

A Circular Polarization MIMO Antenna using Sequentially Rotated Feeding Network for WLAN Applications

Ngoc-Lan Nguyen , Dang-Khoa Ho , Quoc-Hung Bui , and Tan Dao-Duc 

Abstract—Designing circularly polarized (CP) MIMO antennas that simultaneously provide wide impedance bandwidth, broad axial-ratio bandwidth, high gain, and strong inter-element isolation remains a challenging task. To address this issue, this work presents a wideband CP MIMO antenna operating around 5.5 GHz. The proposed design consists of two identical 2×2 aperture-coupled microstrip subarrays separated by a compact spacing arrangement. A 5 mm air gap is introduced to enhance the impedance bandwidth, while a sequential-phase feeding network is employed to maintain stable CP performance over a wide frequency range. The antenna is investigated using CST Studio Suite and validated through measurements of a fabricated prototype. Measured results demonstrate an impedance bandwidth of 62.9% (4.21–7.67 GHz) and a 3-dB axial-ratio bandwidth of 40% (5.1–7.3 GHz). In addition, the antenna achieves a peak gain of 11.5 dBi while maintaining an isolation level better than 25 dB between antenna ports. The fabricated prototype exhibits performance characteristics consistent with those predicted in the simulations. Owing to its favorable combination of bandwidth, gain, circular-polarization performance, and isolation characteristics, the proposed design represents an attractive solution for wideband CP MIMO communication systems.

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Index Terms—Aperture coupled feeding, MIMO antenna, wireless local area network, circular polarized antenna, sequentially rotated feeding.

I. INTRODUCTION

DRIVEN by the rapid growth of wireless services, the demand for high-speed and reliable data links has escalated, especially in wireless local area networks (WLANs). This growth, however, runs directly into the strict limits of available frequency spectrum, making spectrum scarcity a fundamental barrier to system upgrades [1]. To overcome this problem, Multiple-Input Multiple-Output (MIMO) technology has become a standard approach in modern architectures [2]. By utilizing spatial diversity, MIMO systems expand channel capacity and data rates without needing extra bandwidth, thus directly boosting spectral efficiency. Nevertheless, when antenna elements are placed in close proximity, mutual coupling becomes unavoidable. This mutual coupling effect often

degrades radiation performance, creating a key challenge for practical designs [3], [4].

Consequently, a wide range of approaches has been proposed to address this issue including: defected ground structure (DGS) [5], [6], [7], split-ring resonator (SRR) [8], neutralization line [9], [10], metasurface [11], [12], parasitic elements [13], [14], frequency selective surface (FSS) [15], [16]. Although the isolation between elements is ensured above 20 dB, the narrow bandwidth is the limit in these proposals. In addition, the antenna proposed in [7] achieves a relatively low gain, which may limit its suitability for applications requiring enhanced link reliability and coverage.

Besides, the microstrip patch antennas are widely recognized as a preferred choice due to its well-documented advantages. Thanks to features such as low profile, compact geometry, and lightweight structure, microstrip antennas are not only suitable for integration into modern communication systems but also advantageous in terms of ease of fabrication, which enables large-scale deployment. However, these advantages are tempered by inherent drawbacks, most notably their restricted impedance bandwidth and low gain. A widely adopted solution to these limitations is the use of antenna arrays, which consist of multiple radiating elements. By arranging in a certain structure, array antennas achieve higher gain and broader operational bandwidth, making them indispensable in a wide range of applications [17], [18], [19].

In parallel, circularly polarized (CP) antennas have gained considerable attention because of their ability to improve signal reliability, mitigate multipath effects, and accommodate variations in polarization states in dynamic wireless environments [20], [21]. The techniques utilized to achieve circular polarization radiation can be divided into the following groups: slots [22], corner truncation [23], sequential rotation feeding network [24], multi-feed schemes [25]. For antenna arrays, one of the most effective and widely used methods is the sequential-phase feeding scheme, where controlled progressive phase shifts are introduced at the output ports to produce the CP characteristics. This principle has been extensively applied to improve the axial ratio (AR) bandwidth, as reported in several studies [24], [26], [27], [28], [29], [30], [31], [32], [33], [34]. Although the advancement has been achieved, most reported designs only optimize one or two parameters at the expense of others. For example, the antennas reported in [26], [27], [28], [29] achieve good bandwidth, but gain is relatively low. The designs presented in [31], [32], [33] present improved radiation performance; however, AR bandwidth remains limited. Meanwhile, the configuration proposed in [30] introduces increased complexity and fabrication cost, whereas the design in [34] occupies a large physical dimension. There-

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fore, achieving a balanced combination of wide impedance bandwidth, broad axial-ratio bandwidth, high gain, and inter-element isolation within a compact antenna structure remains a challenging research problem.

Motivated by these limitations, this work proposes a wideband CP MIMO antenna consisting of two identical 2×2 aperture-coupled subarrays operating at 5.5 GHz. By incorporating a 5 mm air gap and employing a sequential-phase feeding network in both the array and MIMO configurations, the proposed design simultaneously enhances impedance bandwidth, circular-polarization performance, gain, and isolation. To verify the proposed approach, the antenna is designed and optimized in CST Studio Suite and subsequently fabricated for measurement. Experimental results confirm an impedance bandwidth of 62.9% from 4.21 to 7.67 GHz, a 3-dB axial-ratio bandwidth of 40% covering 5.1–7.3 GHz, a peak realized gain of 11.5 dBi, and inter-element isolation exceeding 25 dB. These results indicate that the proposed antenna can support wideband circularly polarized MIMO operation within the 5–7 GHz frequency range, which includes WLAN and Wi-Fi 6/6E bands.

The contributions of this work can be summarized as follows:

- A wideband circularly polarized MIMO antenna composed of two identical 2×2 subarrays is proposed for operation at 5.5 GHz.
- An aperture-coupled radiating configuration incorporating a 5 mm air gap is employed to substantially broaden the impedance bandwidth.
- A sequential-phase feeding network is integrated into both the array and MIMO structures to improve circular polarization characteristics while supporting wideband operation.
- The proposed design is comprehensively evaluated through numerical simulations and experimental measurements.

II. DESIGN OF MIMO ANTENNA

A. An Individual Antenna Element

This section describes the configuration of the single antenna element and explains the underlying mechanism enabling wideband operation, as illustrated in Fig. 1. The radiating patch is fabricated on an RO4003C substrate with a thickness of 1.524 mm, whereas the feeding microstrip line and the ground plane are implemented on a separate RO4003C substrate of 0.508 mm thickness. The antenna employs a truncated-corner patch, which serves as the primary radiating structure for circular polarization. Energy is transferred from the microstrip feed to the patch through a slot etched in the ground plane, allowing the feed and radiator to be placed on separate substrates. This configuration provides enhanced design flexibility and is well known for improving impedance bandwidth and polarization performance in microstrip antennas. Furthermore, the introduction of the 5 mm air gap decreases the effective dielectric constant and enhances fringing fields around the radiator, leading to a lower Q-factor and improved impedance bandwidth.

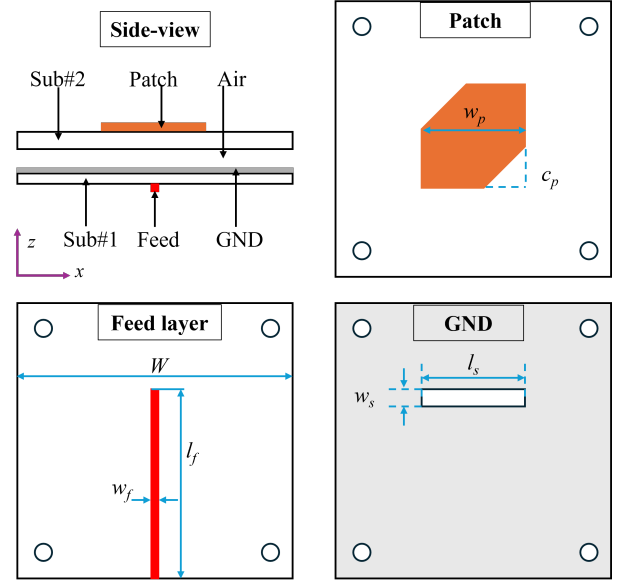


Fig. 1. Configuration of the single element: $W = 40$; $w_f = 1.1$; $l_f = 26$; $w_s = 2.5$; $l_s = 15$; $w_p = 15$; $c_p = 6.5$ (mm).

To validate the effectiveness of the aperture-coupled feeding (ACF) technique, a reference antenna employing a coaxial cable (CC) feed is designed, as shown in Fig. 2. In this design, the radiating patch and ground plane are placed on two opposite sides of an RO4003C substrate. For a fair comparison, the substrate thickness is set equal to the sum of the thicknesses of the two dielectric layers used in the ACF configuration. The overall antenna size is 60×60 mm while the patch element has dimensions of 34.5×34.5 mm.

Fig. 3 exhibits the performance comparison between the CC-fed and ACF-fed antennas. It can be observed that the ACF technique provides improved performance due to the combined resonance of the slot and the patch, leading to enhanced impedance bandwidth and axial ratio (AR). Specifically, the -10 dB impedance bandwidth of the CC-fed antenna is 5.44–5.86 GHz (7.6%), whereas the ACF-fed antenna achieves a significantly wider bandwidth of 4.5–5.93 GHz (26%). A similar improvement is observed in terms of AR bandwidth, where the ACF configuration outperforms the CC-fed design (5.41–5.83 GHz for ACF and 5.48–5.53 GHz for CC). In addition, the ACF-fed antenna maintains a relatively stable and higher gain across the operating band compared to the CC-fed counterpart.

Fig. 4 shows the performance of a single element. As seen, the bandwidth percentage at -10 dB is from 4.5–5.93 GHz (26%), a 3-dB AR bandwidth of 5.41–5.83 GHz (7.6%), and a peak gain of 7.7 dBi, while the pattern shows broadside radiation with low side-lobe levels.

B. Sequentially Rotated Feeding Network

To extend the 3-dB AR bandwidth, a sequential-phase (SP) feeding network is used and its model is illustrated in Fig. 5. The SP network is printed on a substrate of RO4003C with a thickness of 0.508 mm. To achieve the resonance at the desired

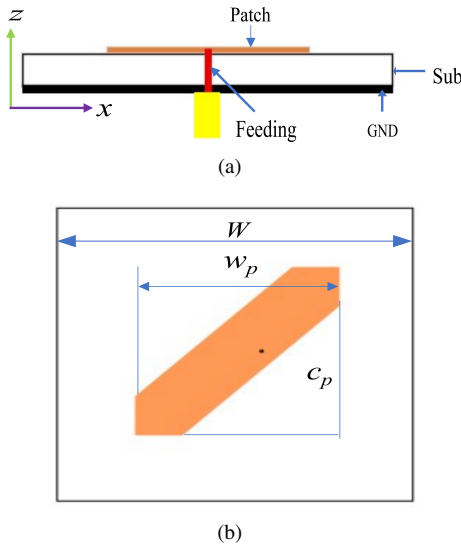


Fig. 2. The geometry of antenna utilizing coaxial cable. $W = 60$; $w_p = 34.5$; $c_p = 26.5$ (mm).

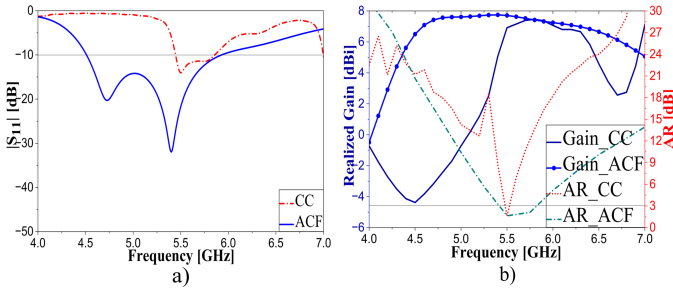


Fig. 3. The comparison of performance between using coaxial cable and aperture-coupled feed.

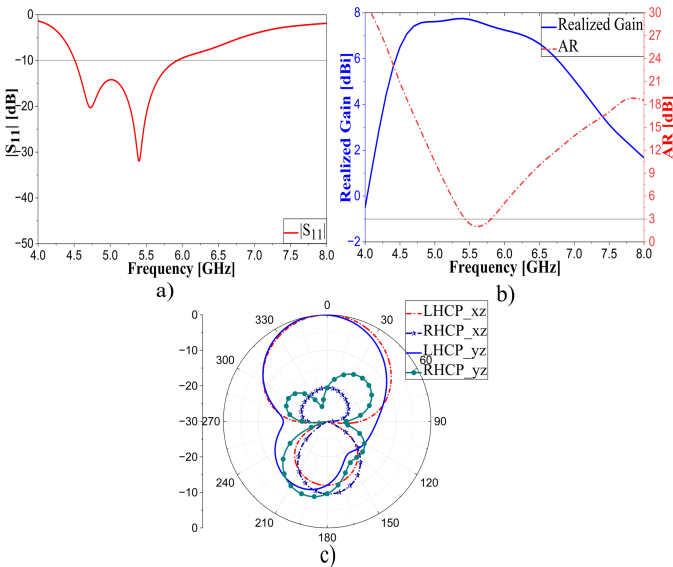


Fig. 4. The performance of single element: (a) reflection coefficient; (b) gain and AR; (c) pattern at 5.5 GHz.

frequency, the radius of SP networking is calculated as follows [35]:

$$r = \frac{\lambda_d}{2\pi} \quad (1)$$

where λ_d denotes the wavelength in the dielectric medium. The SP network is developed from a serial network of feeding to provide appropriate phase-shifting and power splitting between the radiating elements [36]. The input port of the network is connected to a 50Ω SMA connector, while the opposite layer was used as the ground plane. It should be noted that the feeding is designed to achieve equal power distribution from the input port (port 1) to the output ports with a phase shifting of 90° between two adjacent ports.

The simulated performance of the SP network is presented in Fig. 6. It can be observed that the reflection coefficient, $|S_{11}|$ remains below -15 dB in the range of 4–8 GHz. In addition, the transmission coefficients including $|S_{21}|$, $|S_{31}|$, $|S_{41}|$, $|S_{51}|$ are maintained at approximately -6 ± 0.5 dB within the frequency range of 5–8 GHz (54.5%). Meanwhile, a phase difference close to 90° between adjacent output ports is consistently achieved across the band.

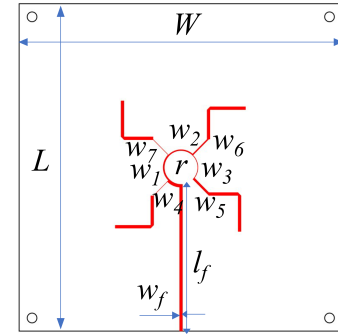


Fig. 5. Sequentially Rotated Feeding Network. $W = 100$; $l_f = 50$; $w_1 = 0.5$; $w_2 = 0.4$; $w_3 = 0.2$; $w_4 = 0.14$; $w_5 = 0.7$; $w_6 = 0.42$; $w_7 = 0.14$ (mm).

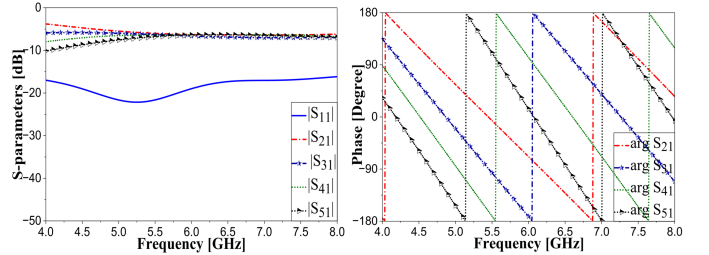


Fig. 6. S-parameters (a) and out phases (b) of the SP network.

C. Antenna Array of 2×2

After completing the design of the single radiating element and the feeding network, a 2×2 array configuration is developed, as illustrated in Fig. 7. The antenna is realized using two Rogers RO4003C substrates with thicknesses of $h_1 = 0.508$ mm and $h_2 = 1.524$ mm, relative permittivity $\epsilon_r = 3.55$, and loss tangent of $\tan \delta = 0.0027$. The feeding network and ground plane are implemented on the two sides of Sub. 1, while the radiating elements are printed on Sub. 2. Circular polarization (CP) is achieved by employing square patch elements with truncated corners, excited through a sequential phase (SP) feeding network.

The overall array size is 100×100 mm, and each radiating element has dimensions of 16×16 mm. An air gap of 5 mm is introduced between the two substrates to enhance the operating bandwidth. The array is optimized to achieve wideband performance in terms of both impedance matching and axial ratio (AR), with a target center frequency around 5.5 GHz.

The simulated results, presented in Fig. 8, show that the antenna achieves a -10 dB impedance bandwidth of 52.54% (4.24–7.13 GHz) and an AR bandwidth of 36.4% (4.76–6.76 GHz). A peak gain of 13.3 dBi is obtained at 5.8 GHz. In addition, the radiation patterns exhibit a stable broadside characteristic with low side-lobe levels. The significant improvement in AR bandwidth can be attributed to the implementation of the sequential phase feeding network.

D. MIMO Antenna

The proposed antenna employs a two-port MIMO architecture, where each port excites an identical 2×2 circularly polarized subarray, as illustrated in Fig. 9. As a result, the complete structure contains eight radiating elements excited through aperture-coupled sequential feeding networks, enabling circular polarization with enhanced axial-ratio bandwidth. The parallel arrangement of the two subarrays also helps improve spatial diversity and reduces the envelope correlation coefficient (ECC), which is beneficial for MIMO communication systems.

Based on RO4003C, the overall size of the antenna is $140 \times 100 \times 7.172$ mm while the gap between elements (d_e) is 34.9 mm. To gain further insight into the antenna performance and clarify the influence of key design parameters, a parametric study is carried out. The investigated parameters include the inter-element spacing (d_e), the height of the air gap (h_a), and the width of the patch (w_p) as illustrated in Fig. 10.

Fig. 10(a) shows that the spacing between radiating elements plays a crucial role in determining the impedance matching, isolation, as well as the radiation characteristics. The best overall performance is achieved when $d_e = 34.9$ mm. When the spacing decreases to $d_e = 31.9$, the depth of impedance matching decreases significantly, leading to noticeable degraded gain, although isolation is still ensured under -25 dB. Conversely, when the spacing increases to $d_e = 37.9$, the impedance mismatch appears in the 6–7 GHz region, which results in a reduction in both gain and AR performance.

The effect of the air-layer height (h_a) on the antenna performance is illustrated in Fig. 10(b). It can be observed that this parameter considerably affects both S-parameters and the radiation characteristics (including gain and AR). When h_a increases, the impedance matching and gain performance are improved due to the reduced dielectric loading. However, an excessively large air gap slightly causes the reduction in AR bandwidth.

Finally, the influence of the patch width (w_p) is presented in Fig. 10(c). This parameter mainly controls the resonant behavior of the antenna. Although there are resonant frequency shifts when the change of w_p , S-parameters and gain remain

relatively stable for the investigated cases. However, a noticeable variation in AR can be observed. With w_p of 11 and 14, the slight disturbance between the orthogonal modes required for circular polarization resulting in a degraded AR response.

III. MEASURED RESULTS AND DISCUSSION

For validation purposes, the antenna prototype was fabricated and experimentally characterized. The fabricated structure is shown in Fig. 11, with overall dimensions of $140 \times 100 \times 7.172$ mm, corresponding to approximately $1.96\lambda_{\min} \times 1.4\lambda_{\min} \times 0.1\lambda_{\min}$, where $\lambda_{\min}$ denotes the free-space wavelength at the lowest operating frequency. All components, including radiating patches, feeding network, and ground plane, were implemented using standard printed circuit board (PCB) technology on dielectric substrates. A thin tin coating was applied to the copper layers to mitigate oxidation. In addition, plastic posts and screws were employed to maintain the mechanical stability and alignment of the stacked substrates.

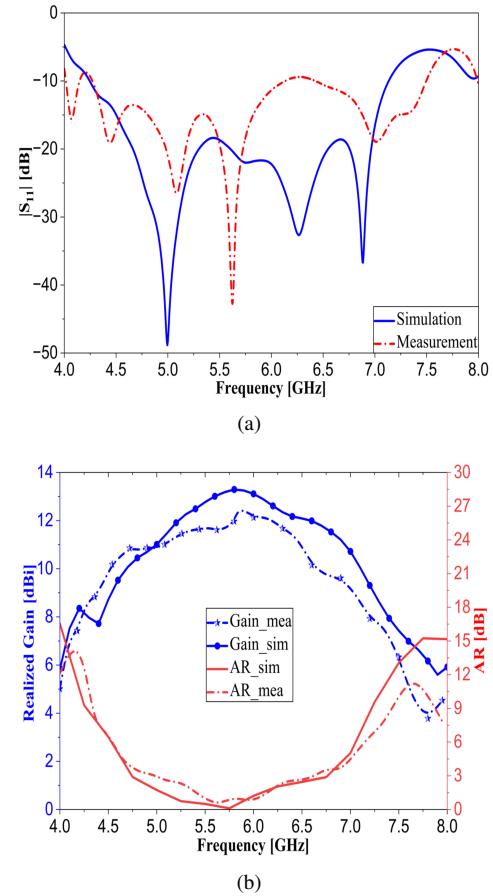


Fig. 12. Measured and simulated results of the antenna array of 2×2 : (a) $|S_{11}|$; (b) gain and AR.

The simulated and measured results including S-parameters, gain, and axial ratio (AR) bandwidth for both the 2×2 array and the MIMO configuration are presented in Figs. 12 and 13, respectively. As shown in Fig. 12, the measured $|S_{11}|$ below -10 dB spans from 4.26 to 7.5 GHz (58.91%), while the simulated bandwidth is 4.24–7.14 GHz (52.73%). The measured gain varies from 7 to 12.6 dBi, and the 3-dB AR

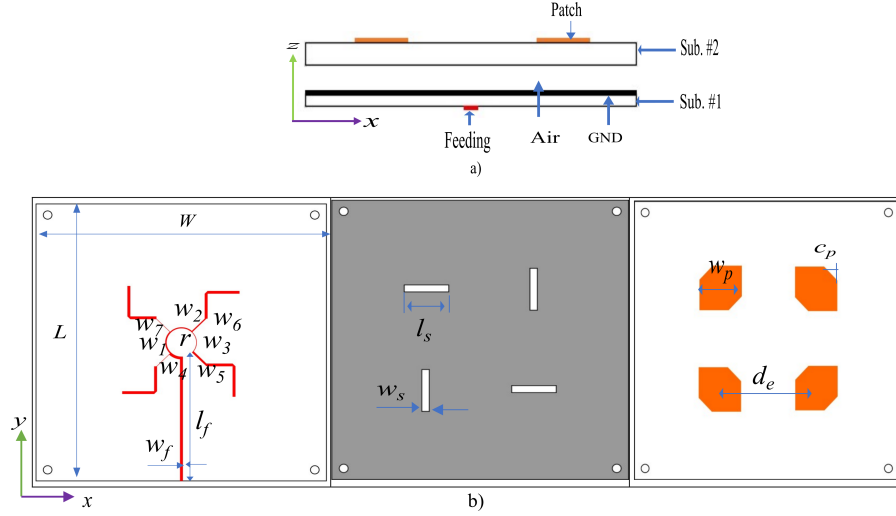


Fig. 7. The geometry of 2×2 array antenna: (a) cross-section view, (b) feeding network, (c) ground, (d) radiation elements. $W = 100$, $L = 100$, $w_1 = 0.5$, $w_2 = 0.4$, $w_3 = 0.2$, $w_4 = 0.14$, $w_5 = 0.7$, $w_6 = 0.42$, $w_7 = 0.14$, $r = 5.1$, $w_f = 1$, $l_f = 50$, $w_s = 2.5$, $l_s = 15$, $w_p = 16$, $c_p = 5$, $d_e = 36.1$ (mm).

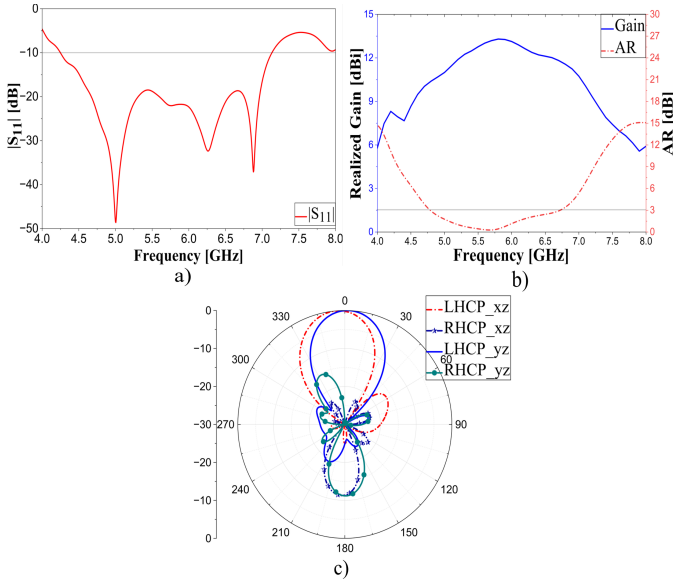


Fig. 8. The performance of 2×2 array antenna: (a) $|S_{11}|$, (b) gain and AR, (c) pattern at 5.5 GHz.

bandwidth yields from 4.99 to 6.65 GHz (30.2%) while the simulated gain ranges from 8 to 13.3 dBi, with a 3-dB AR bandwidth of 4.75–6.75 GHz (36.36%). Similarly, the MIMO antenna illustrated in Fig. 13, the measured bandwidth at -10 dB is 4.21–7.67 GHz (62.91%), and 3-dB AR bandwidth is 5.1–7.3 GHz (40%). Moreover, an isolation over 25 dB is maintained across the operating frequency band.

Figs. 14 and 15 displayed the radiation patterns at selected frequencies of 2×2 array and MIMO antenna, respectively. Despite discrepancies between simulated and measured results, both antenna prototypes exhibit stable broadside radiation characteristics with acceptable results. The observed differences between measurement and simulation can be attributed to several factors, including fabrication tolerances, SMA connector soldering effects, and imperfections in the measurement

environment. In particular, the dielectric layer may experience bending during measurement due to the limited thickness (0.508 mm) of Sub. 1. Nevertheless, the simulated and measured results are reasonably consistent, thereby validating the proposed design.

IV. DIVERSITY PROPERTY

In MIMO systems, envelope correlation coefficient (ECC) is a crucial matrix to evaluate performance. ECC tells how many antenna elements in the MIMO system are independent in their performance and can be calculated by using S-parameters or pattern characteristics as follows [37]:

$$ECC = \frac{|S_{ii}^* S_{ij} + S_{ij}^* S_{jj}|^2}{(1 - |S_{ii}|^2 - |S_{ij}|^2)(1 - |S_{ji}|^2 - |S_{jj}|^2)} \quad (2)$$

or

$$ECC = \frac{\left| \iint_{4\pi} [\vec{F}_i(\theta, \phi) \cdot \vec{F}_j^*(\theta, \phi)] d\Omega \right|^2}{\iint_{4\pi} |\vec{F}_i(\theta, \phi)|^2 d\Omega \iint_{4\pi} |\vec{F}_j(\theta, \phi)|^2 d\Omega} \quad (3)$$

where $F_{i(j)}$ ($i \neq j$) is the complex 3D radiation pattern for ports i, j ; $S_{i(j)i(j)}$ ($i \neq j$) are the complex S-parameters for ports i and/or j . Besides, the diversity gain (D_G) is still one in the important parameters which shows the improvement in transmission quality and it can be given as:

$$D_G = 10\sqrt{1 - ECC^2} \quad (4)$$

Another critical parameter in the MIMO channel is its channel capacity loss (CC_{loss}), which can be estimated:

$$CC_{\text{loss}} = -\log_2 \det(m_c) \quad (5)$$

In which, m_c is the correlation matrix and is given by:

$$m_c = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} \quad (6)$$

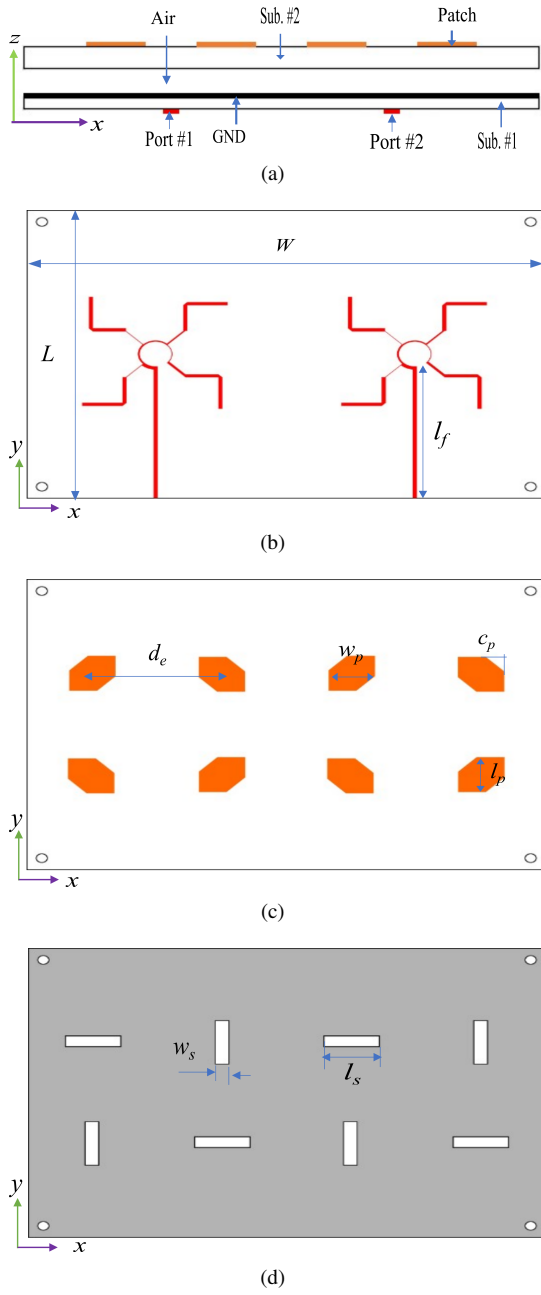


Fig. 9. The configuration of the proposed MIMO antenna: (a) cross-section view, (b) sequential feeding network, (c) ground layer, (d) radiation elements. $W = 140$, $L = 100$, $l_f = 45.7$, $d_e = 34.9$, $w_p = 12.5$, $l_p = 12$, $c_p = 5$, $w_s = 3.7$, $l_s = 15$ (mm).

$$\sigma_{ii} = 1 - (|S_{ii}|^2 - |S_{ij}|^2) \quad (7)$$

$$\sigma_{ij} = 1 - (S_{ii}^* S_{ij} + S_{ji} S_{jj}^*) \quad (8)$$

From the derived formulas, the MIMO performance indicators of the proposed antenna, namely the envelope correlation coefficient (ECC), diversity gain (DG), and channel capacity loss (CC_{loss}) and mean effective gain (MEG), are presented in Fig. 16. The ECC remains below 0.0005, which is considerably lower than the widely accepted limit of 0.5, thereby indicating negligible mutual coupling and highly uncorrelated radiation characteristics. Additionally, the diversity

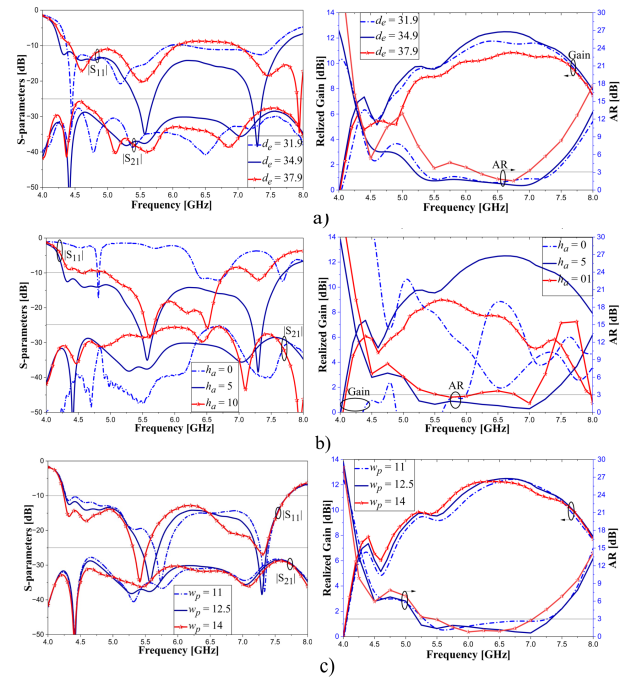


Fig. 10. S-parameters (left) and gain and AR (right) for the changes of parameters: (a) the distance between elements (d_e), (b) the height of air gap (h_a), and (c) the width of patch (w_p).

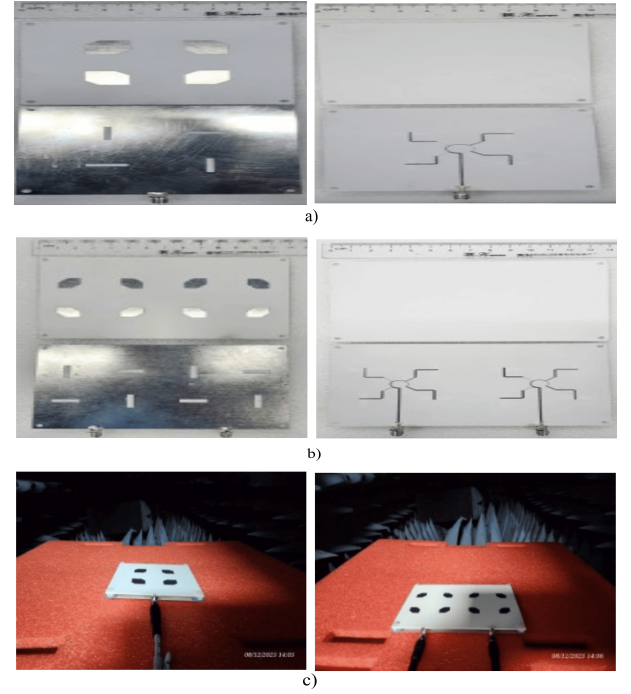


Fig. 11. Fabricated prototype of the proposed antenna: (a) a 2×2 antenna array, (b) MIMO antenna, (c) measurement setup.

gain achieves to be close to 10 dB, demonstrating the antenna's effectiveness in mitigating multipath fading effects. These results show that the proposed antenna can perform effectively in a MIMO configuration. The MEG values are observed to be approximately -3 dB and remain well balanced among the antenna elements, confirming good power distribution and satisfactory diversity performance. Moreover, the CC_{loss} is

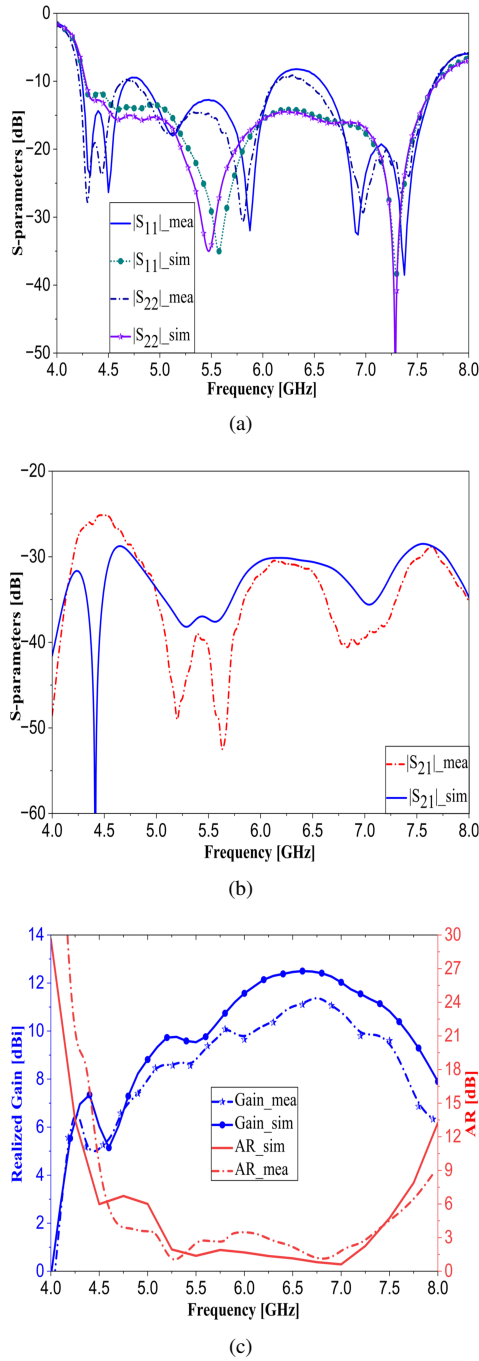


Fig. 13. Measured and simulated results of the MIMO antenna: (a) Return Loss; (b) isolation (c) gain and AR.

ensured below 0.1 bits/s/Hz across the operating frequency range, indicating its potential to enable reliable high-data-rate wireless communications.

V. PERFORMANCE COMPARISON

Table I presents a comparison of the proposed antenna with several recently reported MIMO configurations. One of the most evident distinctions lies in the impedance bandwidth, where the proposed design achieves 62.91%, while most of the existing works report values below 20%. A similar tendency can also be observed for the circular polarization performance.

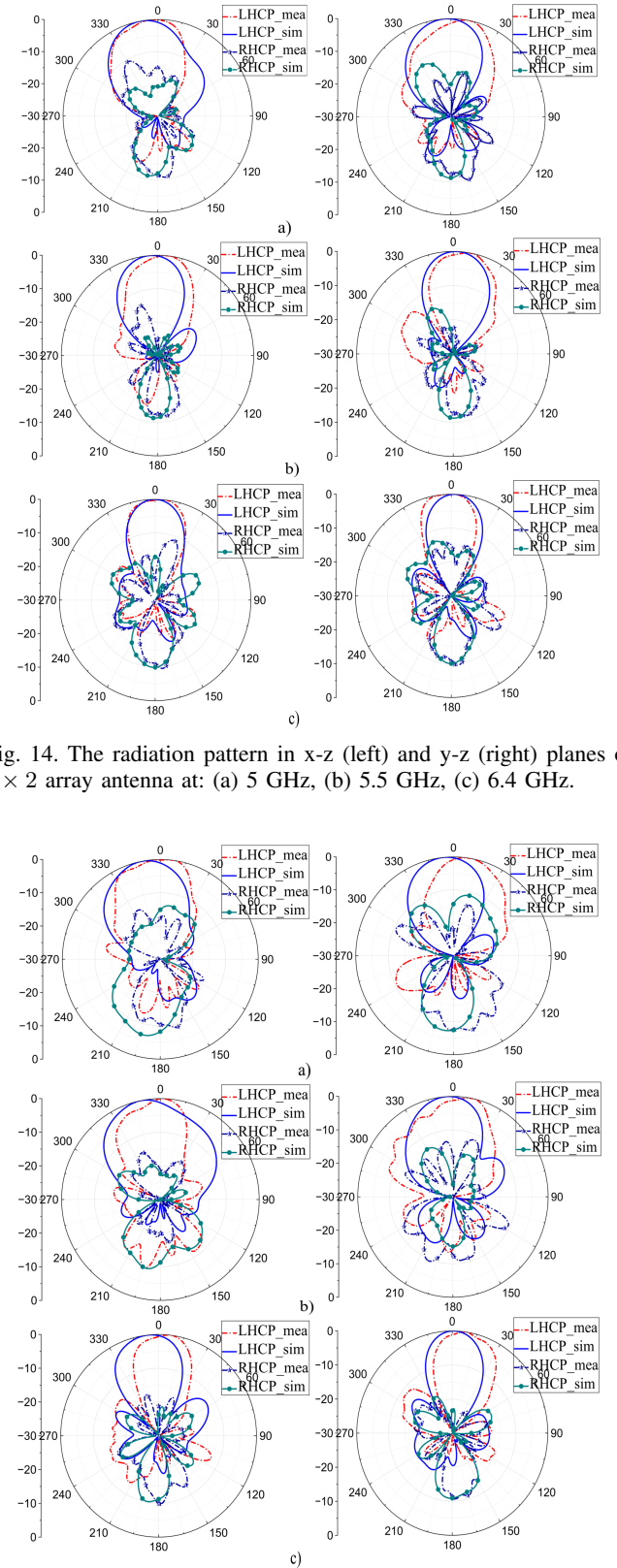


Fig. 14. The radiation pattern in x-z (left) and y-z (right) planes of 2×2 array antenna at: (a) 5 GHz, (b) 5.5 GHz, (c) 6.4 GHz.

Fig. 15. The radiation pattern in x-z (left) and y-z (right) planes of MIMO antenna at: (a) 5 GHz, (b) 5.5 GHz, (c) 6.4 GHz.

In particular, the proposed antenna provides a 3-dB axial-ratio bandwidth of 40%, indicating that circular polarization is maintained over a significantly broader frequency range

TABLE I
A COMPARISON BETWEEN THE PERFORMANCE OF THE PROPOSED DESIGN AND RELATED WORKS

Ref.	Freq. (GHz)	Array Size	-10 dB BW (%)	Pol.	Iso. (dB)	Peak Gain (dBi)	DG (dB)	ECC	CCL (bits/s/Hz)	Size (λ^3)
[5]	39	8	10.5	LP	> 31.5	7.7	10	0.01	0.05	$3.18 \times 3.28 \times 0.16$
[6]	2.45	4	< 5	LP	> 20	N/G	N/G	0.004	N/G	$0.68 \times 0.68 \times 0.01$
[7]	2.05	2	33.17	LP	20	4.1	9.99	0.008	0.4	$0.82 \times 0.41 \times \text{N/G}$
[12]	26	8	8.5	LP	22	9.4	10.00	0.014	0.2	$3.04 \times 3.04 \times 0.07$
[13]	5.8	4	7.05	CP (2.04%)	34	7.68	9.99	0.001	0.15	$1.46 \times 1.46 \times 0.029$
[14]	5.7	4	17.8	LP	32	8.7	9.992	0.0035	N/G	$1.47 \times 1.47 \times 0.028$
[38]	28	4	10.7	CP (10.7%)	30	11.4	10.00	0.00025	N/G	$4.25 \times 1.02 \times \text{N/G}$
[39]	28	8	16.56	LP	26	10.34	9.99	0.0012	0.15	2.24×2.24
[40]	38	8	11.84	LP	27	8.09	N/G	0.0002	0.115	$3.04 \times 4.6 \times \text{N/G}$
[41]	2.2	2	18.2	CP (18%)	10	2.5	9.997	0.2	0.5	$0.32 \times 0.27 \times 0.01$
[42]	5.1–6.1	4	17.3	LP	17.5	6.9	9.94	0.001	0.4	$1.92 \times 1.75 \times 0.29$
This work	5.5	8	62.91	CP (40%)	25	11.51	10.00	< 0.0005	< 0.1	$1.96 \times 1.4 \times 0.1$

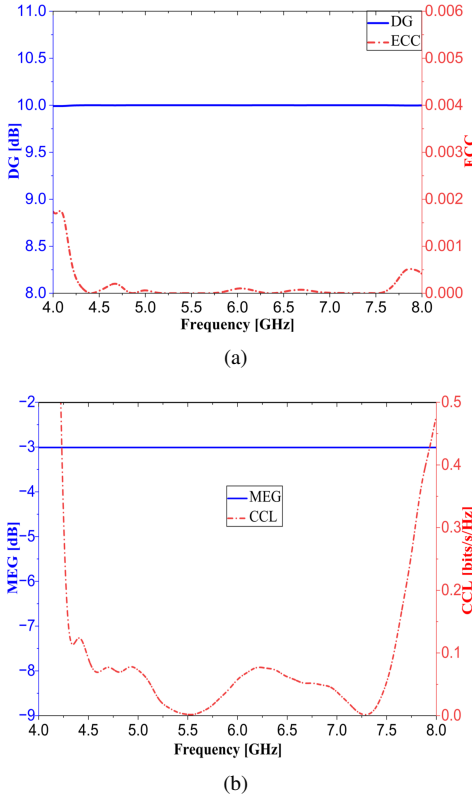


Fig. 16. Diversity performance of the proposed antenna. (a) ECC and DG and (b) MEG and CCL_{loss} .

compared with the CP MIMO antennas listed in the table.

In terms of gain performance, the proposed design achieves 11.51 dBi, which is among the highest values listed in the table. Regarding MIMO characteristics, the measured isolation remains above 25 dB throughout the operating band, indicating limited interaction between the two antenna ports. Although several reported designs provide higher isolation levels, the difference is accompanied by narrower bandwidths or reduced polarization bandwidths.

For the parameters of diversity property, this work maintains the second-lowest CCL among the reported designs and the third-lowest ECC, following the antennas presented in [5], [38], and [40]. These results demonstrate the competitive

diversity performance of the proposed design for MIMO applications.

The comparison further indicates that none of the reported designs achieves superior performance across all metrics simultaneously. Some antennas offer stronger isolation, while others achieve smaller dimensions. In the present work, the design priority is placed on extending both the impedance and AR bandwidths without reducing gain performance. As a result, the proposed antenna does not represent the smallest structure in the comparison; however, it provides a balanced combination of bandwidth, gain, polarization, and port isolation that is well suited to wideband CP MIMO applications.

VI. CONCLUSION

A wideband circularly polarized MIMO antenna system has been presented, consisting of two identical 2×2 sub-arrays. Each radiating element adopts an aperture-coupled configuration with an embedded air gap to effectively enhance the impedance bandwidth. In addition, a sequential-phase feeding network is employed to simultaneously realize stable circular polarization and improve broadband performance. The proposed design achieves an impedance bandwidth of 4.21–7.67 GHz (62.9%), a 3-dB axial ratio bandwidth of 5.1–7.3 GHz (40%), a peak gain of up to 11.5 dBi, while the isolation remains higher than 25 dB across the operating band, indicating effective suppression of mutual coupling. With the combined features of bandwidth enhancement via air-gap coupling, polarization stability enabled by sequential-phase feeding, and strong isolation characteristic, the proposed antenna demonstrates an effective solution for wideband CP MIMO systems. These advantages make it well suited for modern high-data-rate wireless communication applications.

Compared with many recently reported CP MIMO antennas, the proposed design offers a balance among bandwidth, gain, isolation, diversity performance, and implementation complexity. These characteristics overcome several limitations identified in existing designs, where improvements in one performance metric are often achieved at the expense of others. As a result, the proposed antenna provides a solution for high-data-rate WLAN, Wi-Fi 6/6E and other wideband wireless communication applications. In the future, the research may

focus on further size reduction, the development of higher-order MIMO configurations, and experimental validation in practical communication platforms to support emerging wireless systems.

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REFERENCES

- [1] S. Ullah, Y. He, and Y. Huang, "A triband circular-polarized four-port mimo antenna with compact size and low mutual coupling," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 3, pp. 621–625, 2024, doi: 10.1109/LAWP.2024.3510132.
- [2] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of mimo communications—a key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198–218, 2004, doi: 10.1109/JPROC.2003.821915.
- [3] X. Chen, S. Zhang, and Q. Li, "A review of mutual coupling in mimo systems," *Ieee Access*, vol. 6, pp. 24 706–24 719, 2018, doi: 10.1109/ACCESS.2018.2830653.
- [4] X. Liu and M. E. Bialkowski, "Effect of antenna mutual coupling on mimo channel estimation and capacity," *International Journal of Antennas and Propagation*, vol. 2010, no. 1, p. 306173, 2010, doi: 10.1155/2010/306173.
- [5] O. Elalaoui, M. El Ghzaoui, and J. Foshi, "Mutual coupling reduction of a two-port mimo antenna using defected ground structure," *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, vol. 8, p. 100557, 2024, doi: 10.1016/j.prime.2024.100557.
- [6] B. Qian, X. Huang, X. Chen, M. Abdullah, L. Zhao, and A. A. Kishk, "Surrogate-assisted defected ground structure design for reducing mutual coupling in 2×2 microstrip antenna array," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 2, pp. 351–355, 2021, doi: 10.1109/LAWP.2021.3131600.
- [7] D. Pandurangan and N. Mishra, "Design and analysis of two-port self-decoupled highly efficient mimo antenna for 5g new radio mid-band ($n1/n2/n3$) wireless communication," *IEEE Access*, vol. 13, pp. 7110–7122, 2025, doi: 10.1109/ACCESS.2025.3526276.
- [8] M. S. Khan, S. Khan, O. Khan, S. Aqeel, N. Gohar, and M. Dalarsson, "Mutual coupling reduction in mimo dra through metamaterials," *Sensors*, vol. 23, no. 18, p. 7720, 2023, doi: 10.3390/s23187720.
- [9] S. Luo, Y. Li, Y. Xia, and L. Zhang, "A low mutual coupling antenna array with gain enhancement using metamaterial loading and neutralization line structure," *Applied Computational Electromagnetics Society Journal (ACES)*, pp. 411–418, 2019.
- [10] X.-J. Zou, G.-M. Wang, G.-Q. Kang, W. Song, M. Tan, X.-G. Xu, and H. Zhu, "Wideband coupling suppression with neutralization-line-incorporated decoupling network in mimo arrays," *AEU-International Journal of Electronics and Communications*, vol. 167, p. 154688, 2023, doi: 10.1016/j.aeue.2023.154688.
- [11] Z. Wang, L. Zhao, Y. Cai, S. Zheng, and Y. Yin, "A meta-surface antenna array decoupling (maad) method for mutual coupling reduction in a mimo antenna system," *Scientific reports*, vol. 8, no. 1, p. 3152, 2018, doi: 10.1038/s41598-018-21619-z.
- [12] M. Alibakhshikenari, I. Ud Din, E. M. Ali, N. Abd Elmunim, B. S. Virdee, D. Mariyanayagam, S. Ullah, N. Ahmad Abbasi, N. Rashid, C. Hwang See *et al.*, "Metasurface covered millimeter-wave mimo antenna array," *Waves in Random and Complex Media*, pp. 1–16, 2025, doi: 10.1080/17455030.2025.2574631.
- [13] M. A. Sufian, N. Hussain, A. Abbas, J. Lee, S. G. Park, and N. Kim, "Mutual coupling reduction of a circularly polarized mimo antenna using parasitic elements and dgs for v2x communications," *IEEE access*, vol. 10, pp. 56 388–56 400, 2022, doi: 10.1109/ACCESS.2022.3177886.
- [14] S. Pramono, A. S. Nugroho, M. E. Sulisty, and M. Mujawar, "A novel double defected ground structures and parasitic patches for enhanced mimo antenna performance," *Scientific Reports*, 2026, doi: 10.1038/s41598-026-44869-8.
- [15] S. Mandal and C. K. Ghosh, "Mutual coupling reduction in a patch antenna array based on planar frequency selective surface structure," *Radio Science*, vol. 57, no. 2, pp. 1–11, 2022, doi: 10.1029/2021RS007392.
- [16] P. Mondal, D. Dhara, and A. Harish, "A partially reflective fss-based superstrate as a decoupling structure for reducing the mutual coupling of circularly polarized antennas," *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 4, pp. 3652–3661, 2024, doi: 10.1109/TAP.2024.3364750.
- [17] J. Ran, Y. Wu, C. Jin, P. Zhang, and W. Wang, "Dual-band multipolarized aperture-shared antenna array for ku-/ka-band satellite communication," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 5, pp. 3882–3893, 2023, doi: 10.1109/TAP.2023.3248445.
- [18] Y. He, J. Li, S. W. Wong, X. Pan, L. Zhang, and Z. N. Chen, "A miniaturized base station antenna with novel phase shifter for 3g/lte applications," *IEEE Access*, vol. 6, pp. 52 877–52 888, 2018, doi: 10.1109/ACCESS.2018.2866482.
- [19] N. Yan, K. Ma, and H. Zhang, "A novel substrate-integrated suspended line stacked-patch antenna array for wlan," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 7, pp. 3491–3499, 2018, doi: 10.1109/TAP.2018.2826719.
- [20] S. S. Gao, Q. Luo, and F. Zhu, *Circularly polarized antennas*. John Wiley & Sons, 2014.
- [21] N. Yan, K. Ma, and Y. Luo, "An sisl sequentially rotated feeding circularly polarized stacked patch antenna array," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 2060–2067, 2019, doi: 10.1109/TAP.2019.2957096.
- [22] S. H. Yeung, K. F. Man, and W. S. Chan, "A bandwidth improved circularly polarized slot antenna using a slot composed of multiple circular sectors," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 8, pp. 3065–3070, 2011, doi: 10.1109/TAP.2011.2158953.
- [23] P. Wichaidit, S. Dentre, P. Janpanangern, T. Lertwiriaprapa, M. Krairiksh, and C. Phongcharoenpanich, "Broadband cp corner-truncated microstrip antenna with irregularly hexagonal amc for 2.45 ghz applications," *Alexandria Engineering Journal*, vol. 97, pp. 88–99, 2024, doi: 10.1016/j.aej.2024.04.022.
- [24] S. Wang, H. Hao, X. Ma, H. Cheng, and X. Huang, "Wideband circularly polarized array antenna based on sequential phase feeding metasurfaces for 5g (sub-6g) applications," *Journal of Electromagnetic Waves and Applications*, vol. 37, no. 1, pp. 15–24, 2023, doi: 10.1080/09205071.2022.2110948.
- [25] B. Li, J. Zhang, Y. Deng, Z. Zhou, and L. Sun, "Design of broadband circularly polarized patch antenna based on multi-feed method," in *2019 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*. IEEE, 2019, pp. 1–3, doi: 10.1109/ICMMT45702.2019.8992049.
- [26] C. Ming, "Compact wideband microstrip antenna array using sequential-phase feed network and metasurfaces," *Wireless Personal Communications*, vol. 110, no. 2, pp. 563–572, 2020, doi: 10.1007/s11277-019-06742-y.
- [27] X. Zhang, L. Yin, Z. Li, and Y. Hu, "A low-profile sequential-phase fed circularly polarized array antenna with an irregular ground," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 32, no. 12, p. e23450, 2022, doi: 10.1002/mmce.23450.
- [28] W.-J. Dai and Z.-F. Huang, "A broadband circularly polarized stacked microstrip patch antenna with parasitic elements," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 31, no. 11, p. e22842, 2021, doi: 10.1002/mmce.22842.
- [29] K. Ding, R. Hong, D. Guan, L. Liu, and Y. Wu, "Broadband circularly polarised stacked antenna with sequential-phase feed technique," *IET Microwaves, Antennas & Propagation*, vol. 14, no. 8, pp. 779–784, 2020, doi: 10.1049/iet-map.2019.0894.
- [30] M. Akbari, A. Farahbakhsh, and A.-R. Sebak, "Ridge gap waveguide multilevel sequential feeding network for high-gain circularly polarized array antenna," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 1, pp. 251–259, 2018, doi: 10.1109/TAP.2018.2878281.
- [31] M. Elahi, S. Trinh-Van, Y. Yang, K.-Y. Lee, and K.-C. Hwang, "Compact and high gain 4×4 circularly polarized microstrip patch antenna array for next generation small satellite," *Applied Sciences*, vol. 11, no. 19, p. 8869, 2021, doi: 10.3390/app11198869.
- [32] M. D. Alanazi, A. M. A., and A. A. Ibrahim, "Circularly polarized millimeter-wave hemisphere dra employing fss polarizer and dielectric superstrate for 5g applications," *Scientific Reports*, 2026, doi: 10.1038/s41598-025-34558-3.
- [33] A. Jirawattanaphol, N. Supreeyattitkul, K. Kitamura, and M. Cho, "Spiral-loop sequential-phase-fed radial-sector patch cp antenna with metasurface superstrate and parasitic elements for s-band cube-sats," *Technologies*, vol. 14, no. 5, p. 263, 2026, doi: 10.3390/technologies14050263.

- [34] F. Anelli, A. M. Loconsole, R. Losito, and F. Prudenzeno, "Broadband circularly polarized antenna array via metasurface and partially emptied substrate," *IEEE Access*, 2025, 10.1109/ACCESS.2025.3604558.
- [35] D. Inerra, W. Hu, and G. Wen, "Design of a microstrip series power divider for sequentially rotated nonuniform antenna array," *International Journal of Antennas and Propagation*, vol. 2017, no. 1, p. 9482979, 2017, doi: 10.1155/2017/9482979.
- [36] H. Evans, P. Gale, B. Aljibouri, E. Lim, E. Korolkeiwicz, and A. Sambell, "Application of simulated annealing to design of serial feed sequentially rotated 2×2 antenna array," *Electronics Letters*, vol. 36, no. 24, pp. 1987–1988, 2000, doi: 10.1049/el:20001407.
- [37] R. N. Tiwari, P. Singh, and B. K. Kanaujia, "A compact uwb mimo antenna with neutralization line for wlan/ism/mobile applications," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 29, no. 11, p. e21907, 2019, doi: 10.1002/mmce.21907.
- [38] F. Arshad, A. Ahmad, Y. Amin, M. A. B. Abbasi, and D.-Y. Choi, "Mimo antenna array with the capability of dual polarization reconfiguration for 5g mm-wave communication," *Scientific reports*, vol. 12, no. 1, p. 18298, 2022, doi: 10.1038/s41598-022-23163-3.
- [39] M. A. Haque, M. S. Ahammed, R. A. Ananta, K. Aljaloud, N. M. Jizat, W. M. Abdulkawi, K. H. Nahin, and S. S. Al-Bawri, "Broad-band high gain performance mimo antenna array for 5 g mm-wave applications-based gain prediction using machine learning approach," *Alexandria Engineering Journal*, vol. 104, pp. 665–679, 2024, doi: 10.1016/j.aej.2024.08.025.
- [40] M. A. Haque, M. S. Ahammed, S. Socheatra, R. A. Ananta, M. J. H. Nirob, N. S. S. Singh, N. M. Jizat, S. Alsowail, and S. S. Al-Bawri, "Machine learning based compact mimo antenna array for 38 ghz millimeter wave application with robust isolation and high efficiency performance," *Results in Engineering*, vol. 25, p. 104006, 2025, doi: 10.1016/j.rineng.2025.104006.
- [41] A. Chakraborty, R. S. Saxena, I. Singh, J. Kaur, R. Kaur, R. Kalia, and D. D. Bhavani, "Defected ground structure (dgs) based mimo antenna array with decent isolation characteristics for satellite communications in unified s-band (usb)," *Radio Science*, vol. 60, no. 11, pp. 1–17, 2025, doi: 10.1029/2025RS008379.
- [42] S. Sharma and R. Kumar, "4-port mimo antenna backed with frequency selective surface (fss) for improved characteristics in n46 and n47 wlan bands," *International Journal of Electronics*, vol. 113, no. 1, pp. 1–23, 2026, 10.1080/00207217.2025.2493120.



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