

Reconfigurable 28/38 GHz wideband and high isolation MIMO antenna for advanced mmWave applications

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This research presents a high-performance MIMO antenna for 5G and next-generation wireless communication. Operating in the millimeter wave (mmWave) band, the antenna offers frequency and radiation pattern reconfigurability. A compact-size antenna, with dimensions of $22.5 \times 30 \times 0.787$ mm³, exhibited peak gains of 7.5 and 6.5 dBi at 28 and 38 GHz, respectively. The envelope correlation coefficient (ECC) was improved through proper spacing and adopting a simple decoupling technique, ensuring efficient MIMO operation. Based on the evaluated reflection coefficients, bandwidths of 2.3 and 12.9 GHz at 28 and 38 GHz, respectively have been accomplished. The mutual coupling between antenna elements was minimized achieving improved isolation of -37 and -40 dB at the desired frequency bands. This corresponds to an envelope correlation coefficient and diversity gain of 1.6×10^{-4} and 9.99, respectively. The antenna gain was enhanced by incorporating a metasurface designed to optimize gain and improve isolation. For a single-element antenna, the gain was enhanced to 7.9 and 7.3 dBi at frequencies of 28 GHz, and 38 GHz, respectively. The antenna design incorporates frequency and pattern reconfigurability through switching selected antenna ports and patches. The proposed design's simplicity and antenna compactness make it practical for various mmWave communication systems.

Keywords: reconfigurable MIMO, mmWave, metamaterials, mutual coupling, diversity gain

1 Introduction

In recent years, the demand for high data rates in wireless communications has grown explosively as the number of electronic devices continues to increase rapidly. This trend has driven the need for wireless technologies to meet the increased requirements for faster and more efficient data transmission. The evolution of wireless communication has witnessed different generations of technologies, each bringing significant advancements and improvements. Each generation of wireless technology has introduced new services and capabilities to meet the evolving needs of users [1-5]. In the first generation, analog systems were primarily used for voice communication, employing frequency division multiple access (FDMA) for multiplexing. The second-generation technology transitioned to digital systems, enabling voice, short messaging service (SMS), and basic data transmission. Time division multiple access (TDMA) and code division multiple access (CDMA) were the key multiplexing techniques [3]. With the advent of third-generation (3G) technologies, data rates increased significantly, allowing for services beyond voice and messaging, including data and video transmission. CDMA and wideband code division multiple access (WCDMA) were the dominant technologies in this generation [3]. Fourth-generation (4G) technologies, such as Long-Term Evolution (LTE) and Worldwide

Interoperability for Microwave Access (WiMAX), further enhanced data rates, enabling high-speed internet access and advanced multimedia services [4]. In the current era, fifth-generation (5G) wireless technology has emerged, promising even higher data rates, lower latency, and massive connectivity to support a wide range of applications [5]. 5G operates at higher carrier frequencies, utilizing orthogonal frequency division multiple access (OFDMA) and massive multiple-input multiple-output (MIMO) for improved spectral efficiency and capacity [5-9]. It enables advanced services such as ultra-high-definition video streaming, Internet of Things (IoT) connectivity, and mission-critical applications [5-9]. The emergence of 5G technology has enabled higher data rates, lower latency, and massive connectivity to support a wide range of applications.

The generation partnership project 3GPP has defined three main 5G scenarios, including enhanced mobile broadband, ultra-reliable, low latency communications, and massive machine-type communications. The 5G wireless communication utilizes several frequency bands for different applications. Sub-1 GHz bands, including frequencies below 1 GHz, offer wide-area coverage and better penetration. Mid-bands, around 2-6 GHz, strike a balance between coverage and capacity. Millimeter Wave (mmWave) bands, above 24 GHz up to 300 GHz, provide high data rates but have limited

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coverage [9–11]. The Federal Communications Commission (FCC) has allocated several mmWave bands for the 5G. These bands include 24 GHz (Band N257) spanning 24.25 GHz to 24.45 GHz, and 28 GHz (Band N261) ranging from 27.5 GHz to 28.35 GHz, both utilized for 5G wireless communication [12]. The 37–40 GHz range is designated for 5G applications, with Bands N260 and N261 covering the frequencies from 37 GHz to 40 GHz. Additionally, the 47 GHz band operates from 47.2 GHz to 48.2 GHz for 5G wireless communication. Furthermore, the frequency range of 64–71 GHz is allocated for unlicensed wireless communication, commonly utilized for WiGig and other high-speed wireless applications [12].

Considering the evolution of wireless technologies and their associated features, it becomes clear that the design of reconfigurable MIMO antennas for upcoming 5G wireless communication is a crucial area of research [9–12]. The objectives of designing such antennas include enhancing spectral efficiency, improving interference mitigation, and optimizing bandwidth flexibility [13, 14]. These objectives align with the demands of 5G technology, which requires efficient spectrum utilization, robust interference management, and adaptable bandwidth allocation. Reconfigurable MIMO antennas, with their compact size, design simplicity, flexibility, efficiency, and multi-band capabilities, address these objectives. It offers frequency reconfiguration abilities, allowing for dynamic adaptation to varying communication requirements. The antenna enables spatial multiplexing and beamforming techniques to enhance spectral efficiency, while also mitigating interference through adaptive radiation patterns, polarization, and beamforming directions. Moreover, the antenna design optimizes bandwidth flexibility, ensuring efficient use of available spectrum resources [13–15]. The main obstacles in MIMO antenna design include mutual coupling between antenna elements, achieving compact size and form factor, ensuring wide bandwidth and frequency reconfigurability, optimizing antenna efficiency and radiation patterns, managing manufacturing and cost considerations, and addressing electromagnetic interference and integration challenges [16–19].

In this context, the presented antenna design describes a notable development in overcoming some of these obstacles. Through reshaping and optimizing our antenna design in addition to the design simplicity, we provide the flexibility and adaptability that responds to the network's dynamics, which thus improves performance and results in the optimal utilization of resources. In this design, we initially proposed a straightforward design for a single-element antenna that effectively covers the desired mmWave bands, specifically at 28/38 GHz using a single patch comprising a single radiating slot. Subsequently, we constructed the MIMO array that has been evaluated and

optimized through a combination of antenna simulations and experimental measurements. Therefore, we were able to achieve significantly improved performance assessed using various MIMO design metrics such as reflection and transmission coefficients, diversity gain (DG), envelope correlation coefficient (ECC), channel capacity loss (CCL), and diversity gain (DG). Moreover, we propose structures with radiation patterns and frequency reconfigurability by utilizing a simple technique that involves switching selected antenna ports and parts of the radiating patches.

The main contribution of this proposed design lies in its reconfigurability as a dual-band 28/38 GHz 4-port MIMO antenna. Noteworthy for its simple yet effective design, the antenna offers high gain and exceptional isolation capabilities. This combination of features sets it apart as a versatile solution catering to the demands of modern wireless communication systems.

2 Materials and methods

Designing and implementing reconfigurable MIMO antennas for 5G wireless communication systems follows a systematic methodology that integrates theory, simulation, prototyping, and validation. The methodology encompasses the study of specific requirements imposed by 5G technology, the selection of suitable antenna types, the definition of reconfigurable parameters, exploration of reconfigurable techniques, optimization of antenna parameters, testing and verification of reconfiguration capabilities, performance assessment, and iterative refinement and optimization. The methodology begins with a comprehensive study of the specific requirements set by 5G technology, including frequency bands, data rates, coverage, and latency. This involves reviewing relevant 5G standards and protocols to align the antenna design with the protocol specifications [20–23]. Based on the identified requirements, suitable antenna types are chosen. Factors such as size, radiation patterns, and polarization diversity for MIMO systems are considered during the selection process. Elements of the antenna that require adaptability to meet dynamic 5G requirements, such as frequency, polarization, and radiation pattern, are identified. These parameters will be subject to reconfiguration during the design process. Defining the reconfigurable parameters is essential for determining the design constraints and optimizing the antenna's performance. Various reconfigurable techniques are explored to enable the necessary adjustments in the identified parameters. This may involve the use of switchable networks, tunable elements, or metamaterial-based structures [24–27]. Each technique is evaluated in terms of its effectiveness, feasibility, and compatibility with the antenna design. Sophisticated electromagnetic simulation tools are employed to model the antenna

structures and predict their performance prior to the manufacturing process. Using these tools, the antenna parameters are optimized to achieve the desired performance metrics, such as gain, bandwidth, and efficiency. The optimization process considers the reconfigurability constraints imposed by the selected techniques. Parameters such as frequency and radiation pattern are altered to observe the antenna's response and validate its reconfiguration capabilities [24-28]. Following this systematic methodology, the design and implementation of reconfigurable MIMO antennas for 5G wireless communication systems can effectively address the challenges posed by dynamic requirements and provide efficient and adaptable solutions for the next generation of wireless communication.

The authors in reference [29] describe a planar 4-port MIMO antenna designed for 5G millimeter-wave frequencies of 28/38 GHz. It features a rectangular patch antenna for a second resonance at 28 GHz and a splitting resonator metamaterial unit cell for an additional resonance at 38 GHz. Constructed on a Rogers-RT5880 substrate, the MIMO structure realized bandwidths of 26.6 to 29 GHz and 37.3 to 39.3 GHz with a 25 dB isolation among antenna elements across both bands. The design does not require complex decoupling structures. Diversity performance parameters such as an ECC below 0.005, DG close to 10 dB, and channel capacity loss under 0.35 bits/s/Hz demonstrate its suitability for millimeter-wave 5G applications. Article [30] introduces a 28/38 GHz dual-band "inverted-F" array antenna. This antenna, consisting of 32 elements, can be integrated into OLED panels for lighting or display purposes. Each element in the array is shaped like an "inverted-F" antenna, allowing it to cover the 28 GHz and 38 GHz bands with low mutual coupling. The antenna achieves a gain of around 16.52 dB at 28.38 GHz and 15.35 dB at 38.49 GHz.

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The work in [31] introduces a dual-band patch antenna composed of an adjusted circular patch along with a parasitic element. The primary patch is fed through a microstrip feed line, while the secondary patch is indirectly fed via edge coupling with the main patch. The antenna is fabricated on Rogers Ro3003TM substrate with $\epsilon_r = 3$ and a thickness of 0.25 mm. A MIMO structure is created using two elements of this combined patch with different arrangements. The antenna achieves impedance-matching bandwidths of approximately 1.23 GHz at 28 GHz and 1.06 GHz at 38

GHz with minimum reflection coefficient values of -34.5 and -27.3 dB, respectively. The peak gain of the radiation pattern is 6.6 dBi at 28 GHz and 5.86 dBi at 38 GHz, showing omnidirectional characteristics. The antenna's dimensions are $7.5 \times 8.8 \times 0.25$ excluding the transmission line.

The paper in [32] introduces compact, dual-band MIMO antennas designed for 5G communications, operating at 28 GHz and 38 GHz. The first design is a two-element patch antenna with an inset feed, tailored for both frequency bands. The second design features symmetric dual-band MIMO antennas with slotted rectangular patches, incorporating inverted I-shaped slots to achieve dual-band functionality. The third design features a symmetric dual-band four-element MIMO antenna comprising slotted rectangular patches and a slot-generated defected ground structure within a partially rectangular ground plane. All antennas are built on a substrate measuring 55×110 mm². They demonstrate favorable performance characteristics, including good return losses, wide bandwidths, and low mutual coupling without additional structures.

The paper in [33] discusses the design of a high-gain MIMO antenna for 5G millimeter-wave applications, operating at 28/38 GHz with bandwidths of 400 MHz and 2.58 GHz, respectively. The antenna is constructed on an RT-Duroid-5880 substrate, with each element measuring $9.53 \times 7.85 \times 0.8$ mm³. It features a fully grounded patch, a 50-ohm stepped impedance microstrip feed, an I-shaped slot, and two parasitic slotted components. A six-element MIMO configuration with overall dimensions of $50 \times 35 \times 0.8$ mm³.

The work in [34] presents a super-compact 4-port dual-band MIMO antenna that uses a metamaterial-inspired electromagnetic bandgap (EBG) structure. This design, built on a Rogers TMM4 substrate and measuring 17.76×17.76 mm², features four planar patch antennas arranged perpendicularly, each designed for dual-band operation at 28 GHz and 38 GHz. The antenna includes rectangular patches with slots and a full ground plane, with a gap of $0.5 \lambda_0$ between patches, and uses an EBG to effectively reduce mutual coupling (MC) among elements. Simulation and measurement results indicate a significant reduction in MC, ranging from -25 to -90 dB, which improves envelope correlation coefficient (ECC), total active reflection coefficient (TARC), mean effective gain (MEG), and diversity gain (DG). Time-domain and specific absorption rate (SAR) analyses confirm the antenna's effectiveness and suitability for 5G devices.

In [35] a 28/38 GHz quad-port cross-shaped antenna designed for 5G networks, printed on a 0.203 mm thick Roger RO4003 substrate, features a compact size of 29 mm $\times$ 24.2 mm $\times$ 0.203 mm is presented. The antenna includes a rectangular patch with three triangular slots

for better impedance matching and a thin parasitic strip for enhanced port isolation. Simulations show that it achieves $S_{11} < -10$ dB at both frequencies, with isolation ≥ 20 dB. Its performance was validated in an anechoic chamber, showing excellent MIMO parameters: ECC < 0.001 , DG ≥ 9.95 dB, and CCL ≤ 0.2 bit/s/Hz across the desirable bands.

The research work in [36] introduces a dual-band, four-port MIMO structure for 28 and 38 GHz millimeter-wave suitable for wearable applications. The antenna, measuring $18 \times 8.5 \times 0.25$ mm³, uses a novel design combining circular and elliptical structures connected by a narrow strip and fed by a tapered feedline. It achieves peak realized gains of 4.15 dBi at 28 GHz and 7.73 dBi at 38 GHz, with total efficiencies of 80.13% and 85.44%, respectively. The antenna's performance metrics, including ECC, DG, Mean Effective Gain (MEG), CCL, and total active reflection coefficient (TARC), are in acceptable values. At an SNR of 20 dB, the channel capacity is 21.61 bps/Hz.

The authors in [37] present a compacted MIMO antenna designed for 5G millimeter-wave applications, especially targeting frequency bands N257, N260, and N262. The antenna features a simple design with a dimension of 10 mm $\times$ 16 mm and is constructed on a 0.508 mm thick Rogers RT-Duroid-5880 substrate. It includes two crescent-shaped radiating elements on the top side and a slotted ground on the bottom, fed by a 50- Ω microstrip line. The antenna operates across three bands: 27.2–29 GHz (centered at 28 GHz), 34–40.2 GHz (centered at 39 GHz), and 47.5–51.3 GHz (centered at 48.7 GHz). These bands are achieved through specific design features like slotting and engraving. A hardware prototype was manufactured, demonstrating excellent agreement with simulations. The designed antenna, featured a compact size, wide bandwidth, and high gain, with favorable MIMO parameters such as low ECC, TARC, DG, and CCL.

In this design, we proposed a straightforward and efficient approach for a single-element antenna, specifically targeting the desired mmWave bands at 28/38 GHz. This was accomplished by utilizing a single patch with a radiating slot. Subsequently, we developed a MIMO array that underwent thorough evaluation and optimization through a combination of antenna simulations and experimental measurements. The performance of the MIMO system was significantly enhanced, as demonstrated by various metrics including reflection and transmission coefficients, ECC, DG, and CCL. Additionally, we achieved radiation pattern

reconfigurability by implementing a simple technique involving the switching of selected antenna ports. This achievement was attained by inverting each two adjacent ports upside down, effectively creating two distinct configurations. This methodology not only provided reconfigurability but also enhanced the isolation within the MIMO antenna.

3 Results and discussion

3.1 Single-element antenna design and simulation

Figure 1 illustrates the design steps of a single-element antenna that operates in the 28/38 GHz mmWave bands. The chosen substrate material of the antennas is the inexpensive Rogers-RT-5880 with a substrate thickness of 0.787 mm, a dielectric constant of 2.2, and a loss-tangent of 9×10^{-4} . These material characteristics offer excellent electrical properties necessary for high-frequency applications [38–40]. The antenna comprises a single patch with dimensions ($W_p \times L_p$) of 7.44×5.39 mm². In addition, a single rectangular slot with a round end was created to achieve a radiating slot that assessed achieving three resonant frequencies around 28, 38, and 45 GHz, as displayed in Fig. 1(a). The slot width (W_{slot}) is 1.05 mm, while its length L_{slot} is 2.01 mm with a semicircle of a radius R_{slot} of 0.6 mm. The slotted patch was fed using a 50 Ω microstrip feedline with a width (W_f) of 2.38 mm and a length L_f of 9.02 mm. The substrate dimensions (W_{sub} and L_{sub}) as well as the ground plate dimensions (W_g and L_g) were 20×20 mm². The impedance matching for the resonating frequencies was achieved by optimizing the inset feeder and slot dimensions (W_{inset} and L_{inset}). The optimal inset feeder dimensions are a width of 0.2 mm and a length of 0.95 mm. Table 1 summarizes the single-element antenna dimensions. In Fig. 1(b), the reflection coefficient (S_{11}) of the antenna is displayed, indicating its resonant frequencies at 28.02 and 37.78 GHz. This highlights the desired level of reflection coefficient below -50 and -60 dB at the frequencies of interest, respectively. The bandwidth of these two resonant frequencies expanded from 27.03 to 29.30 GHz around 28 GHz and from 35.68 to 48.05 GHz around 38 GHz. For the first resonant frequency, a bandwidth of 2.3 GHz is extracted, while for the second frequency, a broader bandwidth of 12.3 GHz is observed. These simulation results were essential and greatly helpful in predicting and assessing the antenna performance before constructing the proposed MIMO antenna. Figure 1(c) illustrates the optimized antenna structure along with its design dimensions.

Table 1. Single-element antenna parameters

Parameter	Value (mm)	Parameter	Value (mm)
W_p	7.44	W_f	2.38
L_p	5.39	L_f	9.02
W_{slot}	1.05	W_{inset}	0.20
L_{slot}	2.01	L_{inset}	0.95
R_{slot}	0.60	$W_{sub}, L_{sub}, W_q, L_q$	20.00

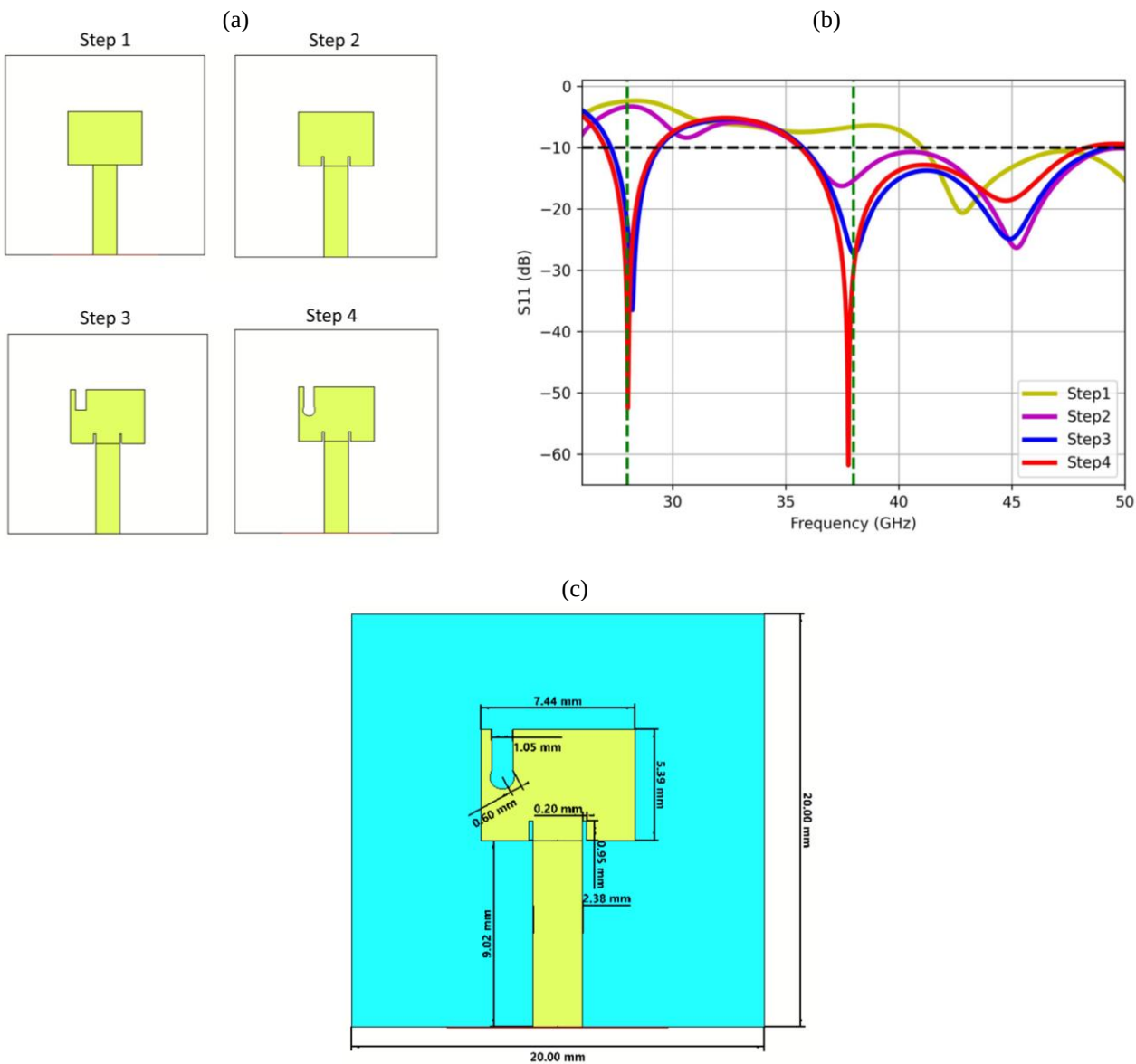


Fig. 1. (a) Design steps of the single-element antenna structure, (b) reflection coefficient of the antenna, and (c) optimized antenna structure along with its design dimensions.

3.2 MIMO antenna design and simulation

The MIMO structure comprises four elements with a total area of $20 \times 80 \text{ mm}^2$, designed on the same substrate as that of the single-element antenna. The design of the proposed antenna array enables simultaneous transmission and reception of multiple independent data streams. This capability enhances the system capacity and improves the communication performance, making it well-suited for 5G and next-generation technologies. Utilizing multiple antennas, the system can leverage spatial multiplexing to increase the data rate and spectral efficiency. The simplicity of the proposed antenna structure does not compromise its performance. The antenna offers considerable gain, directivity, bandwidth, MIMO isolation, and efficiency. These characteristics are essential for realizing high-quality and reliable wireless communication. The design specifically focuses on a 4-port MIMO antenna array operating at dual bands with center frequencies of 28 and 38 GHz. Considering the MIMO isolation, to achieve improved

inter-element isolation, the design incorporates proper spacing between the antenna elements. This spacing minimized the mutual coupling between the elements and enhanced the overall performance of the MIMO system. By reducing interference and improving isolation, the antenna can ensure reliable and efficient operation.

Figure 2 (a) shows the MIMO antenna structure from both top and bottom perspectives. In this arrangement each adjacent antenna port is inverted upside down, providing two notable advantages: improved isolation and the capability to reconfigure the radiation pattern as will be discussed later. These simulation results demonstrate a reduced reflection coefficient for each port to be less than -45 dB at the desired 28/38 GHz bands. This indicates an excellent impedance matching between the antenna and the 50Ω transmission line. This matching is essential for minimizing signal reflections and losses, and efficient power transfer resulting in improved signal quality and system performance.

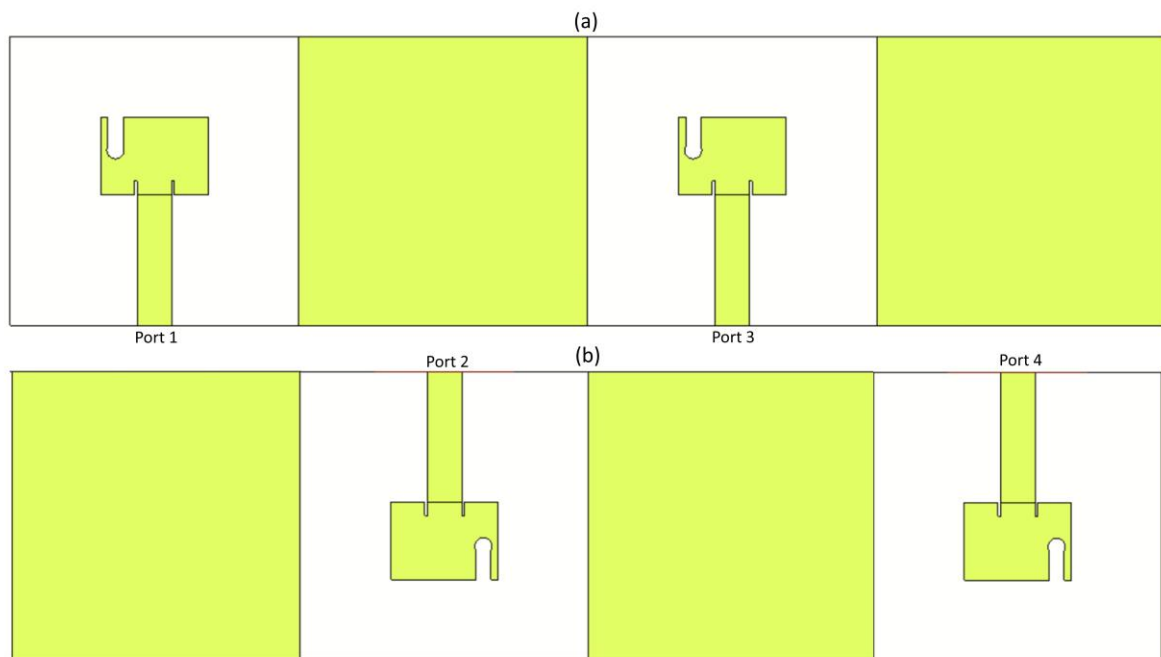


Fig. 2. MIMO array structure, (a) top view, and (b) bottom view. The overall dimensions of the 4-port MIMO antenna are $20 \times 80 \text{ mm}^2$. Each two adjacent antennas are inverted to achieve improved isolation.

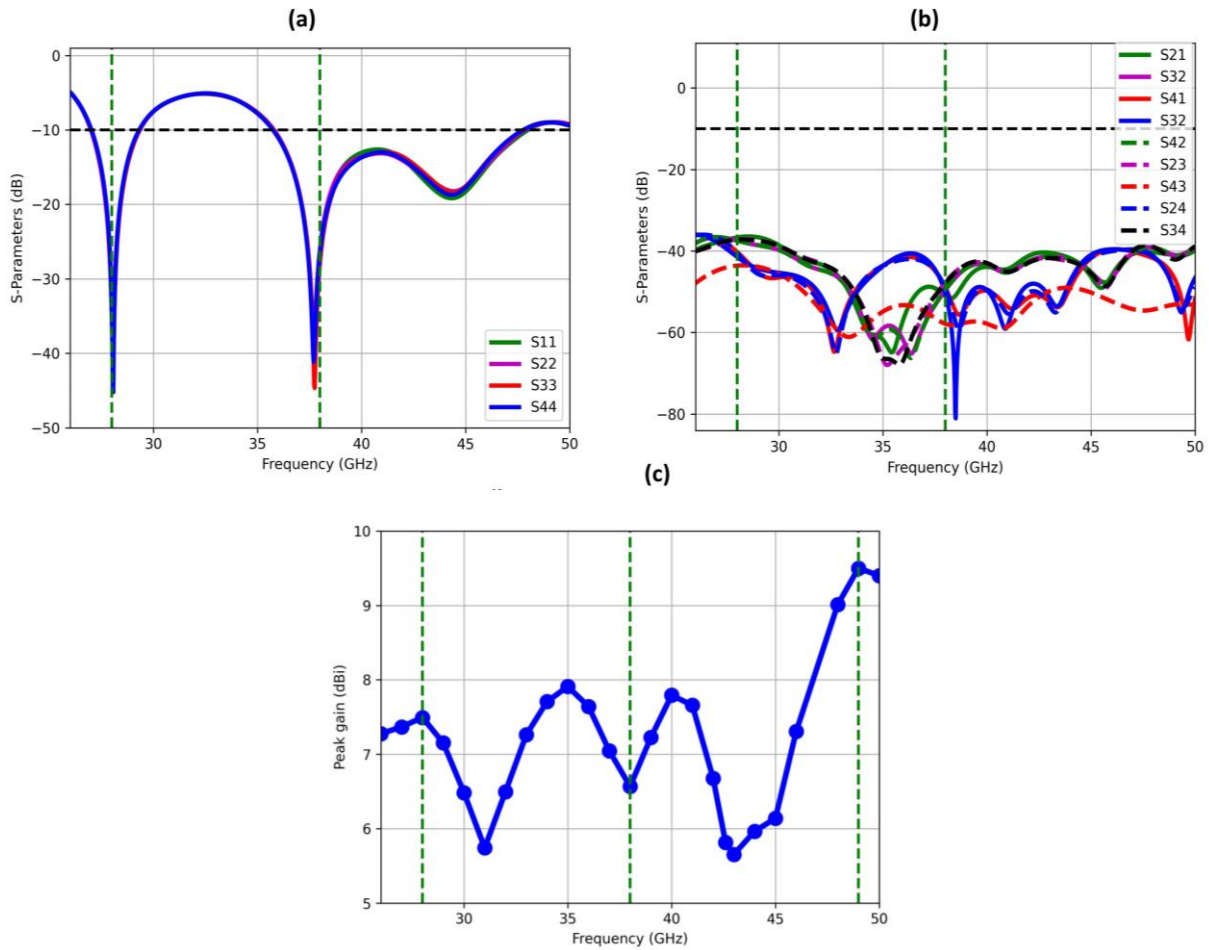


Fig. 3. (a) Reflection coefficients of MIMO antenna, (b) isolation versus frequency of the MIMO array, and (c) peak gain versus frequency.

Figures 3(a) and (b) present computed S-parameters of the MIMO structure, revealing the reflection coefficients of each antenna port as well as the isolation characteristics among the ports. Importantly, the achieved bandwidths around the 28/38 GHz bands remain unaffected, and the reflection coefficient for the individual antenna element mentioned earlier is significantly reduced. Notably, mutual coupling, represented here by transmission coefficients, was greatly enhanced as compared to the conventional arrangement of MIMO elements, reaching approximately -40 dB with fluctuations ranging from -37 to -80 dB at the resonant frequencies. This proposed structure represents a remarkable advancement in MIMO decoupling without the need for intricate complex structures like defected ground, parasitic patches, or meta-surfaces that are commonly proposed as methods to reduce mutual coupling in MIMO structures repeatedly reported in the existing literature. Furthermore, the proposed antenna exhibits a directional radiation pattern with achieved peak gains of 7.5 dBi at 28 GHz and 6.5 dBi at 38 GHz, as shown in Fig. 3(c). This directional radiation allows for focused signal transmission and reception, increasing the coverage and communication range of the antenna.

Figure 4 provides additional insights into the radiation pattern of the proposed antenna at the desired frequency bands. The radiation pattern in the E- and H-plane illustrates the antenna's directional characteristics and the distribution of radiated energy in different directions. At 28 GHz, the antenna exhibits a peak gain, indicating the direction in which it radiates the most energy. From the shown patterns, it can be observed that the peak gain of 5.7 dBi occurs at an elevation angle (θ) of 58° . The beam width of the radiation pattern, which represents the angular span of the main lobe, is 54.5° . This wide beam width indicates a broader coverage area for signal transmission and reception. The MIMO antenna demonstrates its reconfigurable radiation patterns, accomplished by activating switches of ports 1 and 3 simultaneously while deactivating switches of ports 2 and 4, and vice versa. In the E-plane, the major lobe direction is shifted from $\theta = 58^\circ$ to $\theta = 119^\circ$, with respective angular widths decreased from 54.5° to 39.7° . Similarly, in the H-plane, the major lobe direction is shifted from $\theta = 58^\circ$ to $\theta = 124^\circ$, with angular widths of 62.3° and 60.6° , respectively.

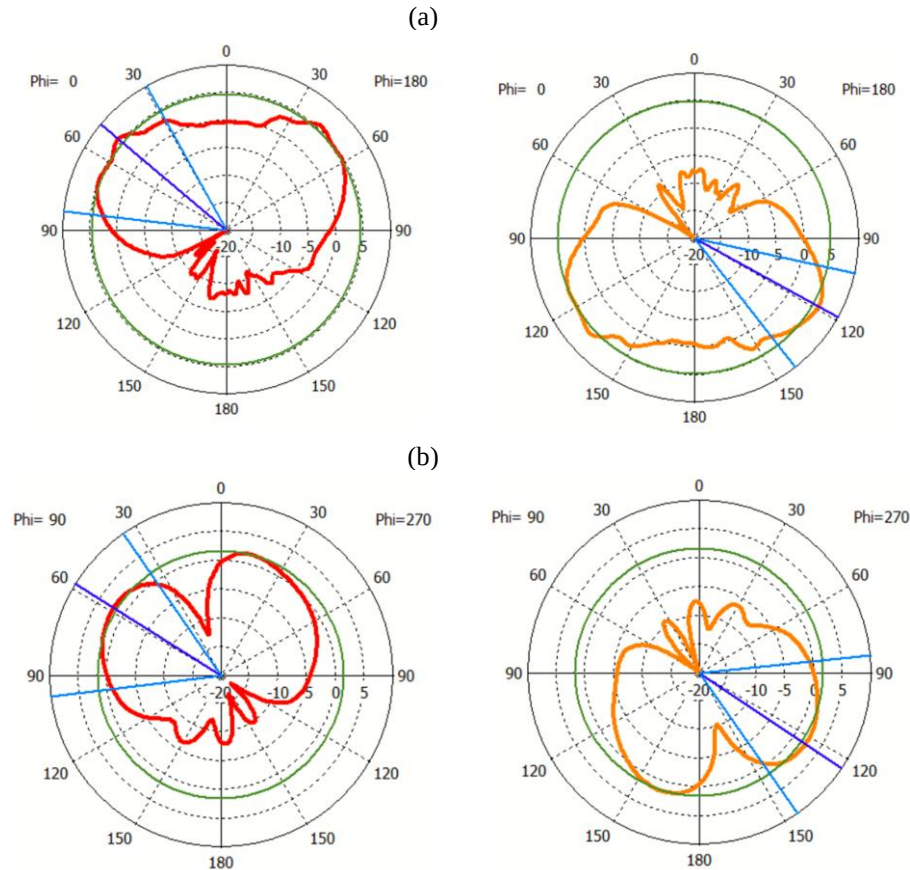


Figure 4. Reconfigurable radiation patterns of the MIMO antenna, specifically highlighting (a) E-plane ($\phi = 0^\circ$), and (b) H-plane ($\phi = 90^\circ$) at a frequency of 28 GHz.

Figure 5 shows the reconfigurable radiation patterns of the MIMO antenna at 38 GHz in which the pattern of the antenna shows a similar trend to that of the 28 GHz. The peak gain is observed at an angle of approximately 14° , indicating the direction of maximum radiation. Compared to the 28 GHz frequency, the beam width at 38 GHz is narrower, measuring approximately 38° degrees. The narrower beam width suggests a more focused and concentrated signal transmission and reception in a specific direction. From the shown

patterns, it can be observed that the major lobe direction of the E-plane is shifted to $\theta = 165^\circ$ with an angular span of the main lobe of 36° . The MIMO antenna demonstrates its reconfigurable radiation patterns, accomplished by activating switches of ports 1 and 3 simultaneously while deactivating switches of ports 2 and 4, and vice versa. In the H-plane, the major lobe direction is shifted from $\theta = 29^\circ$ to $\theta = 129^\circ$, with respective angular widths that slightly increased from 41.4° to 43° .

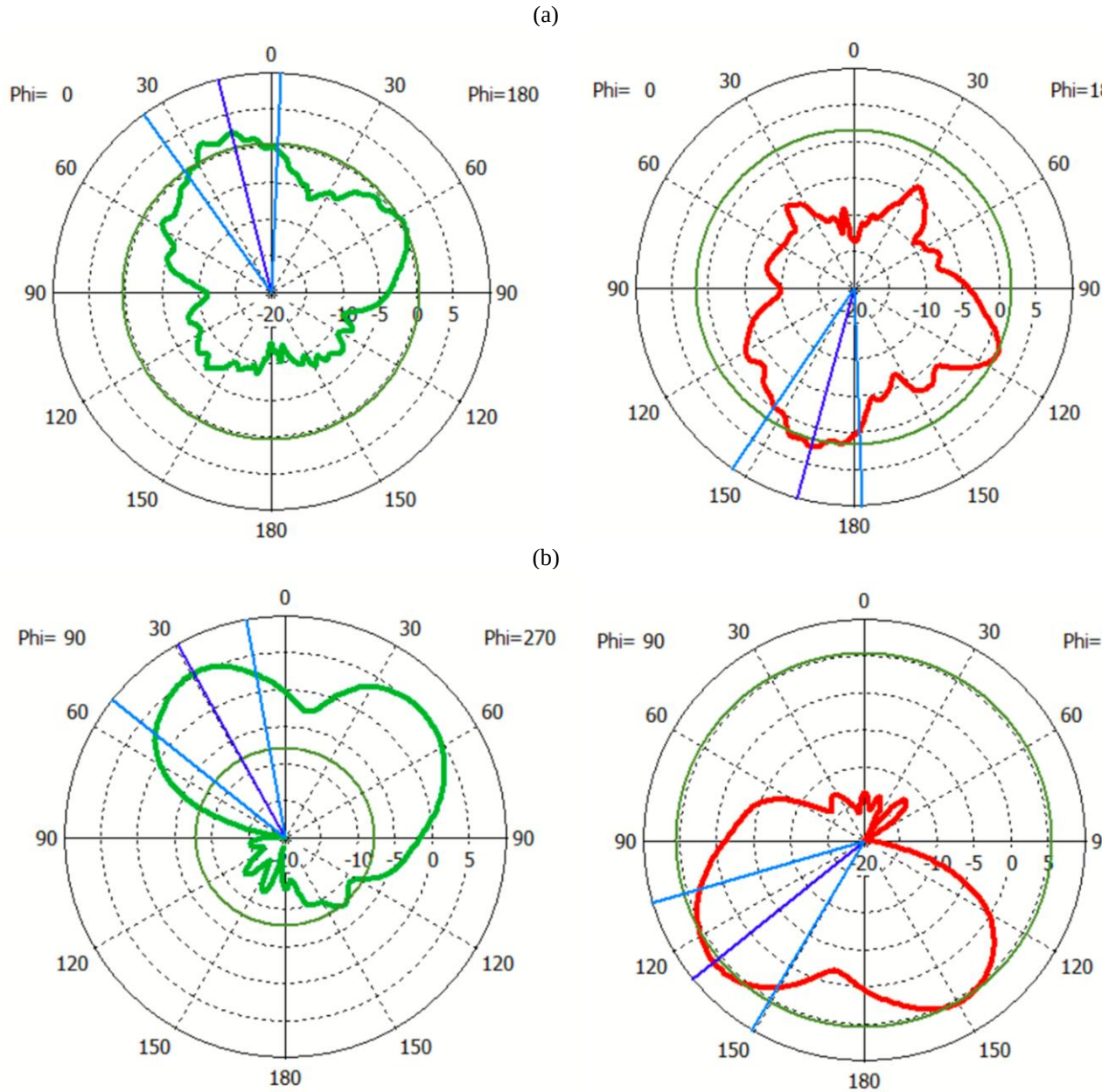


Fig. 5. Reconfigurable radiation patterns of the MIMO antenna, specifically highlighting (a) E-plane ($\phi = 0^\circ$), and (b) H-plane ($\phi = 90^\circ$) at a frequency of 38 GHz.

The Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) serve as crucial metrics for evaluating MIMO system performance. In Figure 6, these metrics were computed and depicted, showcasing the exceptional performance of the proposed MIMO antenna system configuration. For the proposed MIMO antenna, ECCs between adjacent antenna elements were simulated, as demonstrated in Figure 6. ECC is evaluated either using scattering parameters or radiation patterns. The ECC values of the proposed MIMO

antenna are less than 1.6×10^{-4} , falling within an acceptable range and indicating effective MIMO communication capabilities. DG quantifies the reduction in transmission power loss achieved through a diversity scheme employing a MIMO antenna. Ideally, DG should reach 10 dB, though values close to this threshold are acceptable due to various losses. The simulated DG values for the proposed antenna exceed 9.997 dB between adjacent antenna elements, suggesting its potential suitability for diversity scheme applications.

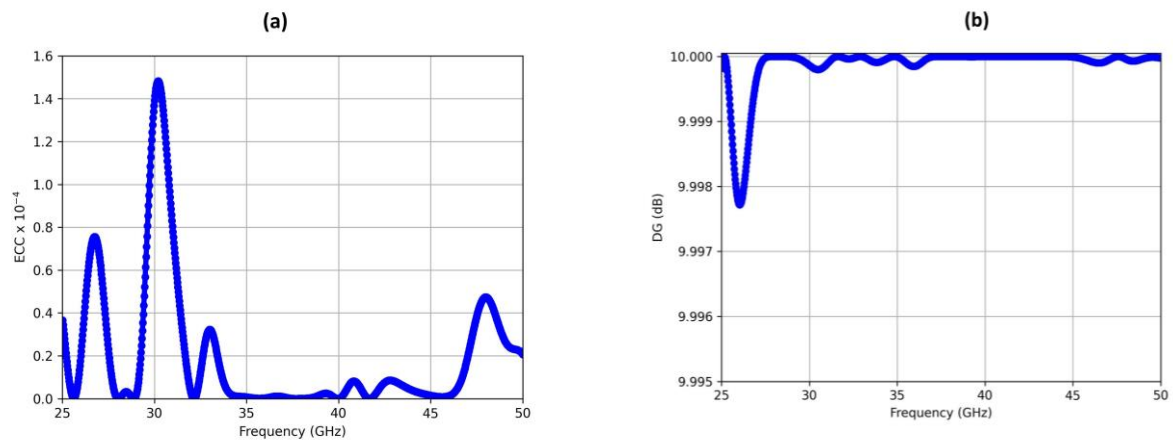


Fig. 6. Variations in the ECC and DG versus frequency

3.3 Frequency reconfigurability

PIN and varactor diodes are critical in providing dynamic control over the antenna's operating frequency. The electrical characteristics of these diodes may be adjusted by supplying a suitable bias voltage, resulting in a change in the effective size of the radiating patch. This alteration caused the antenna's resonance frequency to shift. The antenna's reconfigurability and gain were improved by strategically placing a PIN diode at the optimal location of the radiating patch. By activating the diode, the antenna's operational frequency can be altered. Additionally, this reconfiguration caused a considerable shift in the antenna's radiation pattern. Figure 7(a) shows a single-element antenna with a PIN diode mounted on the radiating slot. When the switch is switched on, the frequency is increased to 29 GHz, and when the switch is turned off, it returns to 28 GHz, as shown in Fig. 7(b). An I-shaped metasurface is put along the patch's borders to serve two objectives. For starters, it offers isolation when the antenna is used in a multi-user MIMO configuration. Second, metasurfaces improve antenna gain by using their unique electromagnetic features. They have

effective medium behavior, which allows for customized electromagnetic responses that improve radiation efficiency and directivity. Subwavelength resonators in metamaterials alter wave propagation by focusing energy in certain directions and hence increasing gain. Anomalous dispersion and negative-index metamaterials allow for irregular wave steering, which increases gain even further. Metamaterials can improve isolation between MIMO elements by acting as electromagnetic shields to prevent unwanted electromagnetic coupling, controlling wave absorption and reflection to reduce interference, exhibiting spatial filtering properties to direct energy away from neighboring elements, and using frequency-selective surfaces to selectively transmit or block specific frequencies. By utilizing these properties, metamaterials enable more control over the electromagnetic environment, minimizing interference and enhancing isolation between MIMO elements, resulting in improved system performance and capacity. Figures 7(c) and (d) show the results for the MIMO structure and the structure's S-parameters, respectively. The isolation values are less than 23 dB and 40 dB at 28 GHz and 38 GHz, respectively.

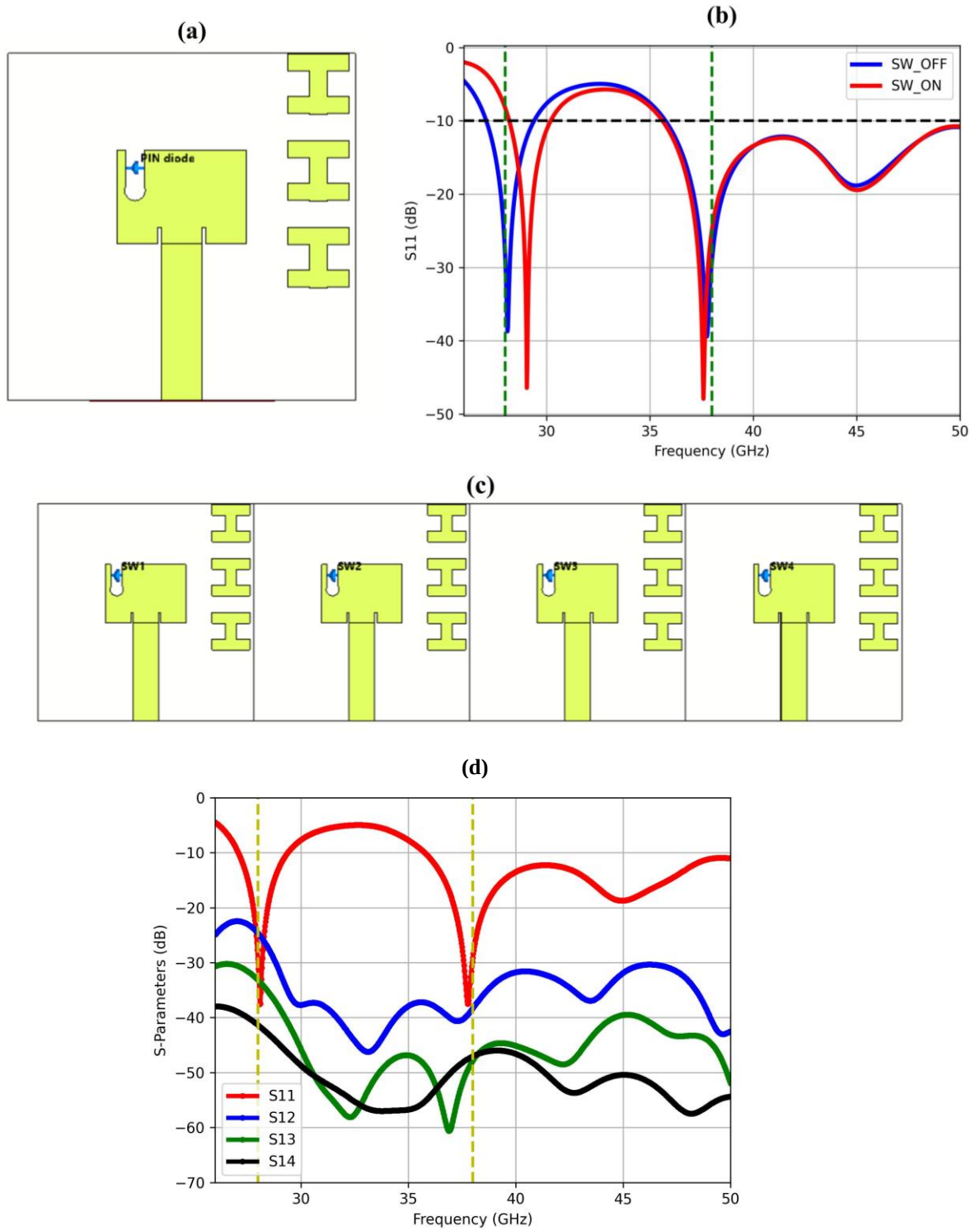


Fig. 7. Metamaterial-based solutions in MIMO antenna structure. (a) single-element antenna with a PIN diode inserted in the radiating slot, (b) frequency reconfigurability utilizing the diode on and off state to shift the frequency between 28 and 29 GHz, (c) MIMO structure with an I-shaped metamaterial, and (d) for the S-parameters of the simulated structure.

3.4 Gain improvement

Metamaterials' characteristics, such as negative permittivity, permeability, and refractive index, enable unconventional wave manipulation. Negative permittivity relates to a material's opposing electrical reaction,

whereas negative permeability denotes its opposite magnetic response. When coupled in negative-index metamaterials, these features may change wave propagation, giving control over directivity and beamforming. This distinct characteristic can boost antenna gain by

increasing radiation efficiency, channeling energy, and allowing for precise wave control. Figure 8(a) shows the acquired metamaterial characteristics of relative permittivity (ϵ_r), relative permeability (μ_r), and refractive index (n). The permittivity initially has a constant value until the frequency of 28.8 GHz, at which point it declines and becomes negative, remaining negative until 40 GHz. In contrast, permeability behaves in the opposite way as permittivity. The refractive index is positive before 28 GHz, then negative at 29 GHz, and finally near zero at 38 to 40 GHz. These findings emphasize the metamaterial's unusual electromagnetic properties, such as negative permittivity and refractive index, therefore we refer to the improved gain and isolation to the metasurface properties that were obtained with proper design and optimization of the position and dimension of that utilized I-shaped metasurface. Figure 8(b) compares the gain

performance of a single element and a MIMO arrangement. The single element obtains gains of 7.9, and 7.3 at 28 GHz, and 38 GHz, respectively. When coupled in a MIMO system, the gains increase dramatically, reaching 13.7 and 12.8 dBi at the respective frequencies, as listed in Table 2. Figure 8(b) depicts the combined gain of a 4-port MIMO construction, demonstrating the significant increase gained across all frequencies. This demonstrates the efficiency of MIMO systems in greatly improving gain performance, signal strength, and overall system capacity. In Figure 9, a comparison is made between the peak gain and the achieved minimum isolation of the MIMO structure with and without the addition of the metasurface (MS). Both figures demonstrate a notable improvement in both gain and isolation. Similar results were reported for other antenna designs and configurations [40-42].

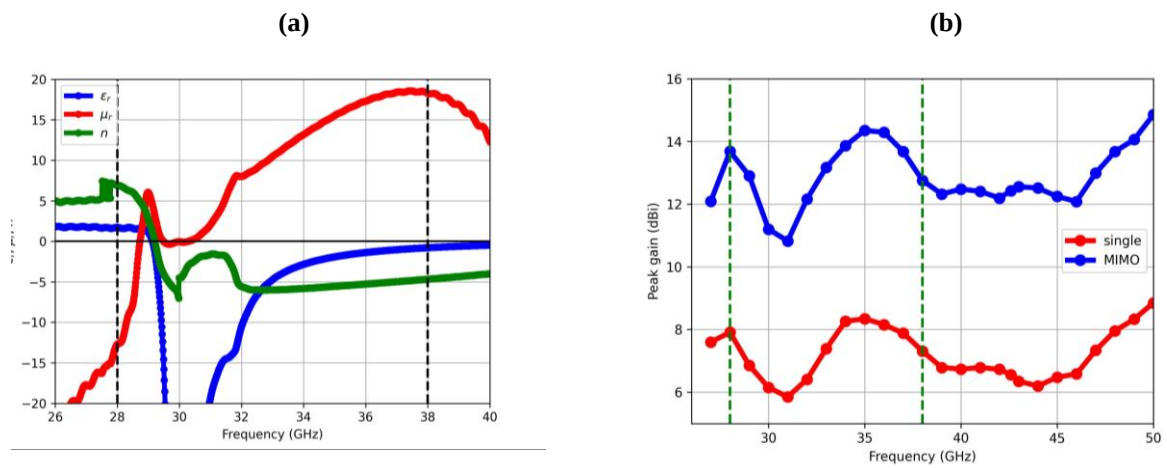


Fig. 8. (a) Relative permittivity, permeability, and refractive index of metamaterial unit cell, and (b) peak gain of a single element and a 4-port MIMO antenna

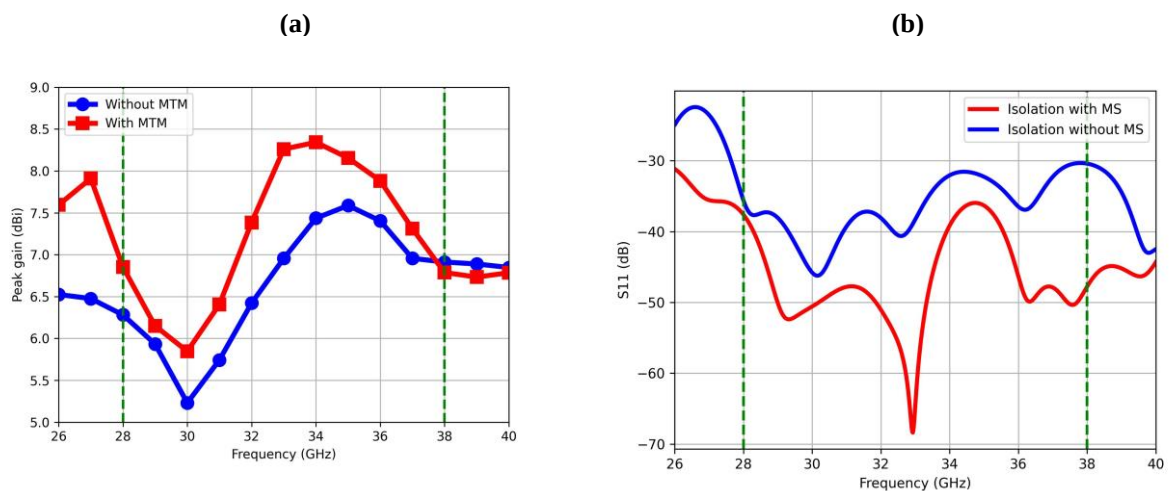


Fig. 9. Plots of (a) peak gain and (b) achieved minimum isolation vs. frequency for both cases with and without MS

Table 2. Summary of antenna gain improvement results

Single-element antenna operating frequency	28 GHz	38 GHz
Gain without metasurface	7.5 dBi	6.5 dBi
Gain with metasurface	7.9 dBi	7.3 dBi
Gain of combined 4-port MIMO structure	13.7 dBi	12.8 dBi
Minimum isolation without metasurface	37.6 dB	30.0 dB
Minimum isolation with metasurface	38.0 dB	47.7 dB

3.5 Antennas fabrication and measurements

The proposed single-element and MIMO antennas were fabricated using a photolithography procedure and measured using a vector network analyzer (VNA Rohde & Schwarz “ZVA 67”). The VNA can measure a wide range of frequencies (10 MHz to 67 GHz). Therefore, this instrument was used to measure the S-Parameters and radiation pattern of the antenna. Figure 9 illustrates the fabricated and measurement setup of the single-element and MIMO antennas. The frequency response of the reflection coefficients S_{11} through S_{44} was measured by the VNA. The comparison between simulation and

measurement results for the frequency dependencies of the reflection coefficient of each port is presented in Fig. 10. The measured operation frequencies range from 25 to 45 GHz, with the lower and upper frequencies centered at 28 GHz and 38 GHz, respectively. This comparison demonstrates good agreement between the simulated and measured results, with a slight shift of the resonant frequency of approximately 2% towards the lower frequency. This might be referred to as a slight mismatch owing to the RF connector being used. The impedance matching bandwidths for $|S_{11}| < -10$ dB obtained through measurements are approximately 9% at 28 GHz (2.5 GHz) and about 3.3% at 38 GHz (1.25 GHz).

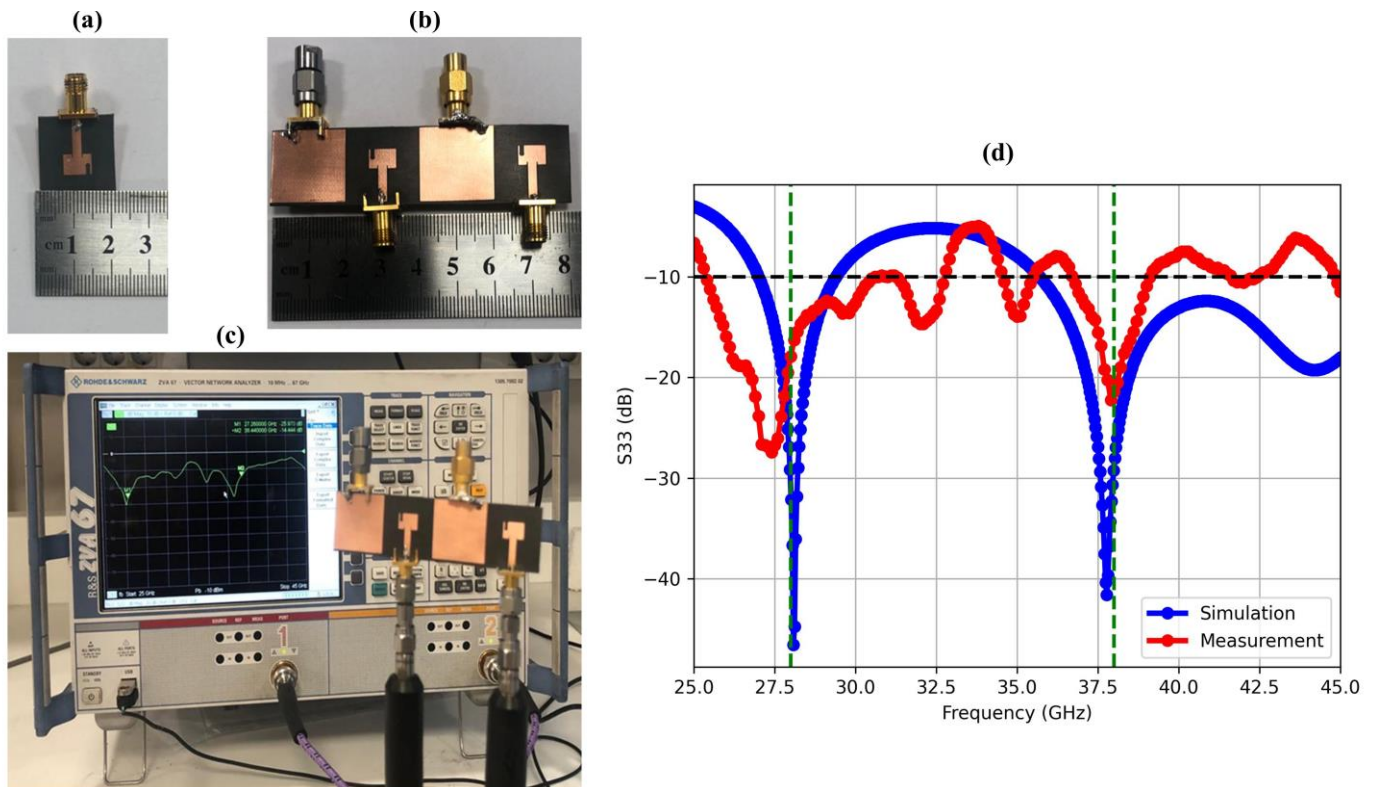


Fig. 10. Prototypes of fabricated and measured (a) single-element, (b) MIMO antennas, (c) measurement setup of MIMO antenna, and (d) measured and simulated frequency responses of reflection coefficients for the proposed MIMO antenna.

Figure 11 displays the measured and simulated radiation pattern of single element antenna measured in E- and H-plane at 28 and 38 GHz. Discrepancies

between measured and simulated radiation patterns of antennas often stem from a combination of factors, including inaccuracies in modeling assumptions,

variations in material properties and manufacturing tolerances, environmental influences, calibration errors, frequency-dependent effects, and the inherent sensitivity of radiation patterns to design nuances and operating conditions. Resolving these discrepancies may entail refining simulation models, incorporating more precise

material data, validating simulations with additional measurements, and considering the impact of environmental factors on antenna performance to achieve better alignment between theoretical predictions and real-world observations.

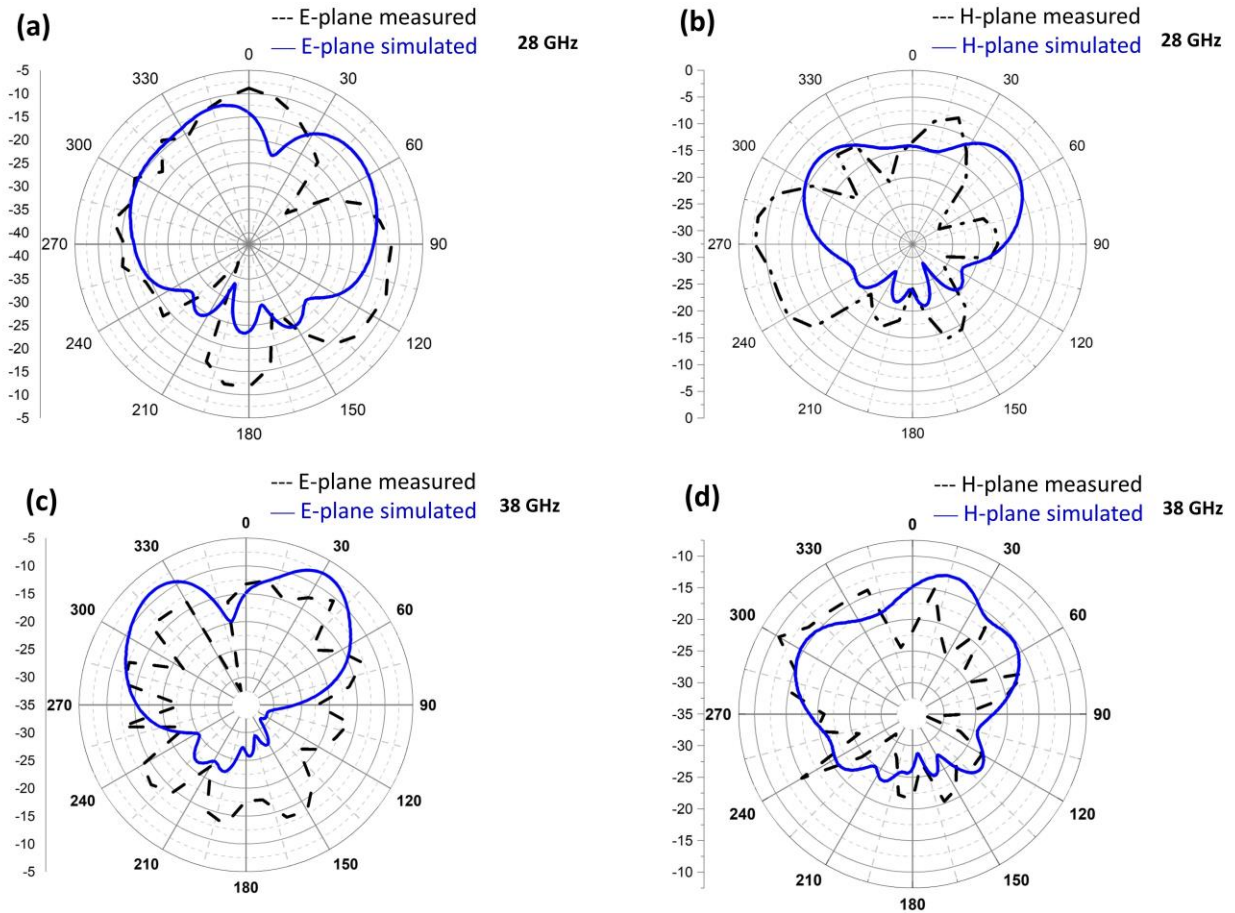


Fig. 11. Measured and simulated radiation pattern of (a) *E*-plane, (b) *H*-plane, at 28 GHz, (c) *E*-plane, and (d) *H*-plane at 38 GHz of single-element antenna

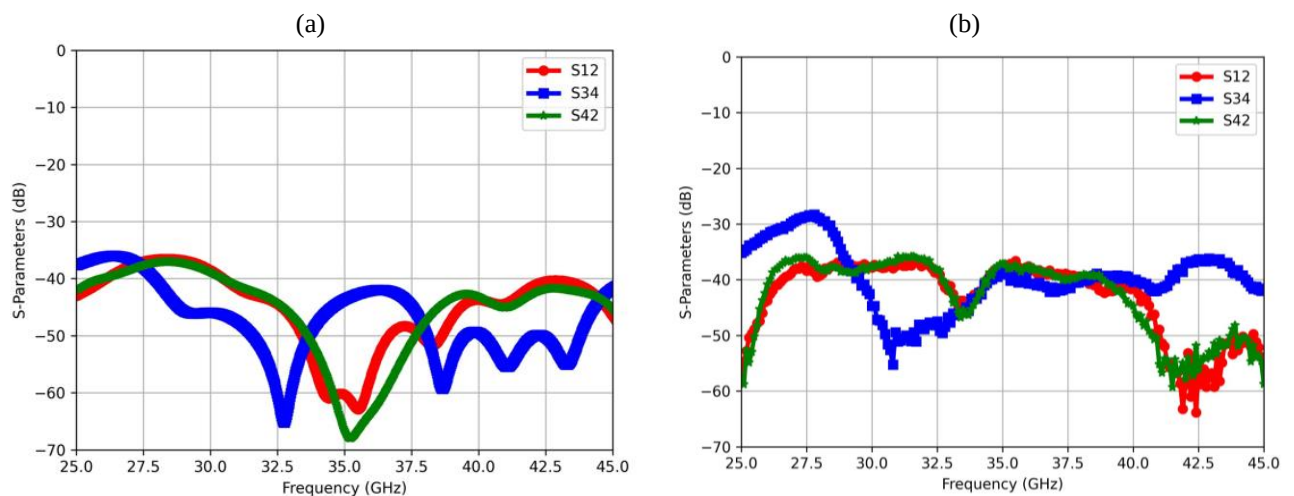


Fig. 12. (a) Simulated and (b) measured frequency response of mutual coupling coefficients of the proposed 4-port antenna

Figure 12 presents the simulated and measured frequency response of the mutual coupling coefficients for the proposed 4-port antenna. The results provide valuable insights into the antenna's performance and specifically highlight the consistency between the simulated and measured mutual coupling. In Fig. 12(a), the simulated frequency response of the mutual coupling coefficients is depicted. This simulation-based analysis allows for a comprehensive understanding of the antenna's behavior in terms of coupling between its individual ports. The graph showcases the fluctuations of the mutual coupling coefficients around -40 dB within the desired frequency band. This indicates that the antenna maintains a high level of isolation between its ports, minimizing interference and enabling efficient MIMO operations. Figure 12(b) presents the measured frequency response of the mutual coupling coefficients. The measured results closely align with the simulated response, which demonstrates the consistency between the two sets of data. The fluctuations observed around -40 dB further validate the anticipated antenna performance in terms of the mutual coupling. The close agreement between the simulated and measured results is crucial for ensuring the accuracy of the antenna design and verifying its intended functionality. The high isolation properties of the proposed 4-port antenna can

be attributed to two key factors. First, the proper spacing between the MIMO elements plays a significant role in reducing mutual coupling. By carefully designing the physical arrangement and separation between the antenna elements, the undesired coupling effects can be minimized, thereby enhancing the isolation properties. Secondly, the inverted structure of the proposed antenna contributes to its high isolation characteristics. Given the simplicity of our design, it achieves peak gains comparable to numerous recently published designs in the literature. Furthermore, in terms of isolation, it surpasses a significant number of them operating at the 28/38 GHz bands [29-37]. The unique design and arrangement of the antenna's components help mitigate mutual coupling, allowing for improved performance. This innovative approach to the antenna's construction contributes to the observed consistency between the simulated and measured mutual coupling coefficients.

Table 3 lists a comparison between the MIMO antennas previously documented in the literature, which were notably similar to our proposed design. Our design surpasses the others in terms of both isolation and gain performance. In addition, the proposed design offers reconfigurability properties.

Table 3. Performance comparison with other MIMO antennas

Ref.	Antenna type	Substrate	Dimensions (mm ³)	Bandwidth (GHz)	Gain (dBi)	Isolation (dB)
[29]	Planar 4-port MIMO	Rogers RT5880	14×14×0.8	2.4 (28 GHz), 2.0 (38 GHz)	8.4 (28 GHz), 6.02 (38 GHz)	25
[30]	Inverted-F Array 32-element MIMO	FR4	64×123×0.2	0.89 (28GHz), 0.99 (38 GHz)	16.52 (28 GHz), 15.35 (38 GHz)	35
[31]	2-Port MIMO	Rogers Ro3003TM	7.5×8.8×0.25	1.23 (28 GHz), 1.06 (38 GHz)	6.6 (28 GHz), 5.86 (38 GHz)	35
[32]	4-port MIMO	FR4	55×110×0.508	1.06 (28 GHz), 1.43 (38 GHz)	7.18 (28 GHz), 9.24 (38 GHz)	28
[33]	6-port MIMO	RT Duroid 5880	9.53×7.85×0.8	0.4 (28 GHz), 2.58 (38 GHz)	13.3 (28 GHz), 10.09 (38 GHz)	20
[34]	4-port MIMO	Rogers TMM4	17.76×17.76×1 .52	0.718(28 GHz), 0.56 (38 GHz)	8.9 (28 GHz)	25 to 90
[35]	4-port Cross-shaped MIMO	Roger RO4003	29×24.2×0.203	1.8 (28 GHz), 1.2 (38 GHz)	8.1 (28 GHz), 7.22 (38 GHz)	20
[36]	4-port MIMO flexible	Rogers 3003	18×8.5×0.25	0.72 (28 GHz), 0.5 (38 GHz)	4.15 (28 GHz), 7.73 (38 GHz)	20
[37]	2-port MIMO	Rogers RT/Duroid 5880	10×16×0.508	1.8 (28 GHz), 6.2 (38 GHz)	9.0 (28 GHz) 9.8 (38 GHz)	17
This work	4-port reconfigurable MIMO	Rogers RT/Duroid 5880	20×80×0.787	2.3 (28 GHz), 12.9 (38 GHz)	7.9 (28 GHz) 7.3 (38 GHz)	37 (28 GHz) 40 (38 GHz)

4 Conclusions

This research presented a design of a compact, linearly polarized MIMO antenna operating in the mmWave band for 5G wireless communication systems. The designed antenna exhibits several key features, including wide bandwidth, low mutual coupling, and radiation pattern reconfigurability. The simulation results have shown that the MIMO antenna array achieves peak gains of 7.5 dBi at 28 GHz and 6.5 dBi at 38 GHz, with reflection coefficients below -40 dB at the operating frequencies. Additionally, the mutual coupling between antenna elements is below -37 and -43 dB at 28 GHz and 38 GHz, respectively. The pattern reconfigurability of the antenna was achieved using a simple approach comprising an inverted structure allowing seamless operation in different frequency ranges. Moreover, utilizing the PIN diode switch inserted in the optimized position on the patch produced frequency reconfigurability. The antenna gain is significantly enhanced by incorporating a metasurface designed to optimize gain and improve isolation. For the single-element antenna, the gain improved to 7.9 and 7.3 dBi at frequencies of 28 GHz and 38 GHz, respectively. These findings demonstrate the effectiveness of the metasurface in boosting the antenna's performance, increasing signal strength, and achieving improved system capacity at different frequencies. This simple and compact solution enables adaptability to the 5G requirements and next-generation communication technologies operating in the mmWave band. The antenna's gain, wide bandwidth, low mutual coupling, and pattern and frequency reconfigurability address the requirements of spectral efficiency, interference mitigation, and bandwidth flexibility. These attributes contribute to the enhancement of network performance, higher data rates, and improved signal quality in 5G and beyond. The primary contribution of this suggested design is its reconfigurability as a dual-band 28/38 GHz 4-port MIMO antenna. Distinguished by its straight-forward yet efficient structure, the antenna provides high gain and considerable isolation capabilities.

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