

A Miniaturized Reconfigurable CP MIMO Antenna With Low Mutual Coupling for 5G Applications

Abdul Majeed, Yejun He, *Senior Member, IEEE*, and Yi Huang, *Fellow, IEEE*

Abstract—This paper presents a miniaturized reconfigurable circularly polarized (CP) multiple-input multiple-output (MIMO) antenna with low mutual coupling for 5G millimeter-wave (mmWave) applications. It features a T-shaped radiating patch fed by a coplanar waveguide (CPW) and uses a modified ground structure (MGS) with two serial surface-mount capacitors to minimize mutual coupling currents and enhance inter-element isolation. Furthermore, a surface-mounted PIN diode (MADP-000907-14020W) is integrated along the decoupling path and connected to the MGS through vias, enabling reconfigurable isolation by switching between ON and OFF states. The proposed CP MIMO antenna achieves an isolation greater than 25 dB, an axial ratio (AR) less than 3 dB, and gain stability across reconfigurable states. Simulation and measurement validate its polarization diversity, with an envelope correlation coefficient of 0.04, indicating its strong potential for 5G mmWave communications.

Index Terms—capacitive decoupling, circular polarization, mmWave, MIMO antenna, reconfigurable.

I. INTRODUCTION

MULTIPLE-input multiple-output (MIMO) technology improves mmWave communication by increasing data rates, channel capacity, and spectrum efficiency [1]. Circularly polarized MIMO antennas are preferred over linearly polarized (LP) ones because they can reduce polarization mismatch and multipath fading [2]. Reconfigurable antennas (RAs) are crucial for reducing channel interference, especially in device-to-device (D2D) communications, by enabling dynamic control of radiation properties and addressing polarization loss issues [3], [4]. Different reconfigurable circularly polarized structures, such as magnetoelectric (ME) [5], cross-dipoles [6], and patch antennas [7], have been studied mostly within the Sub-6 GHz range. However, they face challenges at mmWave frequencies due to array complexity and diode performance limitations, which hinder practical use in 5G D2D communication [8], [9].

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Abdul Majeed and Yejun He are with the State Key Laboratory of Radio Frequency Heterogeneous Integration, Sino-British Antennas and Propagation Joint Laboratory of MOST, Guangdong Engineering Research Center of Base Station Antennas and Propagation, Shenzhen Key Laboratory of Antennas and Propagation, College of Electronics and Information Engineering Shenzhen University, Shenzhen 518060, China (e-mail: abdul@szu.edu.cn; heyejun@126.com)

Yi Huang is with the Department of Electrical Engineering and Electronics, the University of Liverpool, UK (e-mail: Yi.Huang@liverpool.ac.uk)

Recent research identifies three main types of reconfigurable antennas (RAs): frequency-reconfigurable [10], [11], polarization-reconfigurable [12], [13], and pattern-reconfigurable [14], [15], offering advantages such as compactness and cost-effectiveness. Key developments include antennas using PIN diodes and MEMS switches, a frequency-reconfigurable patch antenna with a magnetically controlled switch [11], and a polarization-switching patch antenna [12] and E-shaped slots [13]. Innovations also encompass a wide-band mmWave polarization-reconfigurable array and a multi-band cross patch quadruple PIFA (CPQPIFA) antenna with beam steering and dual band MIMO antenna with isolation reconfiguration via PIN diode is introduced in [16]–[18]. In lumped-element decoupling circuits, compact isolation solutions emerge, with self-curing techniques improving coupling in inverted-F antennas (IFAs) while complicating impedance matching [19]. Alternative methods, such as dash-decoupling [20], and hybrid decoupling approaches [21] facilitate space-efficient designs. In contrast to existing hybrid or lumped-element decoupling techniques, the proposed design offers an innovative approach by utilizing a single PIN-diode-controlled capacitive decoupling path integrated directly into a CPW-fed antenna, with minimal implementation complexity.

The main contributions of this paper are summarized as follows: 1) By placing the elements orthogonally and adding two capacitors to the MGS for capacitive decoupling between antenna elements. 2) A single PIN diode is integrated along the decoupling patch and connected to the MGS through vias, further reducing mutual coupling and providing reconfigurable isolation.

II. CP MIMO ANTENNA DESIGN ANALYSIS

A. Single-element Antenna

Fig. 1 (a) shows the single-element antenna (SEA) configuration. The radiator and modified ground structure with labeled parameters are also illustrated. The antenna is designed on a Rogers RO4003C substrate with $\epsilon_r = 3.55$, loss tangent of $\tan \delta = 0.0027$, and a thickness of 0.203 mm. Fig. 1 (b) shows the coupled, capacitive decoupled and diode-based capacitive decoupled (Proposed) MIMO antenna. The overall dimensions of the MIMO antenna are $1.40 \times 1.87 \times 0.019 \lambda_0^3$. The design has a low profile with a height of $0.019 \lambda_0$, where λ_0 is the free-space wavelength at 28 GHz. The single-element antenna achieves left-hand circular polarization (LHCP) via a modified ground structure that converts linear to circular polarization. This modification ensures overlap between impedance and axial ratio bandwidth, using a perturbation

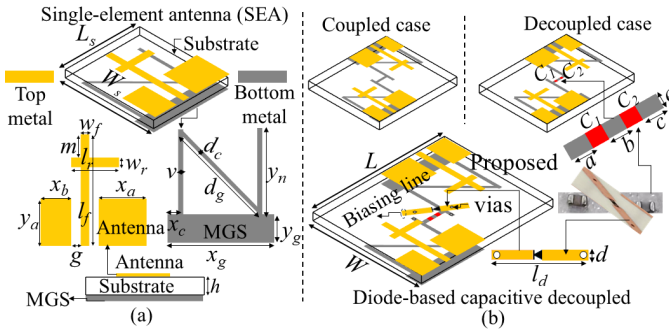


Fig. 1. Configuration of the single-element antenna (SEA) with the dimensions of the antenna and modified ground structure (MGS). All dimensions are in mm: $L_s = 10.0$ and $W_s = 15.0$, $x_g = 10$, $y_g = 3.01$, $x_c = 1.55$, $y_n = 7.50$, $v = 0.40$, $d_g = 9.31$, $d_c = 0.46$, $g = 0.31$, $x_g = 10$, $x_a = 6.0$, $y_a = 5.0$, $x_b = 3.0$, $m = 1.36$, $w_r = 0.5$, $l_r = 3.0$, $w_f = 0.39$ and $l_f = 10.0$. and (b) $W = 15$, $L = 20$, $a = 0.35$, $b = 1.85$, $c = 0.40$, $e = 0.2$, $d = 1.0$ and $l_d = 10$.

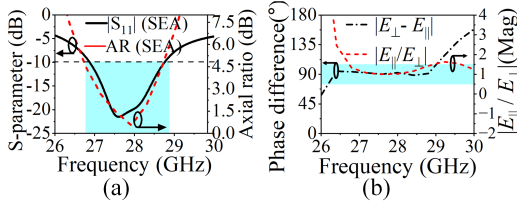


Fig. 2. Simulated results of the single-element antenna (SEA): (a) S-parameters and axial ratio, and (b) phase difference ($\angle E_{\perp} - \angle E_{\parallel}$) with electric field magnitude ratio ($|E_{\perp}|/|E_{\parallel}|$).

technique for polarization rotation. Ground cuts create a 90° phase shift, affecting resonance and polarization behavior. An N-shaped patch splits surface current into paths with differing lengths, creating the necessary phase difference for circular polarization. A slanted patch generates a quarter-wavelength difference, orienting with CP theory where circular polarization is achieved when $|E_{\perp}|/|E_{\parallel}| = 1$ (0 dB) and the phase difference ($\angle E_{\perp} - \angle E_{\parallel}$) equals $\pm 90^\circ$. The simulated S-parameters and axial ratio overlap within the operating band, as shown in Fig. 2(a). A slanted patch, connected with the parallel strips, generates two orthogonal field components of equal magnitude with a 90° phase shift. Fig. 2(b) demonstrates an amplitude of one and a phase difference of about 90° across the band, confirming LHCP.

B. Capacitive Decoupling Scheme

The capacitive decoupling technique improves the modified ground structure of a 2-port MIMO antenna, enhancing isolation and radiation performance without compromising impedance matching. Two Murata series capacitors ($C_1 = 0.1$ pF and $C_2 = 0.15$ pF) are implemented to reduce mutual coupling by inducing compensating currents [22], [23]. S-parameters indicate effective impedance matching ($|S_{11}| \leq 10$ dB) across 26.73–28.75 GHz, with $|S_{21}|$ improving from 48.62 dB to 58.9 dB post-decoupling, yielding a 10.28 dB isolation enhancement, as shown in Fig. 3(a). The axial ratio remains below 3 dB within the frequency range of 28.0–29.06 GHz, confirming circular polarization performance, while the gain stabilizes around 7.1 dBic at 27.14 GHz, ensuring consistent radiation efficiency, as depicted in Fig. 3(b). The radiation characteristics of the monopole antennas are analyzed using

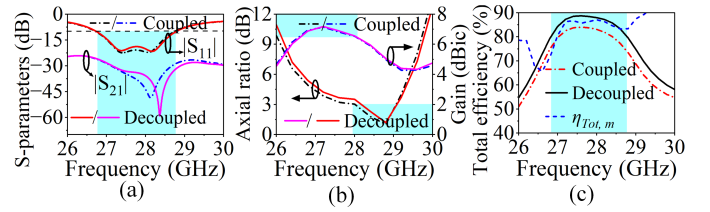


Fig. 3. Simulated results for coupled and decoupled cases: (a) S-parameters ($|S_{11}|$ and $|S_{21}|$), (b) Axial ratio and gain (dBic) and (c) Total efficiency (%).

analytical methods. The total efficiency of the m -th antenna element is expressed as

$$\eta_{\text{tot}, m} = \left(1 - |\Gamma_{mm}|^2 - \sum_{n \neq m} |C_{mn}|^2 \right) \times \eta_{\text{rad}, m} \quad (1)$$

where $\eta_{\text{tot}, m}$ and $\eta_{\text{rad}, m}$ denote the total and radiation efficiency of the m -th antenna element, with other antennas terminated using matched loads. The reflection coefficient of the m -th port is denoted by $|\Gamma_{mm}|$. The transmission coefficient from the m -th to the n -th port (mutual coupling) is denoted by $|C_{mn}|$. Fig. 3(c) shows that the total efficiency is about 80% for the coupled case. With capacitive decoupling, efficiency increases to 80–85% and stays steady within the 27.05–28.40 GHz band, indicating that capacitive decoupling improves isolation while reducing coupling and ohmic losses.

C. Proposed MIMO Antenna (Diode-Based Capacitive Decoupling)

The antenna is fabricated on a Rogers RO4003C substrate with a relative permittivity of 3.55 and a thickness of 0.203 mm. The fabricated prototype, shown in Fig. 4(a), displays front and back views along with 50 Ω standard SMA connectors. It also includes insets illustrating the DC supply, diode, capacitors, capacitive decoupling, and the diode-based capacitive decoupling path with its biasing layout. The proposed reconfigurable decoupling approach uses a single PIN diode with a basic DC biasing network, simplifying implementation and minimizing insertion loss and nonlinear effects by positioning the switching element in the decoupling path. This approach enables compact 28-GHz 5G mmWave antenna applications, evaluating reconfigurability, RF performance, consistent impedance matching, and circular polarization, with a radiation efficiency. To reduce coupling and tune the coupling impedance, capacitors C_1 and C_2 are positioned strategically along the ground connection [24], [25]. A PIN-diode (MADP-000907-14020W) from MACOM [14] is used to connect the capacitors through biasing lines and vias. It alters the capacitance and impedance of the decoupling path based on ON and OFF states. The diode parameters are $R_{\text{ON}} = 7 \Omega$, $L_{\text{ON}} = 0.15$ nH in the ON state, and $R_{\text{OFF}} = 487$ k Ω , $C_{\text{OFF}} = 26.5$ fF and $L_{\text{OFF}} = 0.065$ nH in the OFF state. These states dynamically control the isolation between Ant-1 and Ant-2.

D. S-Parameters, Axial ratio, Gain and Radiation Efficiency

Fig. 4(b) presents the measured and simulated S-parameters for the proposed CP MIMO antenna, using a Ceyear-3674G

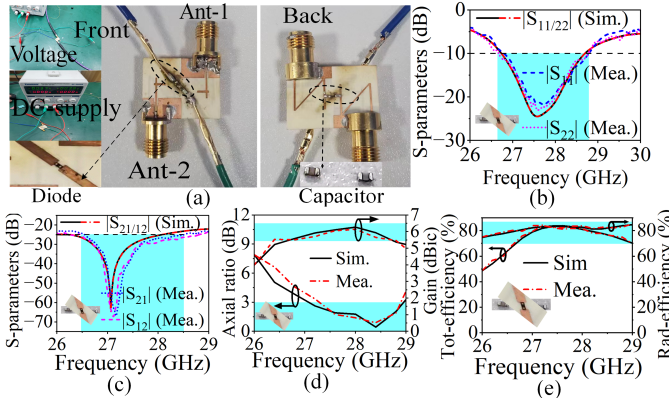


Fig. 4. Comparison of simulated and measured results: (a) Fabricated MIMO antenna, (b) S-parameters ($|S_{11}|$ and $|S_{22}|$), (c) $|S_{12}|$ and $|S_{21}|$, (d) Axial ratio and gain (dBic), and (e) Total and radiation efficiency (%).

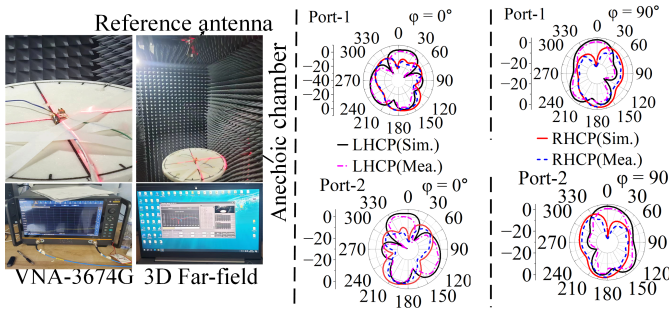


Fig. 5. Simulated and measured far-field radiation patterns (LHCP and RHCP) of Port-1 at 28 GHz in the planes of $\varphi = 0^\circ$ and $\varphi = 90^\circ$.

VNA with a frequency range of 10 MHz to 44 GHz. Operating between 26.74 and 28.67 GHz, both ports exhibit effective impedance matching near 28 GHz. Fig. 4(c) indicates that the isolation between ports exceeds 25 dB within 26.61–28.05 GHz, with an enhancement of 6.06 dB at 27.06 GHz. Fig. 4(d) displays the axial ratio and gain. The axial ratio remains below 3 dB within 27.06 to 28.95 GHz (6.75%), ensuring stable CP operation, while the peak gain reaches approximately 6.26 dBic at 28 GHz. Fig. 4(e) shows the total and radiation-efficiency for both simulated and measured results. The measured total and radiation-efficiency surpasses 83% across the band, indicating low loss and good impedance matching. Discrepancies are minor, influenced by fabrication tolerances and environmental factors.

E. Far-field Radiation Patterns and Surface Current

The far-field radiation patterns are shown in Fig. 5. The evaluation of far-field radiation patterns in the principal planes of $\varphi = 0^\circ$ and $\varphi = 90^\circ$ indicates dominant left-hand circular polarization (LHCP) at Port-1, as confirmed by measurements in an anechoic chamber. The simulated and measured LHCP/RHCP components are consistent, with LHCP exhibiting a higher magnitude than RHCP, confirming the effectiveness of the antenna design. Results show stable polarization, low cross-polarization, good isolation, and robust circular polarization (CP) performance, facilitating effective MIMO operation and polarization control.

Fig. 6 depicts the evolution of surface currents at 0° ,

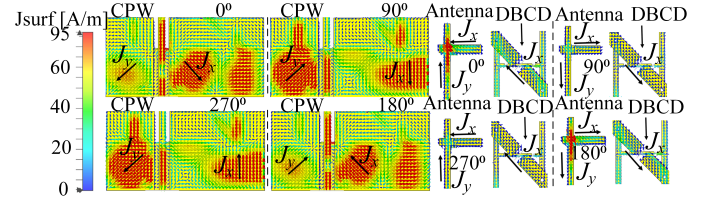


Fig. 6. Vector surface current distributions of the diode-based capacitive decoupling (DBCD) MIMO antenna at phase angles 0° , 90° , 180° , and 270° .

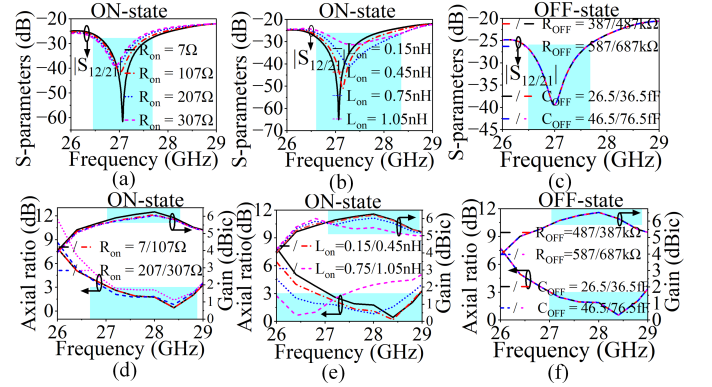


Fig. 7. S-parameters, axial ratio and gain (dBic) of the diode-based capacitive decoupling network for ON and OFF states based on resistance, capacitance, and inductance variations.

90° , 180° , and 270° in a CPW-fed antenna using a diode-based capacitive decoupling (DBCD) structure. The vector currents illustrate the DBCD's effectiveness in managing mutual coupling while maintaining circular polarization. Two primary components are identified: J_y , the current along the microstrip line, and J_x , the induced current on the horizontal stub and DBCD. At 0° , J_y predominates, with a minor contribution from J_x . The DBCD creates a compensating current to mitigate leakage. At 90° , J_x becomes dominant, demonstrating a quadrature phase relationship with J_y . The DBCD adjusts J_x to keep the amplitudes of both components equal. At 180° , both currents align in magnitude but oppose each other, leading to mutual coupling reduction. Finally, at 270° , the current rotation completes, further stabilizing isolation and enhancing circular polarization via compensating currents generated by the DBCD structure.

F. Parametric Analysis (S-parameters, AR and Gain)

Fig. 7 presents the parametric analysis of a diode-based capacitive decoupling network in both ON and OFF states. In the ON state, low resistance (R_{ON}) and small inductance (L_{ON}) enhance decoupling with improved transmission characteristics ($|S_{12/21}| \geq 25$ dB), reducing resistance from 307 to 7 Ω and optimizing inductance (from 0.15 to 1.05 nH), as shown in Fig. 7(a) and (b). The diode and capacitors create a current-cancellation path that minimizes surface current coupling between antennas. In contrast, the OFF state presents high resistance (R_{OFF}) and parasitic capacitance (C_{OFF}), where variations in R_{OFF} (from 387 to 687 k Ω) and C_{OFF} (from 26.5 to 76.5 fF) do not affect isolation bandwidth or decoupling resonance, highlighting that isolation depends more on antenna geometry, as presented in Fig. 7(c). The

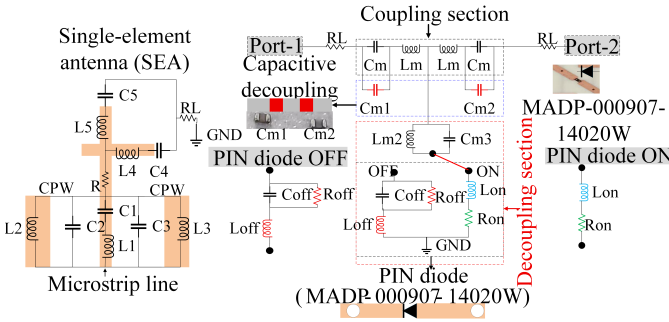


Fig. 8. Equivalent circuit of the single-element and diode-based capacitive decoupling MIMO antenna with parameters: $L_1 = L_4 = L_5 = 1.1789$ nH, $L_2 = L_3 = 0.8096$ nH, $C_1 = C_2 = C_3 = C_4 = C_5 = 0.02656$ pF, $R = 38.62$ Ω , $R_L = 50$ Ω , $L_m = 0.04225$ nH, $C_m = 0.171714$ pF, $C_{m1} = C_{m3} = 0.10$ pF, $C_{m2} = 0.15$ pF, $L_{m2} = 0.010$ nH, $R_{ON} = 7.0$ Ω , $L_{ON} = 0.15$ nH, $R_{OFF} = 487$ k Ω , $L_{OFF} = 0.065$ nH and $C_{OFF} = 26.5$ fF.

analysis of the reconfigurable MIMO antenna reveals that diode parameters significantly impact performance; reducing R_{ON} improves the axial ratio, maintaining it below 3 dB and enhancing phase balance and radiation efficiency at 28 GHz. While increasing L_{ON} broadens the axial ratio bandwidth, excessive values adversely affect performance, as shown in Fig. 7(d) and (e). Changes in R_{OFF} and C_{OFF} do not affect the axial ratio, which remains stable below 3 dB, as shown in Fig. 7(f). The OFF state exhibits negligible current effect, relying on parasitic capacitance for balanced coupling. Ultimately, the ON state supports tuning capabilities, while the OFF state provides stable polarization and gain, ensuring reliable polarization control and strong MIMO isolation.

III. EQUIVALENT CIRCUIT MODEL OF MIMO ANTENNA

Lumped RLC elements are used to model antenna operation as a parallel RLC circuit, addressing impedance mismatch in reconfigurable antennas that share a feed line. The isolation enhancement uses an MGS, capacitive loading, and a PIN diode to achieve over 25 dB port isolation. The MGS improves ground current distribution and increases impedance, reducing surface-wave propagation between antennas. The capacitors and PIN diode enable a controllable capacitive decoupling pathway, regulating coupling current while maintaining impedance matching and circular polarization, thus providing a reconfigurable decoupling solution. The equivalent circuit model (ECM) for the SEA is simulated using Advanced Design System (ADS) 2021, utilizing RLC elements to match the MIMO antenna resonance, and verified with CST-exported real and imaginary components. This model effectively describes the MIMO behavior, as shown in Fig. 8. Two parallel circuits with mutual coupling were analyzed using determined single-element RLC values. The S-parameters and interactions between the MIMO antenna and RLC circuit model show strong agreement, as depicted in Fig. 9 (a) and (b).

Analyzing diversity parameters in MIMO antennas is crucial for enhancing system performance and reliability. The circularly polarized MIMO antenna exhibited significant multipath and polarization diversity. The simulated and measured envelope correlation coefficient (ECC) and diversity gain (DG) are shown in Fig. 9 (c). The ECC was determined to be less than 0.04, indicating minimal signal correlation and effective

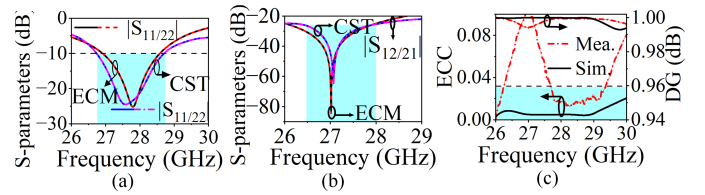


Fig. 9. Comparison of CST and ECM results: (a) $|S_{11/22}|$, (b) $|S_{12/21}|$ and (c) Simulated and measured results of ECC with DG (dB).

TABLE I
COMPARISON OF THE PROPOSED MIMO ANTENNA WITH STATE-OF-ARTS

Ref.	Antenna type / f_0 (GHz)	ARBW(%) / Gain(dBic)	Ports / Pol.	Iso. (dB) / Rad-eff.(%)	Decoupling technique	Size (λ_0^2) / Reconf. (Freq./Iso.)
[12]	Patch / 28	2.8 / ≥ 6.2	1.0 / CP	NA / ≥ 84	PIN-diodes	$1.08 \times 1.08 \times 0.025$ / Yes / NA
[14]	Array / 25.75	23.8 / ≥ 12.7	1.0 / CP	NA / ≥ 83	PIN-diode, capacitor	$4.1 \times 2.88 \times 0.095$ / Yes / NA
[15]	Cavity / 28.2	2.1 / ≥ 6.13	4.0 / CP	≥ 25 / ≥ 89.3	Metal wall	NA / Yes / NA
[20]	Patch / 8.0	59 / ≥ 5.85	4.0 / CP	≥ 25 / ≥ 85	Dash-decoupling	$1.20 \times 1.20 \times 0.042$ / NA / NA
[21]	Monopole / 28	7.6 / ≥ 7.1	2.0 / CP	≥ 22 / ≥ 78	Hybrid decoupling	$1.40 \times 1.87 \times 0.019$ / NA / NA
This Letter	Monopole / 28	6.75 / ≥ 6.26	2 / CP	≥ 25 / ≥ 83	Diode-based capacitive decoupled	$1.40 \times 1.87 \times 0.019$ / NA / Yes

Note: Iso. = Isolation, Pol. = Polarization, Eff. = Efficiency, Reconf. Reconfigurable

isolation of antenna elements, which boosts MIMO reliability. Additionally, the DG approximated the ideal value of 10 dB, underscoring strong diversity performance and high link reliability, making it suitable for 5G MIMO applications requiring reliable, high-capacity links.

IV. COMPARISON PERFORMANCE

Table I compares the two-port CP-MIMO antenna with recent mmWave CP antennas, highlighting that existing designs typically enhance gain, size, or wide AR bandwidth but often rely on fixed decoupling methods such as hybrid, chip-capacitor, or lumped-element techniques. These methods restrict reconfigurability and add complexity to implementation. For example, cavity-backed antennas [15] exhibit high radiation efficiency but limited AR bandwidth, while, patch-based [12], [20] and monopole-based [21] MIMO antennas improve gain and isolation but employ fixed decoupling mechanisms. In contrast, the proposed antenna integrates a single PIN-diode-based capacitive decoupling mechanism into a compact single-layer CPW-fed structure, enabling adaptive isolation with minimal implementation complexity. It achieves high isolation (≥ 25 dB), low ECC (≤ 0.04), a 6.75% AR bandwidth, a stable 6.26 dBic gain, over 83% radiation efficiency. The proposed design supports stable operation for practical 28-GHz 5G mmWave platforms, making it suitable for compact and reconfigurable 5G applications.

V. CONCLUSION

This paper presents a compact CP-MIMO antenna for 28 GHz 5G mmWave applications, using a simple PIN-diode-based capacitive decoupling method. It achieves high isolation and low ECC while delivering a wide axial-ratio bandwidth. The antenna exhibits stable gain and radiation efficiency, effectively reducing mutual coupling and maintaining consistent impedance and circular polarization. The proposed design offers a promising platform for compact 5G terminals, with an investigation of user-hand effects, device packaging, and platform integration planned for future work.

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