$L = \frac{4.86\mu_0}{2}(r_0 - W1 - g)\left[ln\left(\frac{0.98}{\rho}\right) + 1.84\rho\right] \tag{9}$$

where ρ is the filling factor of the inductance and is calculated by

$$\rho = \frac{W1 + g}{r_0 - W1 - g} \tag{10}$$

The effective capacitance is determined by

$$C = \left(r_0 - \frac{3}{2}(W1 + g)C_{pul}\right) \tag{11}$$

where C_{pul} is the per unit length capacitance, which is calculated as

$$C_{pul} = \varepsilon_0\varepsilon_{eff}\frac{K\left(\sqrt{1-k^2}\right)}{K(k)} \tag{12}$$

where ε_{eff} is the effective dielectric constant which can be stated as

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{13}$$

The function K(k) represents the complete elliptical integral of the first kind, where k is defined as

$$k = \frac{g}{g + 2W1} \tag{14}$$

The lumped model equivalent circuit of the SRR is designed using the given expressions, as illustrated in Fig. 1.

D. DESIGN EVALUATION PROCESS

Fig. 2 depicts the three-dimensional structure of the slot antenna from the top and back views. The stepwise design starts with a rectangular slot fed by a 50 Ω microstrip line (introduced in Step-I), followed by the Step-II ("+"-shaped) slot, the Step-III (rectangular slot), and the proposed notched rectangular slot configuration, with overall dimensions of $10\times10\times0.305$ mm^3. Fig. 3 shows the simulated results for each design iteration, including impedance bandwidth, axial ratio, and gain, obtained using CST Microwave Studio 2022. In the initial three configurations (Step-I, Step-II, Step-III), the antenna achieves impedance matching ($|S_{11}| \leq -10$ dB) at resonant frequencies of 24 GHz, 25.9 GHz,

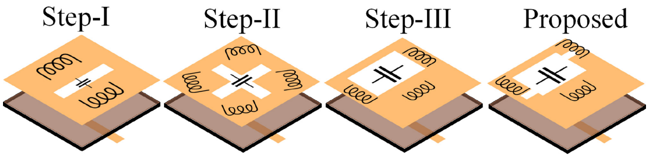
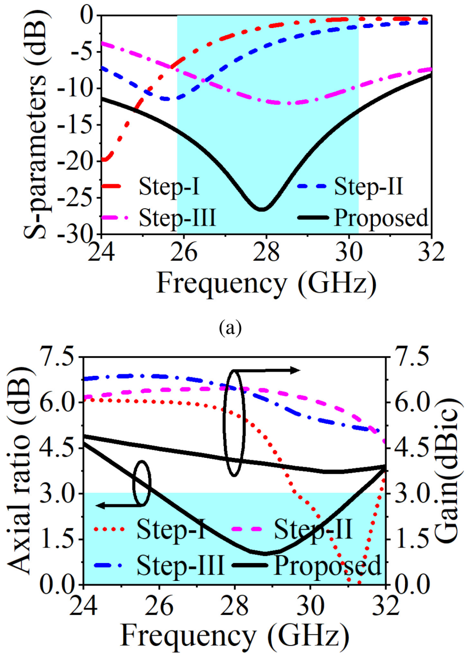


FIGURE 2. 3D configuration stepwise slot antenna design.



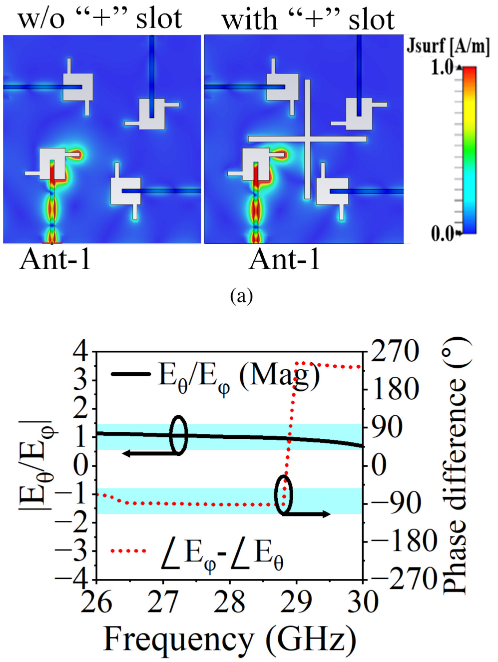
(a)

(b)

FIGURE 3. The simulated results of stepwise antenna design. (a) S-parameters in dB. (b) Axial ratio with a peak gain (dBic).

and 28.3 GHz, corresponding to 10 dB IBW ranges of 24–25 GHz, 25.8–26.2 GHz, and 27.8–28.5 GHz, respectively. However, an axial ratio of 40 dB indicates linear polarization performance, with a gain of approximately 5.0 dBi and 6.0 dBi for the latter designs. By introducing a small rectangular notch into the rectangular slot, the proposed antenna attains a broader IBW of 26.69–28.96 GHz. Moreover, the 3 dB axial ratio bandwidth fully overlaps with the impedance bandwidth, demonstrating effective CP behavior with a gain of 4 dBic, as illustrated in Fig. 3 (a) and (b). As shown in Fig. 4, when several antenna elements are integrated on a single substrate with a shared ground plane, the surface waves become the dominant coupling mechanism without (w/o) isolating structures. To address this issue, a "+"-shaped slot is incorporated into the ground plane, effectively suppressing the dominant surface wave between adjacent antenna elements. This enhancement improves electrical isolation without reducing their physical spacing. The slotted ground plane reduces the surface wave propagation, and achieves the low mutual coupling, as shown in Fig. 4(a).

According to circular polarization theory, the CP is achieved when the magnitude ratio satisfies $|E_\theta/E_\varphi| = 1$ (0 dB) and the phase difference between the orthogonal components $(\angle E_\varphi - \angle E_\theta)$ is $\pm 90°$. Fig. 4(b) presents the magnitude and phase response of the antenna, showing an amplitude ratio close to unity and a phase difference near $-90°$ across the operating frequency band. The negative phase difference indicates that Ant-1 shows RHCP. These findings are further supported by the observed surface current rotation illustrated in Fig. 5. Fig. 6(a) shows the simulated S-parameters result of the MIMO antenna without and with the incorporation of the "+"-shaped slot. The isolation in MIMO systems is a key performance metric that quantifies the level of coupling between antenna elements. The results show that the quad-port antenna w/o the"+"-shaped slot achieves a 10 dB impedance bandwidth of 25.5 to 29 GHz. However, the S-parameters between element-1 and element-4 (i.e., $|S_{12/21}|$, $|S_{31/13}|$, $|S_{41/14}|$, $|S_{23/32}|$, $|S_{42/24}|$, and $|S_{43/34}|$) ranges only from -18 to -27 dB across the operating band. The low isolation indicates significant mutual coupling and high correlation among antenna ports,



(a)

(b)

FIGURE 4. (a) Surface current distribution of Ant-1 w/o and with"+"-shaped slot. (b) $|E_\theta/E_\varphi|$ (Mag) with phase difference (°).

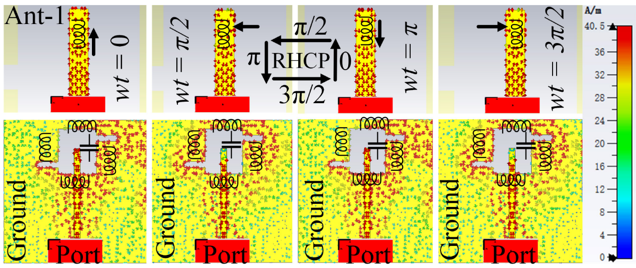
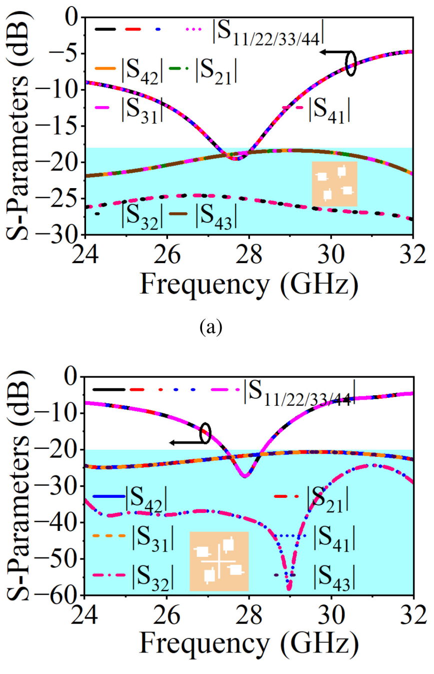


FIGURE 5. Surface current vector notation of Ant-1 with ground plane at ($\omega t = 0$, $\pi/2$, π and $3\pi/2$).



(a)

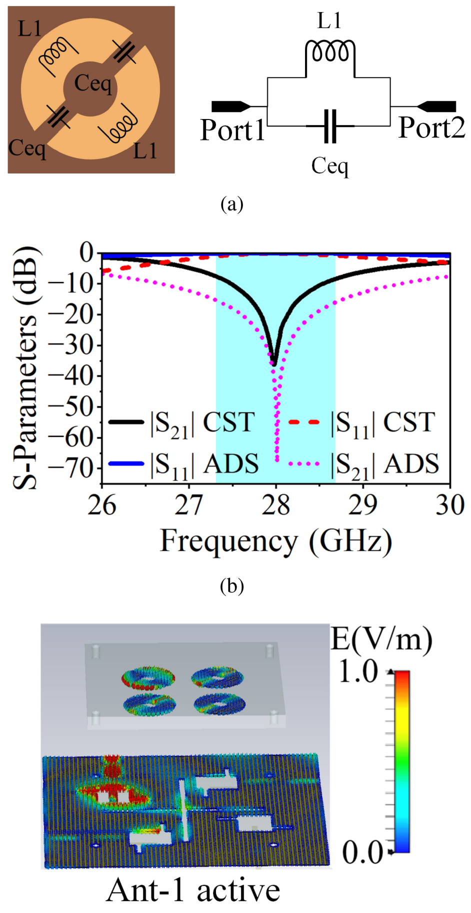
(b)

FIGURE 6. **Simulated results of S-parameters. (a) Without "+"-shaped slot. (b) With "+"-shaped slot.**

potentially affecting the overall performance and radiation characteristics of the MIMO antenna. One effective method for reducing mutual coupling between antenna elements is to increase the distance between them. However, this approach can lead to an undesirable increase in the overall size of the antenna. To overcome this limitation, it is crucial to design a compact isolating structure that enhances isolation w/o expanding the antenna's size. In this paper, we propose a"+"-shaped slot etched into the ground plane, which effectively reduces correlation among the antenna elements. The MIMO antenna with the "+"-slot exhibits an impedance bandwidth from 26.69 GHz to 28.98 GHz, with an isolation level of at least ≤ −20 dB throughout this range, as shown in Fig. 6(b).

III. SRR-REFLECTOR BASED MIMO ANTENNA

The performance of the MIMO antenna can be enhanced in terms of gain and isolation by using a reflector based on a split-ring resonator. Fig. 7(a) shows the SRR unit cell with an equivalent circuit. The dimensions of the SRR unit cell are 7×7 mm ^{2}. The equivalent circuit consists of an inductance of $L_1 = 0.294$ nH and a equivalent capacitor of $C_{eq} = 0.11$ pF [35]. The CST software simulates the SRR reflector using unit cell boundary conditions in the x-and-y directions, with Floquet ports for excitation in the $\pm z$-direction. The Keysight advanced design system (ADS) simulates the equivalent circuit model of the proposed SRR. The S-parameters from the CST software and their equivalent circuit are presented in Fig. 7(b). The deepest level of the $|S_{21}|$ is ≤ -65 dB at 28 GHz, while the SRR exhibits bandstop behavior with $|S_{21}| \leq -10$ dB from 27.5 GHz to 28.5 GHz. The $|S_{11}|$ value is high in the band stop region shown in Fig. 7(a). In this case, the SRR reflects incoming electromagnetic waves at the operating frequency, acting as a reflector. Fig. 7(b) compares the S-parameters from circuit simulators and CST, demonstrating good agreement. Fig. 7(c) illustrates the surface-based electric field of active Ant-1 with SRR-reflector at 28 GHz. As can be observed, the "+"-shaped slot blocked the propagated field to deliver another ports. A notable electric field of the Ant-1 is reflected by the SRR-reflector. Fig. 8(a) shows the S-parameters and the port isolation obtained using a reflector. With a reflector, the port isolation is ≤ –22 dB throughout the frequency range, and the S-parameter values increase to –35 dB at 28 GHz, as shown in Fig. 8(a). Furthermore, Fig. 8(b) shows the axial ratio and gain with and w/o reflector. Adding a reflector significantly improves the gain from 5 dBic to 6 dBic, resulting in an overall enhancement gain of 1 dBic throughout the entire frequency range and also positively influences the axial ratio within the frequency range of 26.56–28.96 GHz.

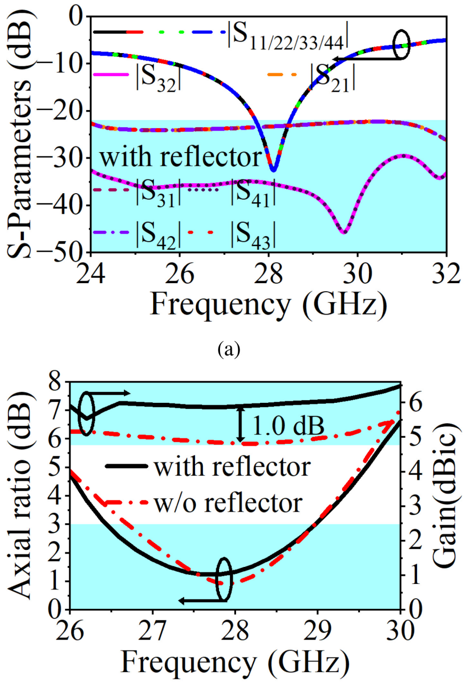


(a)

(b)

(c)

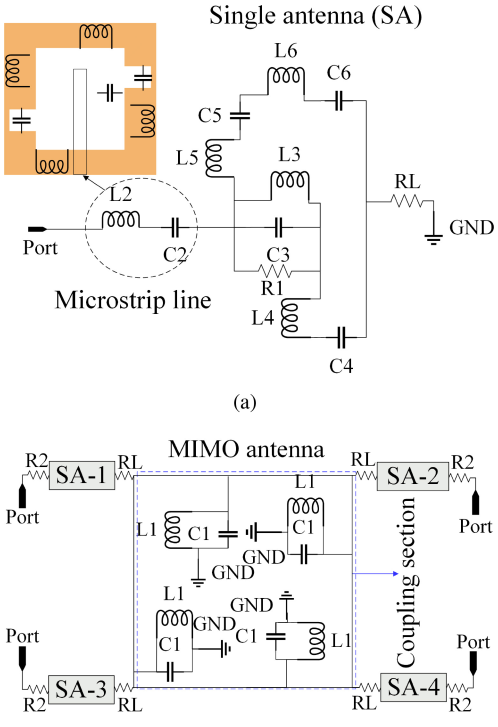
FIGURE 7. **(a) SRR unit cell with equivalent circuit model. (b) S-parameter of ECM. (c) Surface-based electric field of Active Ant-1.**



(a)

(b)

FIGURE 8. Simulated results of MIMO antenna with reflector. (a) S-parameters. (b) Axial ratio with gain (dBic).



(a)

(b)

FIGURE 9. (a) Equivalent circuit model of the single antenna (SA). (b) Comparison S-parameters of CST and ADS.

IV. EQUIVALENT CIRCUIT MODEL

The equivalent circuit model (ECM) provides a detailed understanding of an antenna's behavior by presenting its operation in terms of lumped circuit elements. The determination of the equivalent circuit for the proposed antenna relies on key parameters such as the feeding line, shape, and number of SRRs. The lumped circuit model is an alternative representation of the equivalent circuit for a conventional planar antenna, which consists of capacitance (C), inductance (L), and resistance (R). The equivalent circuit of a single antenna is modeled and simulated using ADS software, as shown in Fig. 9(a). Four unit cells of the SRR are positioned at a specific height above the quad-port MIMO antenna to reduce mutual coupling. In terms of circuit design, a 2×2 array of SRR is placed centrally and connected in parallel (L, C), as shown in Fig. 9(b). The real and imaginary values helpful in computing the lumped elements calculations are exported from CST. The design consists of four identical elements. Thus, an equivalent circuit of a single-element antenna is sufficient to explain the behavior of the MIMO design. The inductance (L_0) and capacitance (C_0) of the transmission line at resonance frequency [34] are determined as

$$L_0 = 100h\left(4\sqrt{\frac{W_f}{h}} - 4.21\right) \tag{15}$$

$$C_0 = W_f\left[(9.5\varepsilon_r + 1.25)\frac{W_f}{h} + 5.2\varepsilon_r + 7\right] \tag{16}$$

The remaining lumped elements are calculated using (17) and (18).

$$L = \frac{img(Z_{11})}{2\pi f} \tag{17}$$

$$C = \left[(2\pi f)^2 L\right]^{-1} \tag{18}$$

where W_f is the width of feedline and Z_{11} is the port impedance. Now, to determine the port impedance at a specific resonance frequency, we first convert the S_{11} parameter into input impedance as follows [34]:

$$Z_{in} = Z_0\frac{(1+S_{11})}{(1-S_{11})} \tag{19}$$

The equation (19) can be presented in a different manner for a better comprehension as follows

$$Z_{in} = Z_0\frac{[Z_L + jZ_0 tan(\beta l)\ ]}{[Z_0 + jZ_L tan(\beta l)\ ]} \tag{20}$$

where β is the propagation constant and l is the feed line length.

In the subsequent step, the input impedance is calculated by combining real and imaginary values as follows

$$Z_{in} = R_{in} + jX_{in} \tag{21}$$

where jX_{in} is the reactance and R_{in} is the radiation resistance of the resonance frequency.

If jX_{in} value is positive, the reactance is inductive, expressed as

$$X_{in} = \omega L \Rightarrow L = \frac{X_{in}}{\omega} \tag{22}$$

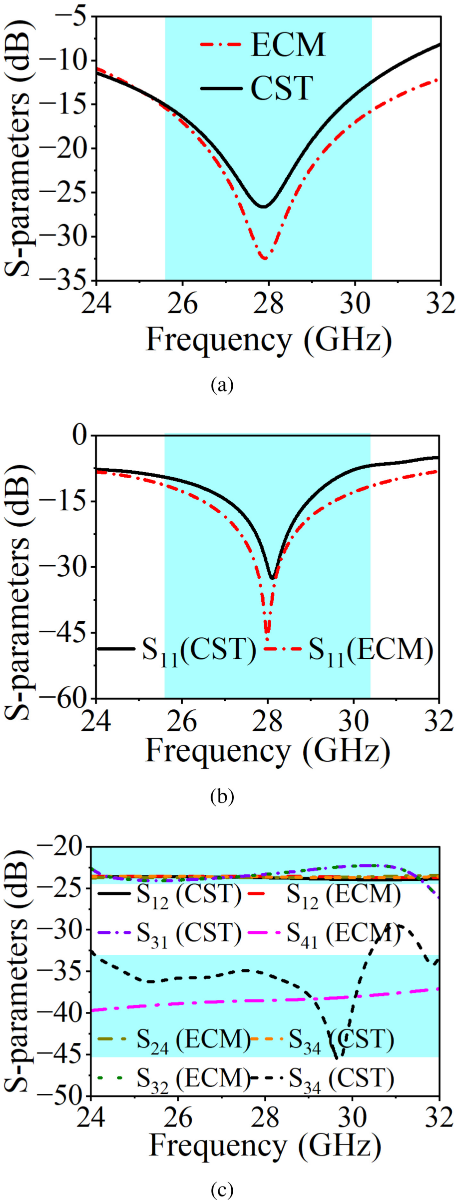


FIGURE 10. (a) Equivalent circuit model of MIMO antenna. (b) Comparison S-parameters of CST and ADS. (c) S-parameters (Isolation).

If the value of jX_{in} is negative, the reactance is considered capacitive, which can be calculated using the following formula

$$X_{in} = -\frac{1}{\omega C} \Rightarrow C = -\frac{1}{\omega X_{in}} \tag{23}$$

Finally, the resonant frequency for each branch can be calculated as follows

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{24}$$

The four parallel circuits are arranged based on design orientation and mutual coupling after calculating the values of the single-element antenna RLC. The Advanced Design System simulation tool is utilized to validate the S-parameters from CST after calculating all circuit elements.

TABLE 2. Optimized RLC values of the single and MIMO antenna equivalent circuit model.

Parameter	Value	Parameter	Value	Parameter	Value
L_2	0.254 nH	C_2	0.108 pF	L_3	0.294 nH
L_4	0.294 nH	L_5	0.294 nH	L_6	0.294 nH
C_3	0.140 pF	C_4	0.140 pF	C_5	0.140 pF
C_6	0.140 pF	R_1	52.8 Ω	RL	50 Ω
L_1	0.754 nH	R_2	25.11 Ω	C_1	0.035 pF

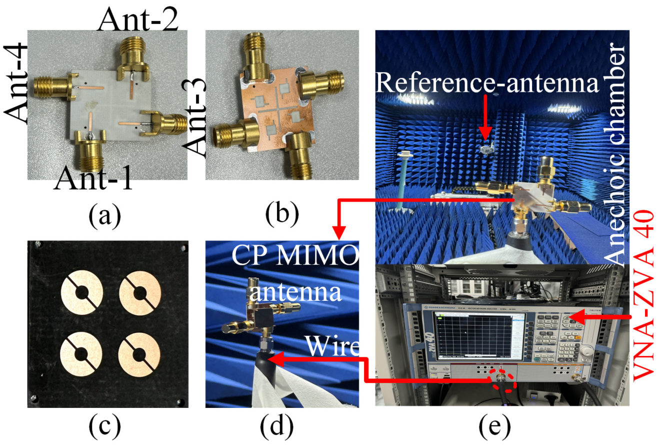
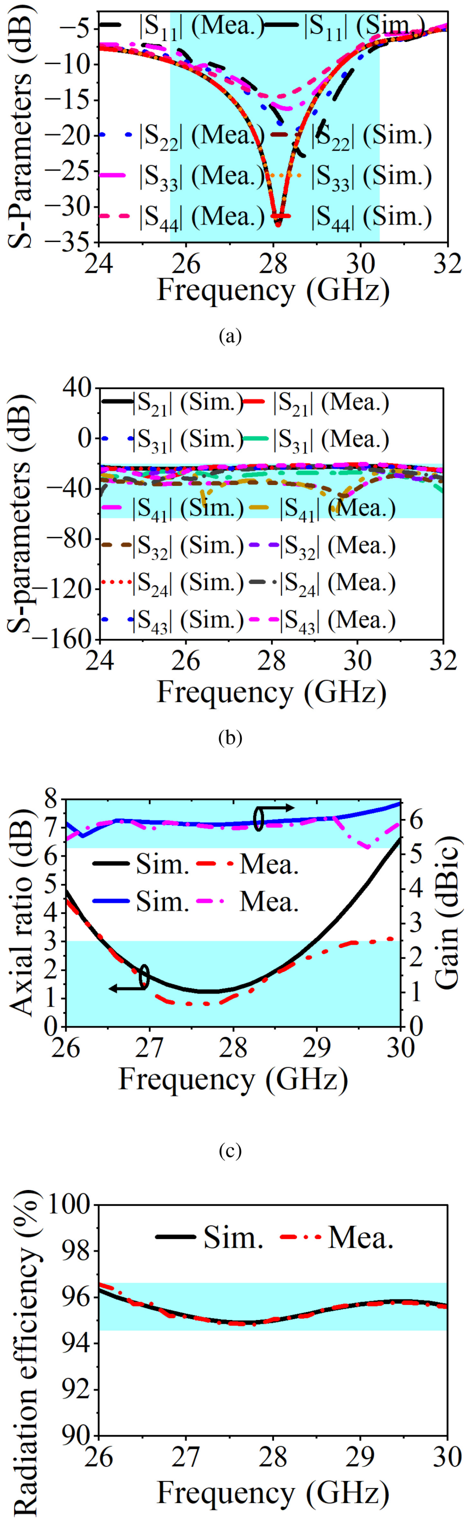


FIGURE 11. Fabricated MIMO antenna. (a) Front view. (b) Back view. (c) SRR-reflector. (d) MIMO antenna with SRR-reflector. (e) Measurements setup.

Table 2 lists the optimized RLC values for the single element and the SRR circuit. The S-parameters of single and MIMO antennas show good agreement between the simulated and calculated circuit models, as depicted in Fig. 10(a), (b) and (c). Fig. 10 indicates that the S-parameters from CST and ADS are in good agreement.

V. EXPERIMENTAL RESULTS

Fig. 11 illustrates the fabrication process of the four-port MIMO antenna and the SRR reflector implemented on Rogers RO4003C and RT5880 substrates, with thicknesses of 0.305 mm and 0.508 mm, respectively. The fabricated prototype features: a front view of the microstrip feed line in Fig. 11(a), a back view of the slotted ground in Fig. 11(b), the SRR reflector in Fig. 11(c), and the SRR-based MIMO antenna with a 50 Ω load connector in Fig. 11(d). Fig. 11(e) shows the experimental setup inside an anechoic chamber, using a reference antenna and a vector network analyzer (VNA-ZVA 40). To validate the simulated results, we conducted measurements of the proposed MIMO antenna. Fig. 12 compares the simulated and measured S-parameters, axial ratio, gain (dBic), and radiation efficiency (%). Fig. 12(a) demonstrates a strong agreement between the simulated and measured S-parameters. Fig. 12(b) shows that both simulated and measured S-parameters (isolation) remain below −22 dB across the operating frequency range. Measurements are performed at the boresight direction ($\theta = 0°$, $\varphi = 0°$) reveal a 3 dB axial ratio bandwidth of 8.6% (26.56–28.96 GHz) from simulation and 10.01% (26.56–29.36 GHz) from measurement, with peak gain of



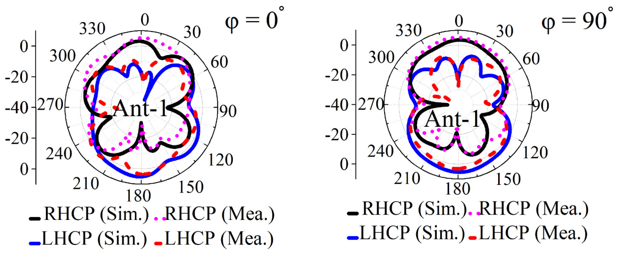
(a)

(b)

(c)

(d)

FIGURE 12. Simulated and measured results. (a), (b) S-parameters. (c) Axial ratio with gain (dBic). (d) Radiation efficiency (%).



(a)

(b)

FIGURE 13. 2D radiation patterns (RHCP and LHCP) of active Ant-1 at 28 GHz: (a) $\varphi = 0°$ and (b) $\varphi = 90°$.

6.0 dBic within the same frequency band, as illustrated in Fig. 12(c). Especially, the measured 3 dB axial ratio bandwidth corresponds closely with the simulated 10 dB impedance bandwidth, indicating no polarization mismatch. The radiation efficiency, depicted in Fig. 12(d), exceeds 94% for both simulated and measured data across the entire frequency range. Fig. 13 shows the simulated and measured 2D radiation patterns of the active Ant-1 element at 28 GHz, showing right-hand circular polarization and left-hand circular polarization at $\varphi = 0°$ and 90°. The results clearly indicate that RHCP exhibits a 3 dB wider beamwidth than LHCP. Additionally, the simulated and measured patterns are in good agreement.

VI. DIVERSITY PERFORMANCES

Analyzing the diversity parameters [30], [31] in MIMO antennas improve the efficiency, reliability, and performance metrics such as envelope correlation coefficient, diversity gain, mean effective gain, and channel capacity loss. This analysis helps assess the independence of antenna elements and plays a crucial role in multi-path performance, impacting signal propagation paths and reducing correlation factors.

A. ENVELOPE CORRELATION COEFFICIENT

The envelope correlation coefficient is a crucial factor in assessing the performance of MIMO antennas, as it indicates the independence of antenna elements. A zero ECC is preferred, but systems below 0.5 are acceptable. The ECC should be less than 0.1 for optimal performance, as a lower correlation value indicates better performance. This paper uses the far-field radiation patterns to calculate the ECC for a multi-antenna model in the far field [30].

$$\rho_{porti,portj} = \frac{\frac{1}{2Z_0}\int\int_{\Omega} E_{porti}.E^{*}_{portj}d\Omega}{\sqrt{P_{rad,porti}}\sqrt{P_{rad,portj}}} \tag{25}$$

where Ω represents the solid angle. The far-field pattern of the antenna is denoted by E_{porti} when port i is activated, and E_{portj} when port j is excited. The proposed quad-port circularly polarized MIMO antenna exhibits acceptable envelope correlation coefficients across operating frequency bands, as depicted in Fig. 14(a). The simulated and measured ECC values between Ant-1 and Ant-4 (ECC-14) and between Ant-2 and Ant-3 (ECC-23) are depicted in Fig. 14(a). The ECC-14 and ECC-23 exhibit excellent diversity performance, with their values remaining below 0.002 throughout the entire operating frequency band.

B. DIVERSITY GAIN

Diversity gain is a crucial parameter in MIMO antenna systems, indicating the influence of the diversity scheme on transmitted power, calculated using the correlation matrix α [30].

$$DG = \frac{tr(\alpha^2)}{||\alpha||_{Fr}} \tag{26}$$

The matrix trace (tr) and Frobenius norm $||X\alpha||_{Fr}$ are crucial concepts in matrix analysis. The Frobenius norm is defined as $||\alpha||_{Fr} := \sum_{m,n} |\rho_{mn}|^2$. where ρ_{mn} denotes the elements of the matrix α. The matrix trace is the sum of the diagonal elements of the matrix α^2. A MIMO antenna typically has a directivity gain between 0 and 1 in magnitude or 0 and 10 dB. Fig. 14(a) shows the variation in the DG of the proposed quad-port CP MIMO antenna, both simulated and measured across the overall frequency range. The MIMO antenna exhibits a DG-14 and DG-23 that surpass 9.99 dB across the entire frequency band, which aligns with the measured results.

C. MEAN EFFECTIVE GAIN

Mean effective gain is a measure of an antenna's efficiency in receiving or transmitting signals, with higher MEG values indicating better performance. MEG values typically fall within a specific range: $-3 \leq$ MEG (dB) ≤ -12. The mean effective gain for port i can be calculated using (27) [31].

$$MEG_i = 0.5\eta_i, rad = 0.5\left[1 - \sum_{j=1}^{M} \left|S_{i,j}\right|^2\right] \tag{27}$$

where M represents the total count of antennas, 'i' indicates a specific active antenna, and η_i, rad denotes the efficiency of the antenna. The simulated quad-port MIMO antenna has a MEG value below the recommended threshold, as shown in Fig. 14(b), which agrees with the measured result.

D. CHANNEL CAPACITY LOSS

Channel capacity loss is a crucial metric in diversity analysis, indicating the optimal transmission of electromagnetic signals for maximum data rate and minimal distortion. The CCL values in free space are within a limit of $<$ 0.5 bits/sec/Hz, and can be calculated using (28)–(31) [31].

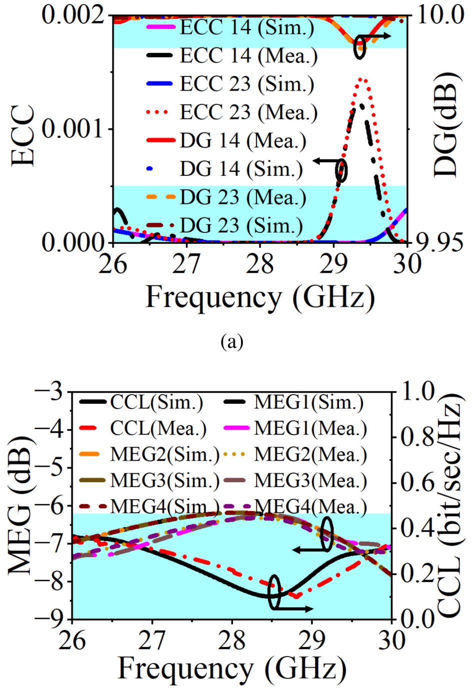
$$CCL = -\log_2 det(\Psi_{ant}) \tag{28}$$

where Ψ_{ant} is the correlation matrix of the antenna and it is given by

$$\Psi_{ant} = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix} \tag{29}$$

where

$$\rho_{ii} = 1 - \left|\sum_{n=1}^{n=4} S_{in}^{*} S_{ni}\right|, \text{for } i, j = 1, 2, 3 \text{ or } 4 \tag{30}$$



(a)

(b)

FIGURE 14. Simulated and measured results: (a) ECC with DG (dB) and (b) MEG (dB) with CCL (bits/sec/Hz).

and

$$\rho_{ij} = -\left|\sum_{n=1}^{n=4} S_{in}^{*} S_{nj}\right|, \text{for } i, j = 1, 2, 3 \text{ or } 4 \tag{31}$$

Also, Fig. 14(b) illustrates that the CCL remains below 0.25 bits/sec/Hz across the entire frequency range, further demonstrating robust system performance. Fig. 14(b) demonstrates that the measured and simulated CCL values for the quad-port CP MIMO antenna meet the acceptable limits.

VII. COMPARISON

Table 3 provides a comparative analysis of related parameters between the proposed antenna and previous works. Ikram et al. [19] reported on a tapered slot MIMO antenna design capable of dual-band operation in the microwave and mmWave ranges. Lai et al. [29] proposed a ME-dipole antenna using parasitic stubs in the mmWave frequency bands. However, these designs have wide impedance bandwidths and high gain, but large element spacings, low isolation, and low radiation efficiency, primarily featuring linearly polarized radiation without diversity performance. Sofi et al. [30] presented a CP MIMO antenna intended for K-/Ka-band satellite applications, while Tiwari et al. [31] detailed a semi-flexible diversified CP wearable antenna for 5G mmWave applications. However, both designs in [30] and [31] exhibit small impedance and axial ratio bandwidths, low gain, and low isolation in mmWave frequency ranges. In contrast, the proposed work presents additional advantages,

TABLE 3. Comparison of the proposed MIMO antenna with previous works.

Reference	[19]	[29]	[30]	[31]	**This Work**
Year	2019	2024	2022	2023	2025
Size (mm^3)	104.0×104.0 ×0.51	42×18 ×1.829	23.85×44.90 ×1.52	22.5×36.0 ×0.508	**20.0×20.0 ×0.813 (w/o air)**
Number of ports	4 (high freq.)	8	2	2	**4**
Frquency (GHz)	23–30	25.8–35.3	29.25–30.35	25.84–27.35	**25.56–28.96**
Axial ratio (%)	–	–	3.69	5.6	**8.60**
Element spacing	0.44λ_0	0.44λ_0	–	0.61λ_0	**0.42λ_0**
Polarization	LP	LP	CP	CP	**CP**
Gain (dBic)	11.0	6.0	4.77	6.1	**6.0**
Isolation (dB)	≥ 16	≥ 17	≥ 20	≥ 20	$\geq$ **22**
ECC/ DG (dB)	≤ 0.0001 / –	≤ 0.009 / –	– / ≥ 9.99	≤ 0.003 / ≥ 9.99	$\leq$ **0.002/** $\geq$ **9.99**
MEG (dB)/ CCL (bps/Hz)	– / –	– / –	– / ≤ 0.25	≤ -6.0 / ≤ 0.26	$\leq -$ **6.0/** $\leq$ **0.25**
Radiation efficiency	≥ 85	≥ 95	≥ 97	≥ 80	$\geq$ **94**
Size (λ_0^3)	9.71×9.71 ×0.047	4.2×1.68 ×0.170	1.55×2.92 ×0.099	2.9×1.8 ×0.04	**1.87×1.87 × 0.076**

such as wider impedance bandwidth, axial ratio bandwidth, small element spacings, compact size, and higher isolation. Moreover, the proposed four-port MIMO antenna obtains low ECC and enhanced diversity gain. Hence, the proposed design represents the miniaturized quad-port CP MIMO slot antenna that simultaneously achieves a compact size, wide CP bandwidth, and high radiation efficiency. By integrating a "+"-shaped defected ground structure and an SRR-based reflector, the antenna offers enhanced isolation and gain without increasing footprint. These features make it highly suitable for 5G mmWave communication, Internet of Things (IoT) devices, and next-generation smart wireless systems, where compactness, efficiency, and reliable polarization diversity are essential.

VIII. CONCLUSION

A miniaturized quad-port circularly polarized MIMO slot antenna has been investigated, demonstrating high isolation and enhanced diversity performance. The antenna uses four identical rectangular notched slots, each fed by a 50 Ω microstrip line, with an incorporated "+"-shaped slot in the ground to achieve isolation less than −20 dB. A 2×2 array of SRR reflectors is positioned above the antenna to improve gain by approximately 1 dBic and to maintain isolation better than −22 dB. The simulated and measured 10 dB impedance bandwidth and 3 dB axial ratio bandwidth overlap, demonstrating excellent impedance matching and circular polarization performance. The radiation patterns confirm polarization diversity, with a peak gain of 6.0 dBic and radiation efficiency exceeding 94% across the operating frequency range. In addition, diversity metrics such as ECC, DG, MEG, and CCL further confirm the superior performance of the MIMO antenna. Therefore, the proposed CP MIMO antenna is well-suited for mmWave applications.

REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, and A. C. K. Soong, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] J. Zhang, X. Yu, and K. B. Letaief, "Hybrid beamforming for 5G and beyond millimeter-wave systems: A holistic view," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 77–91, 2020.

[3] F. A. Dicandia, S. Genovesi and A. Monorchio, "Analysis of the performance enhancement of MIMO systems employing circular polarization," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4824–4835, Sep. 2017.

[4] U. Ullah, M. Al-Hasan, S. Koziel, and I. B. Mabrouk, "Series-slot-fed circularly polarized multiple-input–multiple-output antenna array enabling circular polarization diversity for 5G 28 GHz indoor applications," *IET Commun.*, vol. 69, no. 9, pp. 5607–5616, Sep. 2021.

[5] N. Hussain et al., "Dual-sense slot-based CP MIMO antenna with polarization bandwidth reconfigurability," *Sci. Rep.*, vol. 13, Sep. 2023, Art. no. 16132.

[6] R. Wang, M. Ikram, Y. Yu, H. Zhang, and A. Shamim, "Dual-band circularly polarized shared-aperture Vivaldi MIMO antenna with linear-to-circular polarizer for 5G and 6G communication," *IEEE Trans. Antennas Propag.*, vol. 73, no. 7, pp. 4300–4310, Jul. 2025.

[7] Y. Dou, Z. Chen, J. Bai, Q. Cai, and G. Liu, "Two-port CPW-fed dual band MIMO antenna for IEEE802.11a/b/g applications," *Int. J. Antennas Propag.*, vol. 2021, Jun. 2021, Art. no. 5572887.

[8] A. G. Alharbi, J. Kulkarni, A. Desai, C. Y. D. Sim, and A. Poddar, "A multi-slot two-antenna MIMO with high isolation for sub-6 GHz 5G/IEEE802.11ac/ax/C-band/X-band wireless and satellite applications," *Electronics*, vol. 11, no. 3, p. 473, Feb. 2022.

[9] M. H. Reddy, D. Sheela, and A. Swaminath, "A four port circularly polarized printed multiple-input multiple-output antenna with enhanced isolation," *Int. J. Commun. Syst.*, vol. 35, no. 4, Mar. 2022, Art. no. e5061.

[10] Z. Ma, J. Chen, and C. Li, and Y. Jiang, "A monopole broadband circularly polarized antenna with coupled disc and folded microstrip stub lines," *J. Wireless Commun. Netw.*, vol. 2023, p. 30, Mar. 2023.

[11] W. Li, W. Xue, Y. Li, K. L. Chung, and Z. Huang, "A wideband differentially fed circularly polarized slotted patch antenna with a large beamwidth," *J. Electromagn. Eng. Sci.*, vol. 23, no. 6, pp. 512–520, Nov. 2023.

[12] D. Wu, J. Liang, and L. Ge, "A wideband dual-circularly polarized series-fed corner-truncated patch array using coplanar proximity coupling," *IEEE Trans. Antennas Propag.*, vol. 72, no. 4, pp. 3292–3301, Apr. 2024.
[13] S. M. Mikki and Y. M. M. Antar, "On cross correlation in antenna arrays with applications to spatial diversity and MIMO systems," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1798–1810, Apr. 2015.
[14] Y. Banday, G. M. Rather, and G. R. Begh "Effect of atmospheric absorption on millimetre wave frequencies for 5G cellular networks," *IET Commun.*, vol. 13, no. 3, pp. 265–270, Feb. 2019.
[15] S. Ullah, Y. He, A. Majeed, and Y. Huang, "A low-profile wideband dual-sense circularly polarized MIMO antenna for mmWave applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 24, no. 8, pp. 2163–2167, Aug. 2025.
[16] H. Zahra, W. A. Awan, W. A. E. Ali, N. Hussain, S. M. Abbas, and S. Mukhopadhyay, "A 28 GHz broadband helical inspired endfire antenna and its MIMO configuration for 5G pattern diversity applications," *Electronics*, vol. 10, no. 4, p. 405, Feb. 2021.
[17] I. Khan et al., "Dual-technique MIMO antenna Design for IoT millimeter-wave circular polarization," *IEEE Antennas Wireless Propag. Lett.*, vol. 24, no. 8, pp. 2158–2162, Aug. 2025.
[18] F. Lin, Y. Qi, J. Fan, and Y. -C. Jiao, "0.7–20-GHz dual-polarized bilateral tapered slot antenna for EMC measurements," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1271–1275, Dec. 2014.
[19] M. Ikram, N. Nguyen-Trong, and A. Abbosh, "Multiband MIMO microwave and millimeter antenna system employing dual-function tapered slot structure," *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 5705–5710, Aug. 2019.
[20] Y. Xiao et al., "A planar low-profile meander antenna design for wireless terminal achieving low RF interference and high isolation in multi-antenna systems," *IEEE Trans. Electromagn. Compat.*, vol. 64, no. 3, pp. 674–682, Jun. 2022.
[21] G. Santra and P. N. Patel, "Horizontally polarized omnidirectional antenna using slotted rectangular patch and defected ground structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 4, pp. 704–708, Apr. 2023.
[22] Z. H. Jiang, L. Zhang, Y. Zhang, C. Yu, L. Cai, and S. Zheng "A compact triple-band antenna with a notched ultra-wideband and its MIMO array," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 7021–7031, Dec. 2018.
[23] I. Khan, K. Zhang, L. Ali, and Q. Wu, " A compact FSS-based four-port MIMO antenna for low mutual coupling," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 12, pp. 2836–2840, Dec. 2023.
[24] L. Wang et al., "Compact UWB MIMO antenna with high isolation using fence-type decoupling structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 8, pp. 1641–1645, Aug. 2019.
[25] S. Li and Q.-X. Chu, "Broadband mutual coupling reduction of multiple electrical-current nulls for quad-port shared-radiator slot antenna using characteristic mode analysis," *IEEE Antennas Wireless Propag. Lett.*, vol. 23, no. 1, pp. 409–413, Jan. 2024.
[26] N. Alaa, R. A. Elsayed, A. E. Farahat, K. F. A. Hussein, and W. S. El-Deeb, "Q-band MIMO antennas with circular polarization for spatial and polarization diversity," *J. Infr. Millimeter THz. Waves*, vol. 45, pp. 393–432, Jun. 2024.
[27] I. Khan, K. Zhang, L. Ali, and Q. Wu, "Enhanced quad-port MIMO antenna isolation with metamaterial superstrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 23, no. 1, pp. 439–443, Jan. 2024.
[28] M. J. Al-Hasan, T. A. Denidni, and A. R. Sebak, "Millimeter-wave compact EBG structure for mutual coupling reduction applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 2, pp. 823–828, Feb. 2015.
[29] Q. X. Lai, Z. L. Hu, and Y. M. Pan, "A simple decoupling method for wideband millimeter-wave MIMO magnetoelectric dipole antenna array using parasitic stubs," *IEEE Trans. Antennas Propag.*, vol. 72, no. 10, pp. 7470–7479, Oct. 2024.
[30] M. A. Sofi, K. Saurav, and S. K. Koul, "Four-port orthogonal circularly polarized dual-band MIMO antenna with polarization and spatial diversity using a dual-band linear-to-circular polarization converter," *IEEE Trans. Antennas Propag.*, vol. 70, no. 9, pp. 8554–8559, Sep. 2022.
[31] R. N. Tiwari, V. Kaim, P. Singh, T. Khan, and B. K. Kanaujia, "Semi-flexible diversified circularly polarized millimeter-wave MIMO antenna for wearable biotechnologies," *IEEE Trans. Antenna Propag.*, vol. 71, no. 5, pp. 3968–3981, May 2023.
[32] F. Merzaki, P. Besnier, M. Himdi, X. Castel, M. Sergolle, and T. Levavasseur, "A compact double-sided FSS absorbing wall for decoupling 5G antenna arrays," *IEEE Trans. Electromagn. Compat.*, vol. 64, no. 2, pp. 303–314, Apr. 2022.
[33] G. Ramyasree and N. Suman, "Dual-band 4-port vivaldi MIMO antenna for 5G mmWave applications at 28/39 GHz," *Prog. Electromagn. Res.*, vol. 119, pp. 13–24, May 2023.
[34] S. Khan, O. Khan, S. A. Ali Shah, J. Nasir, B. T. Malik, and S. Khan, "Highly compact wideband high-gain four-element MIMO antenna for 5G new radio IoT," *IEEE Internet Things J.*, vol. 12, no. 12, pp. 22350–22365, Jun. 2025.
[35] F. Bilotti, A. Toscano, and L. Vegni, "Design of spiral and multiple split-ring resonators for the realization of miniaturized metamaterial samples," *IEEE Trans. Antennas Propag.*, vol. 55, no. 8, pp. 2258–2267, Aug. 2007.

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