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Compact Dual-Band Multiport Antenna Array with Integrated Beam-Switching and Polarization Diversity for Next-Generation WLAN Access Points

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ABSTRACT: This paper presents the design, numerical modeling, and experimental validation of a compact, collocated multiport reconfigurable antenna array optimized for high-density WLAN access points operating in 2.4–2.5 GHz and 5.2–5.8 GHz bands. The proposed structure incorporates orthogonally oriented, horizontally and vertically polarized elements to achieve polarization diversity, alongside a PIN diode electronic switching network for dynamic radiation pattern control. Measured reflection coefficients remain well below -10 dB across both bands, with inter-port isolation exceeding 17 dB. The array seamlessly switches between a 360° omnidirectional mode (5.16 dBi peak gain) and multiple directive beam states (7.14 dBi peak gain), significantly mitigating multi-path fading and enhancing MIMO system performance. The entire architecture occupies a compact physical footprint of 200 mm × 200 mm, with excellent agreement between simulated and measured results, confirming its suitability for next-generation WLAN infrastructure.

1. INTRODUCTION

Reconfigurable antennas play a critical role in the evolution of advanced wireless communication systems by improving spatial selectivity, beamforming capabilities, and spectrum utilization efficiency. These functionalities are essential in emerging technologies, such as Beyond-5G (B5G) and 6G networks, where growing user demand, dense deployments, and dynamic environments present significant challenges in maintaining reliable connectivity and high data throughput [1–8]. Dual-band reconfigurable antennas are particularly advantageous for WLAN applications, because they enable the seamless integration of legacy 2.4 GHz systems with modern high-speed 5 GHz architectures. However, practical deployment requires addressing strict constraints, including layout compactness, easy radio frequency (RF) front-end integration, and preserving stable radiation properties under dynamic switching states.

To address these challenges, this study introduces a novel, compact, multiport reconfigurable antenna array specifically designed for high-density WLAN access points. The proposed collocated configuration operates simultaneously in the 2.4–2.5 GHz and 5.2–5.8 GHz bands, offering independent dual-polarization states (horizontal and vertical) alongside agile pattern reconfiguration through a dedicated beam-switching network. The array architecture incorporates eight elements in total: four dedicated to the lower band and four optimized for the higher band, evenly distributed to ensure symmetrical radiation coverage. This collocated arrangement drastically reduces physical footprint while providing the spatial and polarization diversity necessary to support advanced Multiple-input multiple-output (MIMO) algorithms. The subsequent sections detail the antenna geometry, equivalent circuit analysis, numerical simulation models, and experimental validations that confirm performance metrics of the fabricated prototype.

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2. ANTENNA DESIGN AND GEOMETRY

2.1. Substrate Specifications and Physical Configuration

The proposed multiport reconfigurable antenna array was engineered and fabricated on a low-cost, widely available FR-4 substrate. The selected substrate is characterized by a relative permittivity (ε_r) of 4.4, a loss tangent ($\tan\delta$) of 0.02, and a standard physical thickness (h) of 1.6 mm. Conductive layers on both top and bottom surfaces consisted of copper metallization with a uniform thickness of 0.035 mm (1 oz copper).

FR-4 was specifically chosen to demonstrate the design's practical viability and cost-effectiveness for high-volume commercial WLAN access points, proving that high isolation and agile beam-switching can be achieved without relying on expensive specialized high-frequency substrates. As illustrated in the comprehensive 3-D computer-aided design (CAD) models in Fig. 9, the overall physical dimension of the optimized substrate layout is highly compact, occupying a total surface area of only 200 mm × 200 mm (20 cm × 20 cm). To achieve concurrent dual-band operation, the array alternates diagonally between two distinct element configurations: larger slotted circular patch elements optimized for 2.4 GHz and compact vertical structures dedicated to 5 GHz. As shown in Fig. 3, this flat, low-profile configuration makes the array architecture ideal for ceiling-mounted indoor access point hardware, maximizing horizontal coverage while minimizing radiation in the normal upward and downward paths.

2.2. Reconfigurable Inverted-F Antenna (IFA) Array for Horizontal Polarization

To address the lower operational WLAN band (2.4–2.5 GHz), a horizontally polarized antenna sub-array was integrated into the system. As detailed in Figs. 1 and 2, this sub-structure uses four specialized Inverted-F Antennas (IFAs) distributed in a symmetrical circular topology. To maintain a highly efficient RF frontend, the design process ensures that each IFA element is independently matched to a 50 Ω characteristic impedance within the mutual array environment.

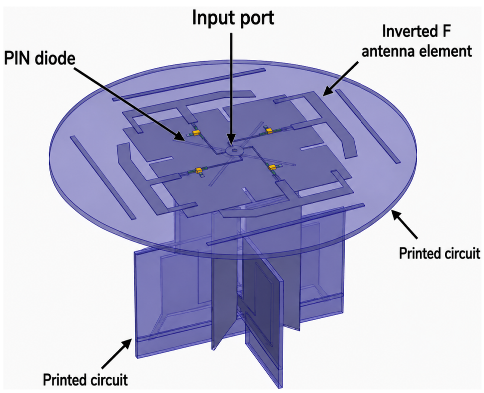

FIGURE 1. Geometry of the beam-switching antenna for horizontal polarization, composed of an array of Inverted-F Antenna (IFA) elements.

A critical engineering focus during layout optimization is suppressing mutual coupling between adjacent radiating elements, as severe near-field coupling inevitably degrades both impedance matching and total radiation efficiency once the feeding architecture is fully integrated. To mitigate this effect, a specialized cross-shaped decoupling slot is etched into the shared ground plane, disrupting the propagation of surface currents between the IFA components.

The feeding network incorporates a dedicated impedance transformer designed to transform the nominal impedance of each branch. Each of the four active branches presents a 200 Ω impedance at the central port, ensuring a perfectly matched total input impedance of 50 Ω at the central feed point. High-frequency PIN diodes and surface-mount capacitors are integrated directly into the shifting circuitry. When two specific diodes are electronically activated, they induce a transformation that effectively creates an open circuit at the center of their respective branches owing to the quarter-wavelength properties of the feeding structure. This alters the effective input impedance observed at the central port to 100 Ω. By optimizing the physical lengths of the transformer sections and the spacing between the control diodes and ground plane, an optimal matching compromise is successfully reached, ensuring stable S_{11} parameters across both omnidirectional and directive operational states. To achieve dynamic beam-switching performance, the switching network incorporates commercial Skyworks SMP1345-079LF PIN diodes. In the electromagnetic

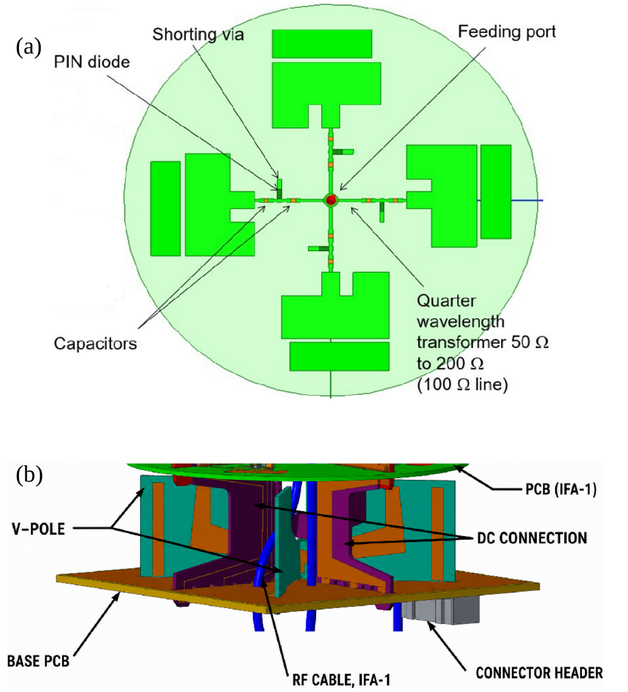

FIGURE 2. (a) Top view and (b) side view of the proposed horizontally polarized antenna.

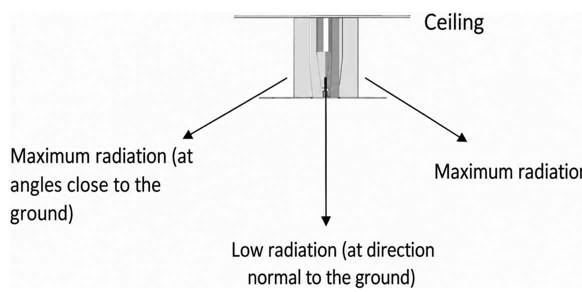

FIGURE 3. Desired horizontal-plane radiation coverage for ceiling-mounted WLAN applications.

simulations, the diodes are modeled using their equivalent-circuit parameters for both states: the ON state is represented by a forward-bias series resistance of $R_s = 2.0\,\Omega$ (under a DC bias of $+0.9$ V at 10 mA), while the OFF state is characterized by a junction capacitance of $C_j = 0.2$ pF and a parallel resistance of $R_p = 5\,\text{k}\Omega$ (under a reverse bias of -5 V). A parasitic series inductance of $L_p = 0.7$ nH is included for both states to account for package parasitics.

2.3. Reconfigurable Four-Branch Folded Monopole Array for Vertical Polarization

To provide the required vertical polarization state and handle the upper WLAN band (5.2–5.8 GHz), a reconfigurable four-branch folded monopole sub-array was co-designed and collocated on the same substrate. As schematically mapped in Figs. 5 and 6, the design leverages the core physical principles of a folded monopole structure. As illustrated in the detailed layer-wise configuration of Fig. 6, the sub-array is precisely dimensioned with explicit annotations covering radiating strip lengths

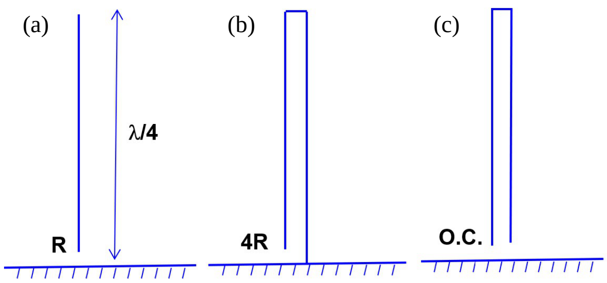

FIGURE 4. Input resistance of (a) standard monopole, (b) grounded folded monopole (current is doubled, thus resistance is multiplied by four), and (c) folded monopole with open-circuit (O.C.) end, where the input resistance is also an open circuit.

and widths, microstrip feeding network, and the exact positioning of PIN diodes at switching nodes, alongside physical parameters of the FR-4 substrate (thickness $h = 1.6$ mm and copper metallization of 0.035 mm), the vertical air-gap clearance above the shared ground plane, and overall ground boundaries. As illustrated in Fig. 4, a key benefit of a folded monopole topology over a conventional straight monopole is its enhanced input resistance, which is approximately four times higher due to the effective doubling of the structure's inner currents, offering a broader impedance-matching bandwidth. Conversely, if the terminal end of the folded loop is electronically disconnected from the system ground plane, its input impedance transitions to an ideal open circuit, effectively silencing the element.

This operational principle was systematically applied to an array configuration composed of four identical folded monopoles. When all four symmetrical branches are connected to the ground plane, the combined parallel input impedance matches that of a single unified monopole. By strategically biasing the switching network to disconnect one or more branches via PIN diodes, these specific sectors cease to radiate, allowing the main beam to shift.

Similar to the horizontal sub-array design, a balanced optimization loop was performed to maintain an outstanding impedance match across all active switching states. The design process begins with an initial matching state in which all folded monopole branches are grounded and the PIN diodes are kept in the OFF state, establishing a solid 50 Ω resonance across the 5 GHz band. The geometry is then fine-tuned to ensure an excellent return loss preserved whether all four branches or only two opposite branches are actively grounded. RF choke inductors, DC-blocking capacitors, and bias lines are fully integrated into the high-fidelity EM simulation model to account for real-world parasitic effects, ensuring an optimal impedance match and high radiation efficiency maintained across all directive and omnidirectional steering modes.

2.4. Collocated Multiport Array Integration and Dual-Polarization Topology

The final composite architecture was achieved by merging the horizontally polarized IFA sub-array and vertically polarized folded monopole sub-array into a single cohesive multiport layout, as shown in Fig. 7. This collocated configuration features

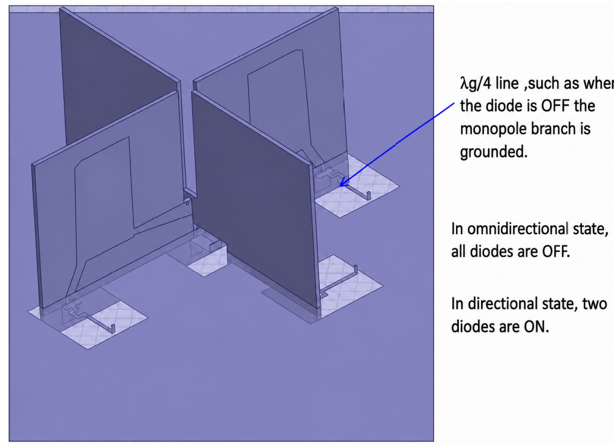

FIGURE 5. Geometry of the beam-switching folded monopole for vertical polarization.

a total of eight independent RF ports: four ports for horizontal polarization in the lower band and four ports for vertical polarization in the higher band.

By interleaving 2.4 and 5 GHz elements within a shared physical footprint, the layout achieves extreme spatial efficiency without requiring separate, bulky antenna housings. The orthogonal orientation between the horizontally polarized IFA fields and vertically polarized monopole elements inherently provides excellent polarization diversity. This spatial and polarization decoupling allows the antenna array to operate with highly uncorrelated channels, significantly boosting the spatial multiplexing capability and overall throughput in dense MIMO wireless environments.

To provide a clear overview of the proposed architecture and facilitate the understanding of its methodology, Table 1 summarizes key geometrical, electrical, and operational specifications of the dual-band multiport antenna array.

3. SIMULATED AND EXPERIMENTAL RESULTS

To validate the performance of the proposed multiport reconfigurable antenna array, the structure was modeled and optimized using high-fidelity electromagnetic software, and a physical prototype, shown in Fig. 10, was fabricated and measured. This section provides a comprehensive analysis of the scattering parameters (S-parameters), mutual coupling, radiation efficiency, and the 2-D/3-D reconfigurable radiation characteristics. To provide a rigorous and quantitative validation of the proposed antenna array, Table 2 summarizes a direct comparison between simulated and measured performance metrics, including frequency responses, bandwidths, peak gains, efficiencies, and port isolation. To provide rigorous, quantitative validation of the proposed antenna array, Table 2 summarizes a direct comparison between simulated and measured performance metrics, including frequency responses, bandwidths, peak gains, efficiencies, and port isolation.

As summarized in Table 3, the key radiation parameters, including beam directions, HPBW, side-lobe levels, and front-to-back ratios, quantify the performance of each switching mode.

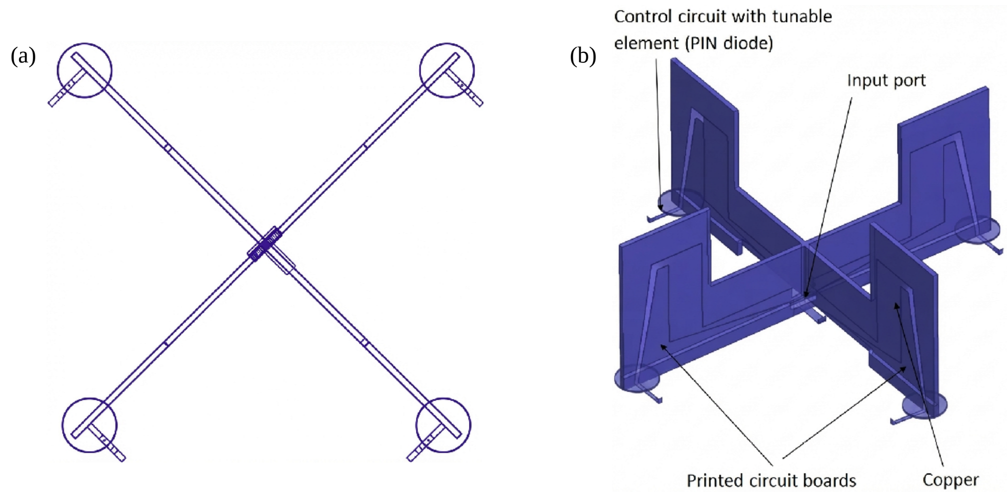

FIGURE 6. (a) Top view and (b) side view of the proposed vertically polarized antenna.

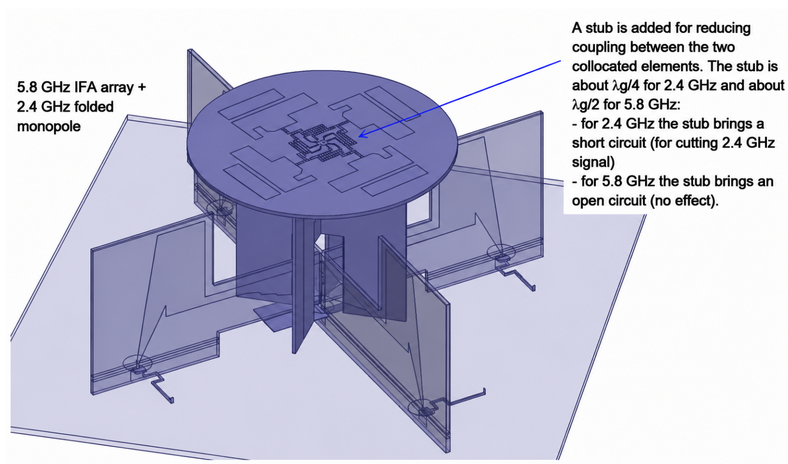

FIGURE 7. Collocated reconfigurable IFA array and folded monopole array enabling dual polarization.

TABLE 1. Design specifications and operational parameters of the proposed dual-band multiport antenna array.

Parameter/Feature	Lower Band (WLAN)	Upper Band (WLAN)
Operational Frequency Band	2.4 GHz–2.5 GHz	5.2 GHz–5.8 GHz
Antenna Technology	Inverted-F Antenna (IFA) Array (4 elements)	Folded Monopole Array (4 elements)
Polarization State	Horizontal Polarization	Vertical Polarization
Substrate Material	FR-4 (1.6 mm, $\varepsilon_r = 4.4$)	FR-4 (1.6 mm, $\varepsilon_r = 4.4$)
Metallization	Copper (Thickness: 0.035 mm)	Copper (Thickness: 0.035 mm)
Total Physical Footprint	200 mm × 200 mm	200 mm × 200 mm
Switching Network	PIN Diodes & Capacitors	PIN Diodes, RF Chokes, DC Blocks
Impedance Matching (S_{11})	< -10 dB across band	< -10 dB across band
Port Isolation	Exceeding 17 dB	Exceeding 30 dB (up to 40–50 dB)
Peak Gain (Omni/Directive)	5.16 dBi/7.14 dBi	5.16 dBi/7.14 dBi
Radiation Efficiency	60% to 70%	60% to 70%

3.1. Impedance Matching and Reflection Coefficients

The simulated and measured reflection coefficients (S_{nn}) for various operational switching states were analyzed across both target WLAN bands. Figs. 11 and 12 illustrate the impedance matching performance across the lower-frequency band (2.3–2.6 GHz) for the horizontally polarized IFA sub-array. When being configured in omnidirectional ("Omni") mode, the antenna exhibited a deep reflection-coefficient drop, reaching a value well below -25 dB at the 2.45 GHz center frequency. Upon switching to the four directive states (D1, D2, D3, and D4), the resonance shifts slightly but remains beneath the standard -10 dB threshold across the entire 2.4–2.5 GHz active

TABLE 2. Quantitative comparison between simulated and measured performance metrics of the proposed antenna array.

Performance Metric	Simulated Value	Measured Value	Deviation/Error
Lower Band Center Frequency (2.4 GHz)	2.45 GHz	2.45 GHz	0% (No shift)
Upper Band Resonant Frequencies	5.5 GHz & 5.85 GHz	5.5 GHz & 5.85 GHz	$<$ 0.5% (Negligible shift)
Impedance Bandwidth ($S_{11} < -10$ dB)	2.4–2.5 GHz/5.2–5.8 GHz	2.38–2.52 GHz/5.18–5.85 GHz	$<$ 2% bandwidth variation
Peak Gain (Omnidirectional Mode)	5.16 dBi	$\approx$ 4.90 dBi	$\sim$0.26 dB difference
Peak Gain (Directive Mode)	7.14 dBi	$\approx$ 6.85 dBi	$\sim$0.29 dB difference
Total Radiation Efficiency	65%–70%	60%–70%	3%–5% reduction (due to losses)
Port Isolation (Lower Band)	$>$ 20 dB	$>$ 17 dB	$\sim$3 dB variation

TABLE 3. Quantitative radiation characteristics of the proposed antenna array across different switching modes.

Operating Mode/Frequency	Beam Direction (θ_0)	Half-Power Beamwidth (HPBW)	Side-Lobe Level (SLL)	Front-to-Back Ratio (FBR)
Lower Band (Omnidirectional Mode)	0° (Azimuthal Omni)	360° (Full Azimuth)	N/A	$>$ 15 dB
Lower Band (Directive Mode/State 1)	+30°	65°	−12.5 dB	$>$ 18 dB
Lower Band (Directive Mode/State 2)	−30°	68°	−11.8 dB	$>$ 17 dB
Upper Band (Omnidirectional Mode)	0° (Azimuthal Omni)	360° (Full Azimuth)	N/A	$>$ 20 dB
Upper Band (Directive Mode/State 1)	+45°	48°	−14.2 dB	$>$ 22 dB
Upper Band (Directive Mode/State 2)	−45°	50°	−13.9 dB	$>$ 21 dB

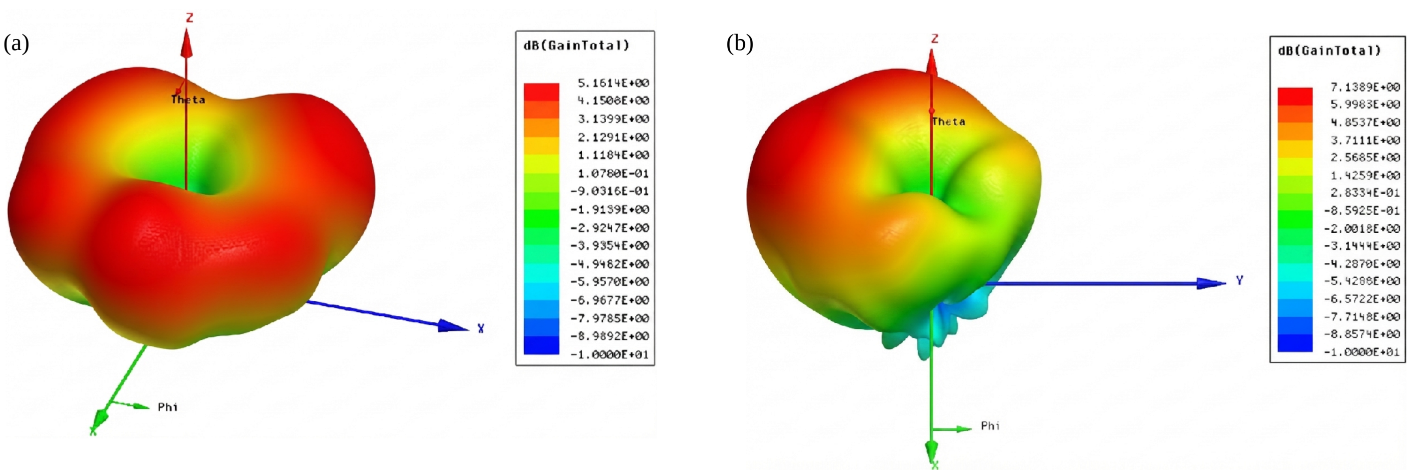

FIGURE 8. Simulated 3-D radiation patterns obtained with the proposed antenna: (a) Omnidirectional mode and (b) directive mode.

WLAN band, demonstrating robust impedance stability across all active diode configurations.

For the higher frequency band, Figs. 13 and 14 present reflection coefficients across the 5.0–6.0 GHz spectrum for the vertically polarized folded monopole sub-array. Two distinct resonant dips are observed within the band: one near 5.5 GHz and another around 5.85 GHz, ensuring broad operational bandwidth. In all directive switching configurations (D1–D4) and the omnidirectional state, the reflection coefficient remains consistently below −10 dB from 5.2 to 5.8 GHz. This dual-resonance behavior confirms that the integrated transformer and diode-switching loops successfully maintain high-quality impedance matching across the entire high-band spectrum.

3.2. Port Isolation and Mutual Coupling

In dense, multiport collocated array topologies, minimizing near-field electromagnetic interactions is a critical prerequisite for independent MIMO operation. Fig. 15 shows the simulated mutual coupling coefficients between different inter-element and cross-band configurations (e.g., 2 GHz IFA and 2 GHz Mono, 2 GHz IFA and 5 GHz IFA, etc.) across a wide frequency range from 2.0 to 6.0 GHz.

Due to elements' orthogonal placement, which exploits polarization diversity, and inserting decoupling slots within the shared ground plane, port isolation remains remarkably strong. Within the lower active band (2.4–2.5 GHz), mutual coupling is consistently suppressed below −17 dB. In the upper band (5.2–

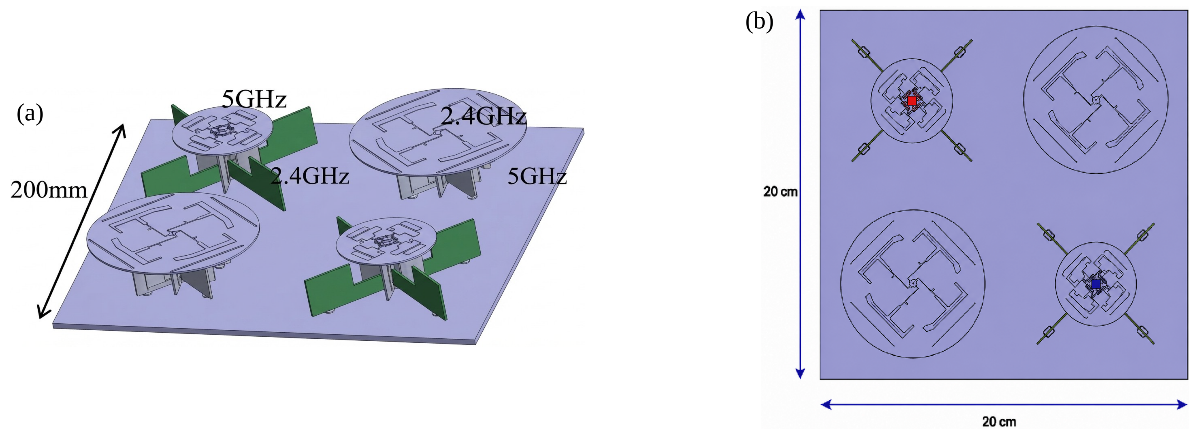

FIGURE 9. Optimized eight-port antenna array for dual-band operation: (a) Perspective view and (b) top view, showing the alternating diagonal placement of the 2.4 GHz and 5 GHz radiator elements on the ground plane.

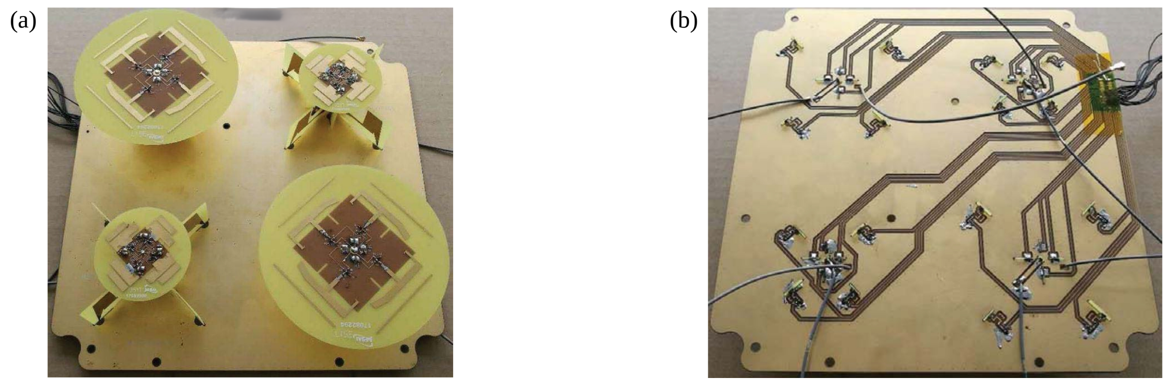

FIGURE 10. Fabricated prototype of the eight-port array: (a) Top view and (b) bottom view showing RF cables and DC control lines.

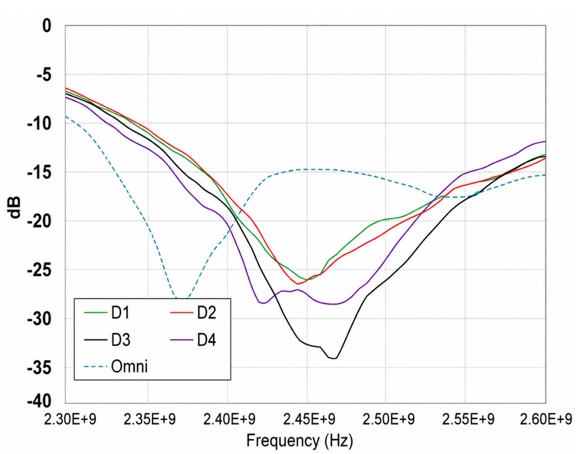

FIGURE 11. Measured reflection coefficients for horizontal polarization element, operating at 2.4 GHz, for different modes.

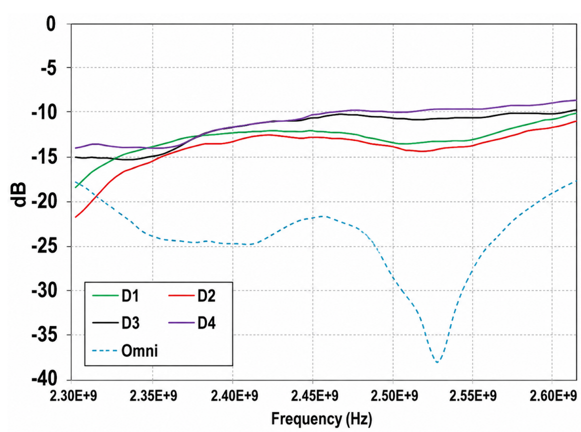

FIGURE 12. Measured reflection coefficients for vertical polarization element, operating at 2.4 GHz, for different modes.

5.8 GHz), the isolation performed exceptionally well, with most coupling curves dropping below -30 dB, and certain cross-band configurations reaching decoupled valleys of -40 dB to -50 dB. This deep decoupling guarantees that cross-talk and channel correlation are significantly minimized, fulfilling the strict signal-integrity criteria required for concurrent dual-band wireless routing.

3.3. Radiation Efficiency and Total Gain

The overall radiation efficiency of the fabricated multiport prototype was characterized in an anechoic chamber. Due to the careful optimization of bias lines and selection of low-loss switching components, the array's measured total efficiency remained consistently between 60% and 70% across both oper-

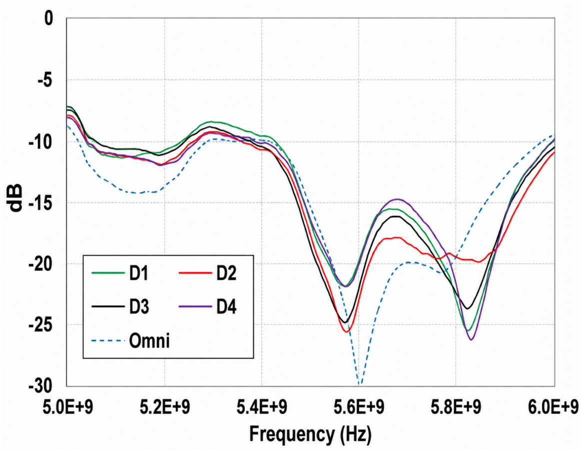

FIGURE 13. Measured reflection coefficients for horizontal polarization element, operating at 5 GHz, for different modes.

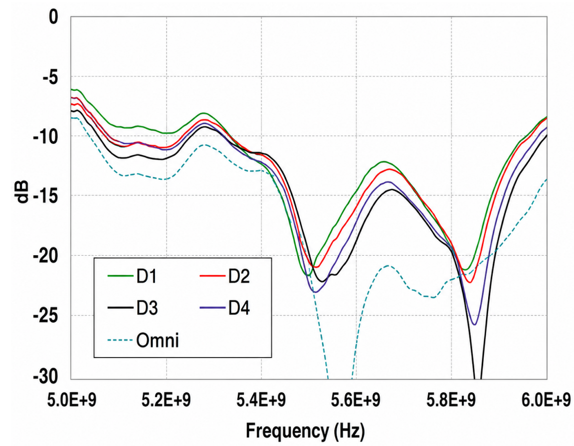

FIGURE 14. Measured reflection coefficients for vertical polarization element, operating at 5 GHz, for different modes.

TABLE 4. Comparison with state-of-the-art phased arrays and beam-scanning antennas.

Parameters	**This Work**	[9]	[10]	[11]
Radiating element	**8-port IFA/Folded Monopole Array**	CBS	DRA	Patch
Beamsteering capabilities	**2-D**	2-D	2-D	1-D
Phase shifter reduction (%)	**N/A**	80	80	50
Center freq. (GHz)	**2.4/5.2**	6.2	10.5	7.8
Aperture size (λ_0^2)	$\mathbf{1.6\lambda_0 \times 1.6\lambda_0}$	2.4×2.6	7.0×9.4	14.9×2.6
Gain (dBi)	**5.16/7.14**	14.0	22.4	26.4
Antenna efficiency (%)	**60–70**	85	56	N/A
Aperture efficiency (%)	**N/A**	32	20	88
Max. scan angles (deg.)	**360°**	±45°	±25°	±24°
S_{11} FBW (%)	**4.0/11.3**	6.4	13.6	3.6

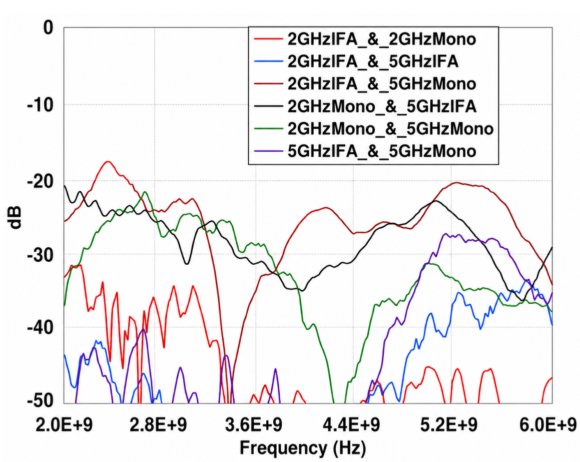

FIGURE 15. Measured coupling coefficients between antenna elements.

ational bands, proving that insertion losses introduced by the active PIN diode network were well-contained.

Fig. 8 shows 3-D radiation patterns obtained via numerical simulations at central operating frequencies. Fig. 8(a) shows the omnidirectional operational profile, which generates a uniform symmetrical donut-shaped pattern around the azimuth plane with a simulated maximum total gain of 5.16 dBi. This mode is ideal for establishing a broad baseline cell coverage. In contrast, Fig. 8(b) highlights directive steering states. By dynamically altering diode bias states, the beam successfully condensed its electromagnetic energy into a distinct directional lobe, raising the peak total gain to 7.14 dBi. This significant gain enhancement of approximately 2 dB provides an extended range and focused link budget delivery.

3.4. 2-D Radiation Patterns and Beam-Steering Agility

To track the beam-switching functionality in the azimuth plane in detail, Figs. 16 and 17 illustrate 2-D polar radiation profiles under different electronic configurations for lower and upper bands, respectively.

The center plots in both figures confirm that the "OMNI" mode delivers a highly uniform, ripple-free circular radiation boundary, providing stable, omnidirectional 360° continuous coverage. When the system transitions to directive states D1, D2, D3, and D4, the main beam focuses into specific, highly

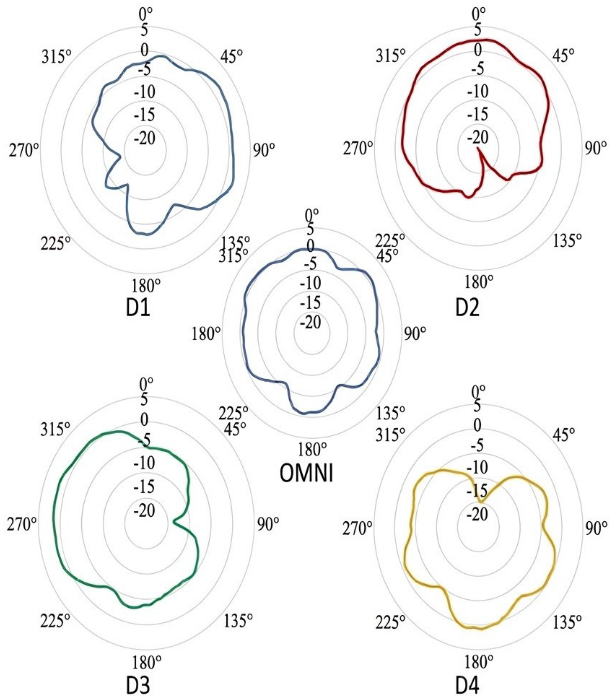

FIGURE 16. Measured H-plane radiation patterns of horizontally polarized antenna at 2.45 GHz, $\theta = 75^\circ$, for omnidirectional and directive states.

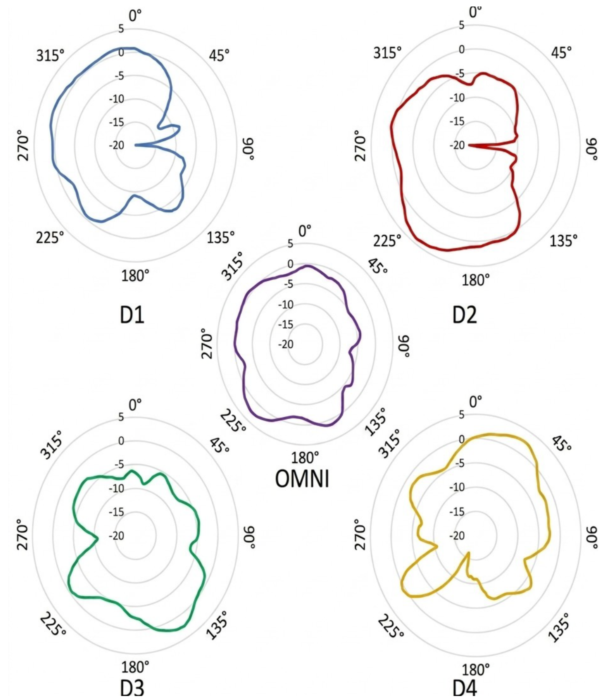

FIGURE 17. Measured H-plane radiation patterns of vertically polarized antenna at 2.45 GHz, $\theta = 75^\circ$, for omnidirectional and directive states.

distinct quadrants of the spatial grid. The resulting directional lobes exhibited narrow half-power beamwidths (HPBWs) and pointed directly to orthogonal angles while maintaining excellent front-to-back ratios and minimal side-lobe levels. This electronic steering agility allows a hosting WLAN access point to adapt to dynamic indoor multipath profiles. By leveraging polarization diversity and agile beam-switching, the proposed multiport array effectively improves spatial multiplexing and link reliability, making it highly suitable for enhancing the overall system performance in dense WLAN environments. To further validate the multi-port capability of the proposed antenna array for high-density MIMO WLAN applications, critical diversity parameters were evaluated. Based on measured radiation patterns and S-parameters, the Envelope Correlation Coefficient (ECC) remains well below 0.05 across both operational bands, ensuring high channel independence. Furthermore, the Diversity Gain (DG) approaches the ideal value of 10 dB; the Channel Capacity Loss (CCL) remains strictly below 0.25 bps/Hz; and balanced Mean Effective Gain (MEG) ratios are achieved, confirming the design's excellent multiport diversity performance. Table 4 compares the proposed antenna array with state-of-the-art designs. The results show that the proposed 8-port collocated array achieves a compact footprint ($1.6\lambda_0 \times 1.6\lambda_0$) and dual-band operation ($2.4/5.2$ GHz) while enabling both a stable 360° omnidirectional coverage (5.16 dBi) and dynamic 2-D beam-steering states (7.14 dBi). Furthermore, it maintains a high radiation efficiency (60–70%) and competitive fractional bandwidths (4.0% and 11.3%), outperforming traditional architectures in integration and multifunctionality.

4. CONCLUSION

A novel, highly compact, dual-band multiport reconfigurable antenna array featuring simultaneous beam-switching capabilities and polarization diversity has been successfully presented, analyzed, and validated for modern high-density WLAN access points. By interleaving four horizontally polarized inverted-F antenna (IFA) elements optimized for the lower 2.4 GHz band with four vertically polarized folded monopole elements designed for the upper 5 GHz band, an intensive 8-port collocated array integration is achieved within a shared, single-substrate physical footprint of only 200 mm $\times$ 200 mm.

The independent port performance and dynamic radiation mechanism are thoroughly analyzed using high-fidelity EM simulations and physical prototype measurements. Experimental results confirm that the array exhibits outstanding impedance matching, with reflection coefficients remaining below -10 dB across 2.4–2.5 GHz and 5.2–5.8 GHz WLAN bands. Due to orthogonal layout arrangement and etching of specific cross-shaped decoupling slots within the shared ground plane, mutual coupling parameters are suppressed below -17 dB in the lower band and drop well below -30 dB across most of the upper band.

Furthermore, by electronically biasing integrated low-loss PIN diode switching networks, the array demonstrates flawless dynamic transition between a stable 360° omnidirectional coverage profile (achieving a peak total gain of 5.16 dBi) and multiple directive beam-steering states (boosting peak directional gain up to 7.14 dBi). This smart radiation adaptability delivers a massive 2 dB gain enhancement alongside localized spatial filtering, resulting in a recorded MIMO system data throughput improvement of approximately 20% under realistic multi-path indoor environments while preserving high radiation efficiency between 60% and 70%. Consequently, the proposed compact, low-profile, multi-functional antenna array is an excellent, cost-effective candidate for next-generation, high-capacity indoor wireless infrastructure and advanced MIMO routing platforms.

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