

Compact Four-Element UWB-MIMO Antenna Incorporating a Composite Decoupling Structure

Qi Li*, Tiegang Zhong, and Songqi Li

School of Electronics and Information Engineering, Liaoning Technical University, Huludao, China

ABSTRACT: To address the problem of increased electromagnetic mutual coupling caused by multi-antenna integration in compact wireless communication terminals, this study presents a compact four-element, high-isolation, ultra-wideband (UWB), multiple-input multiple-output (MIMO) antenna operating in the 6.5–14 GHz frequency band. The proposed antenna is compact, measuring $36\text{ mm} \times 36\text{ mm} \times 1.6\text{ mm}$. The radiating elements adopt an orthogonally symmetric configuration, with chamfered corners and slot-loading techniques used to enhance impedance matching and broaden impedance bandwidth. To effectively reduce mutual coupling between adjacent elements, a composite decoupling structure is developed, which integrates a non-through isolation slot, embedded metallic patches, and a cross-shaped defected ground structure (cross-DGS). The proposed structure effectively enhances in-band isolation by altering coupling current paths and redistributing surface currents on the ground plane. The results demonstrate that, in the 6.5–14 GHz operating band, the antenna achieves $S_{11} < -10\text{ dB}$, the adjacent-port isolation (S_{21}) exceeding 20 dB, an envelope correlation coefficient (ECC) below 0.0035, and a diversity gain (DG) close to 10 dB. The proposed antenna combines a compact size, wide operating bandwidth, enhanced isolation, and good diversity performance, providing a potential candidate for compact UWB-MIMO terminals, requiring low mutual coupling.

1. INTRODUCTION

With the ever-increasing demand for high data rates and highly reliable transmissions, in broadband wireless communication systems, multiple-input multiple-output (MIMO) technology has become a crucial means for enhancing system capacity and spectral efficiency. However, in compact terminal devices, antenna elements are often densely arranged to meet miniaturization requirements, which significantly increases the electromagnetic mutual coupling between elements. Strong mutual coupling not only degrades impedance matching and reduces radiation efficiency, but also leads to increased channel correlation and decreased channel capacity, severely constraining the overall performance of MIMO systems [2, 3]. Therefore, realizing a MIMO antenna design with broadband operation, high isolation, and low correlation under stringent size constraints remains a considerable challenge. In recent years, with the development of broadband wireless communications, positioning systems, and X-band applications, wideband MIMO antennas covering the 6.5–14 GHz frequency range have attracted extensive attention. However, as the operating frequency increases and antenna dimensions are further reduced, near-field coupling between radiating elements and ground-current coupling becomes more pronounced, making it difficult for conventional isolation-enhancement techniques to simultaneously satisfy the requirements of wide bandwidth and miniaturization.

To suppress mutual coupling in MIMO antennas, various decoupling techniques have been proposed, which can be broadly

classified into defected ground structures (DGSs), electromagnetic bandgap (EBG) structures, circuit compensation methods, and composite decoupling structures.

Ground-plane-based decoupling techniques mainly use DGSs and EBG structures to redistribute surface currents and suppress mutual coupling. Previous studies have demonstrated that EBG-based structures can reduce mutual coupling in UWB-MIMO antennas [6, 7], while metal-via-based structures have also been introduced to modify ground-current distribution and improve isolation performance in quad-port UWB-MIMO antennas [15]. DGS-based, slot-based, and mesh-like decoupling structures have been explored to achieve broadband isolation enhancement [4, 11]. However, EBG structures usually require periodic arrangements, increasing antenna size and complexity, and the isolation performance of DGS-based methods may vary significantly over ultra-wideband ranges.

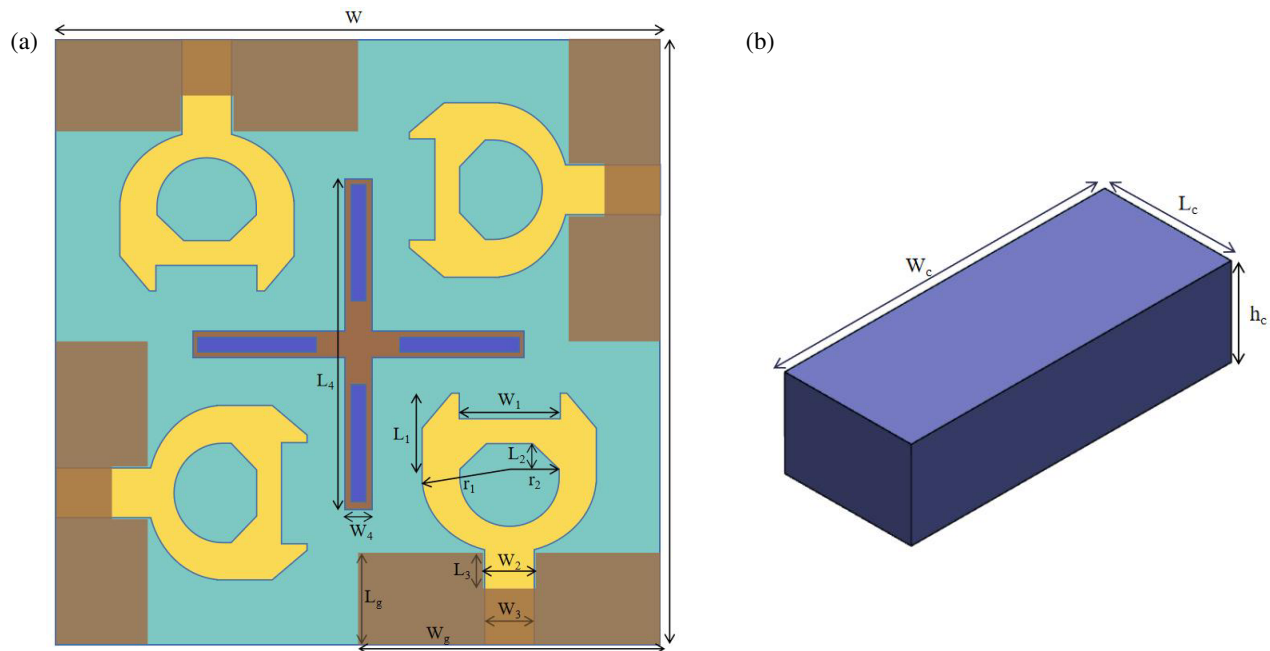
Circuit-compensation-based methods reduce mutual coupling by introducing neutralization lines or decoupling networks to establish compensation paths. These approaches have been reported to improve isolation performance through additional compensation paths [8, 9]. However, these methods generally rely on specific compensation paths, and their performance is sensitive to variations in frequency and structural parameters.

Composite decoupling structures have attracted increasing attention in recent years to further improve broadband isolation performance. Recently, various composite decoupling techniques have been investigated for UWB-MIMO antennas. RMS-ZINC-based structures regulate electromagnetic

* Corresponding author: Qi Li (2781671056@qq.com).

TABLE 1. Geometric parameters of the proposed antenna (mm).

Parameter	L	W	L_g	W_g	L_1	W_1	L_2	W_2	L_3	W_3	L_4	W_4	r_1	r_2	L_C	W_C	h_c
Dimension	36	36	5.5	18	4	6	1.5	3.2	2.15	3.2	19.7	1.55	5.5	3	0.8	7	1.1

**FIGURE 1.** Geometry of the proposed antenna. (a) Top view and (b) isolation slot dimensions.

coupling paths between adjacent antenna elements [12], while ground-plane modification, multi-polarization, and neutralization-ring structures have also been explored to improve MIMO performance [5, 16, 17].

However, these approaches generally involve relatively complex configurations and large physical dimensions, which limit their applicability in compact terminal applications.

Although the above methods have demonstrated effective coupling suppression under different conditions, a trade-off still exists among broadband isolation, high isolation, and miniaturization in compact MIMO antenna design. Existing methods are generally optimized for a single dominant coupling path, making it difficult to suppress multiple coupling mechanisms, including near-field coupling and ground-current coupling. However, achieving high isolation is often accompanied by increased structural complexity or large physical dimensions. To overcome these limitations, this study proposes a composite decoupling structure consisting of a non-through isolation slot, an embedded metal patch, and a cross-shaped DGS. By jointly manipulating coupling current paths, local electromagnetic responses, and ground-plane current distribution, the proposed structure enhances broadband isolation performance while maintaining a compact antenna size. The proposed structure enables simultaneous control of multiple coupling paths, including direct near-field coupling and ground-current coupling, resulting in improved mutual coupling suppression over a wide operating bandwidth.

2. ANTENNA STRUCTURE DESIGN

Figure 1 shows the geometric configuration of the proposed four-port UWB-MIMO antenna. The antenna was fabricated on an FR4 dielectric substrate with a thickness of 1.6 mm. The relative permittivity $\epsilon_r = 4.4$, loss tangent $\tan \delta = 0.02$, and copper thickness is 0.035 mm. The antenna's overall size is 36 mm $\times$ 36 mm. The four radiating elements are orthogonally arranged on the substrate's top layer, forming a regular, compact configuration suitable for miniaturized antenna applications. To reduce electromagnetic coupling between adjacent elements, a composite decoupling structure is introduced along the substrate's geometrical symmetry axes. Specifically, a non-through isolation slot with a depth of 1.1 mm was etched on the top layer, and a metal patch was embedded within the slot. Meanwhile, a cross-shaped defective ground structure (cross-DGS) was etched on the corresponding region of the ground plane. Figure 1 shows detailed structural parameters, and Table 1 lists optimized dimensions.

2.1. Single-Antenna Design

Initial dimensions of the antenna element are determined based on the quarter-wavelength resonance principle of a monopole antenna. The obtained parameters are further optimized through full-wave electromagnetic simulations to achieve the required impedance characteristics. Antenna's electromagnetic characteristics are analyzed using Ansys High

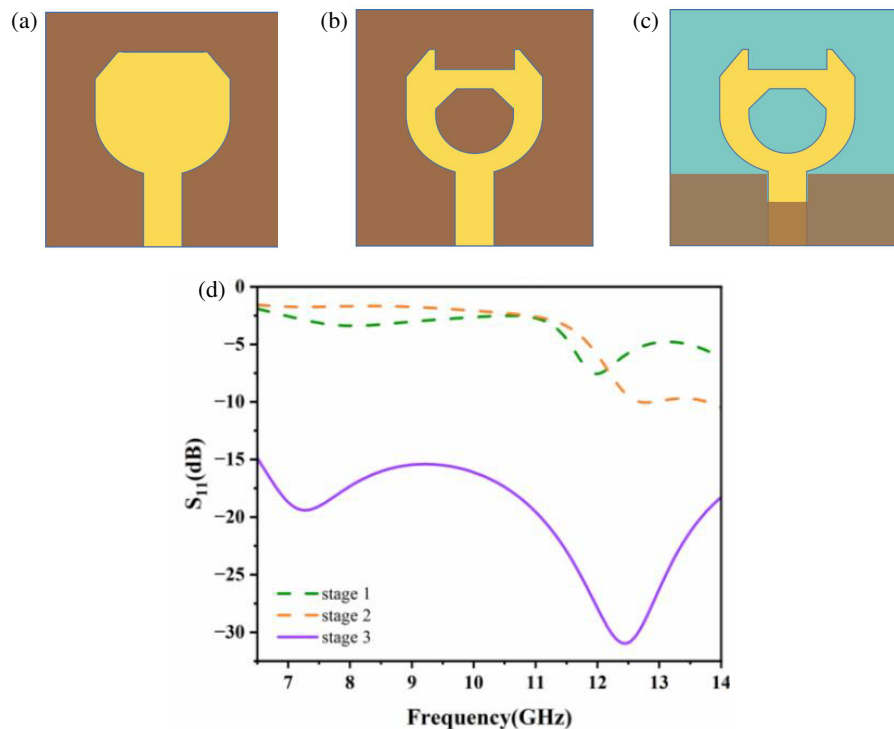


FIGURE 2. Evolution process of the antenna element and S_{11} characteristics of different stages.

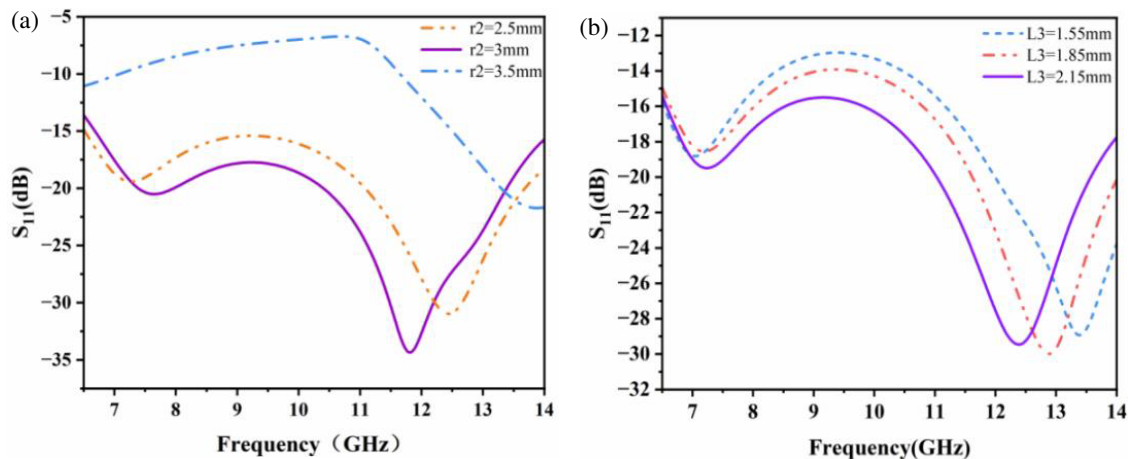


FIGURE 3. S_{11} curves versus r_2 and L_3 variations.

Frequency Structure Simulator (HFSS) based on the finite element method.

Figures 2 illustrates the three-stage evolution of the radiating element and corresponding reflection coefficient characteristics. Antenna 1 consists of a combined semicircular and rectangular radiating element. Due to its simple configuration, the impedance-tuning capability is limited, leading to impedance mismatch over a broad frequency range, particularly at higher frequencies. Therefore, Antenna 1 fails to achieve the desired impedance bandwidth of 6.5–14 GHz. To improve impedance characteristics, a slot was introduced at the center of the radiating element to form Antenna 2. The inserted slot modifies the surface current distribution and effectively adjusts the current path, improving input impedance matching. As shown in

Figure 3, compared with Antenna 1, Antenna 2 has a lower reflection coefficient in the mid-to-high frequency range, demonstrating that the slot contributes to improved impedance matching at these frequencies. However, noticeable fluctuations remained in the 12–14 GHz band. Further optimization is performed on Antenna 3, where a half-ground structure is incorporated with the slot design. The modified ground plane regulates the current return path and electromagnetic interaction between the radiator and ground, further improving impedance matching over a broader frequency range. Finally, via the combined optimization of the radiating element and ground structure, the proposed antenna achieves broadband impedance matching with $S_{11} < -10$ dB from 6.5 to 14 GHz.

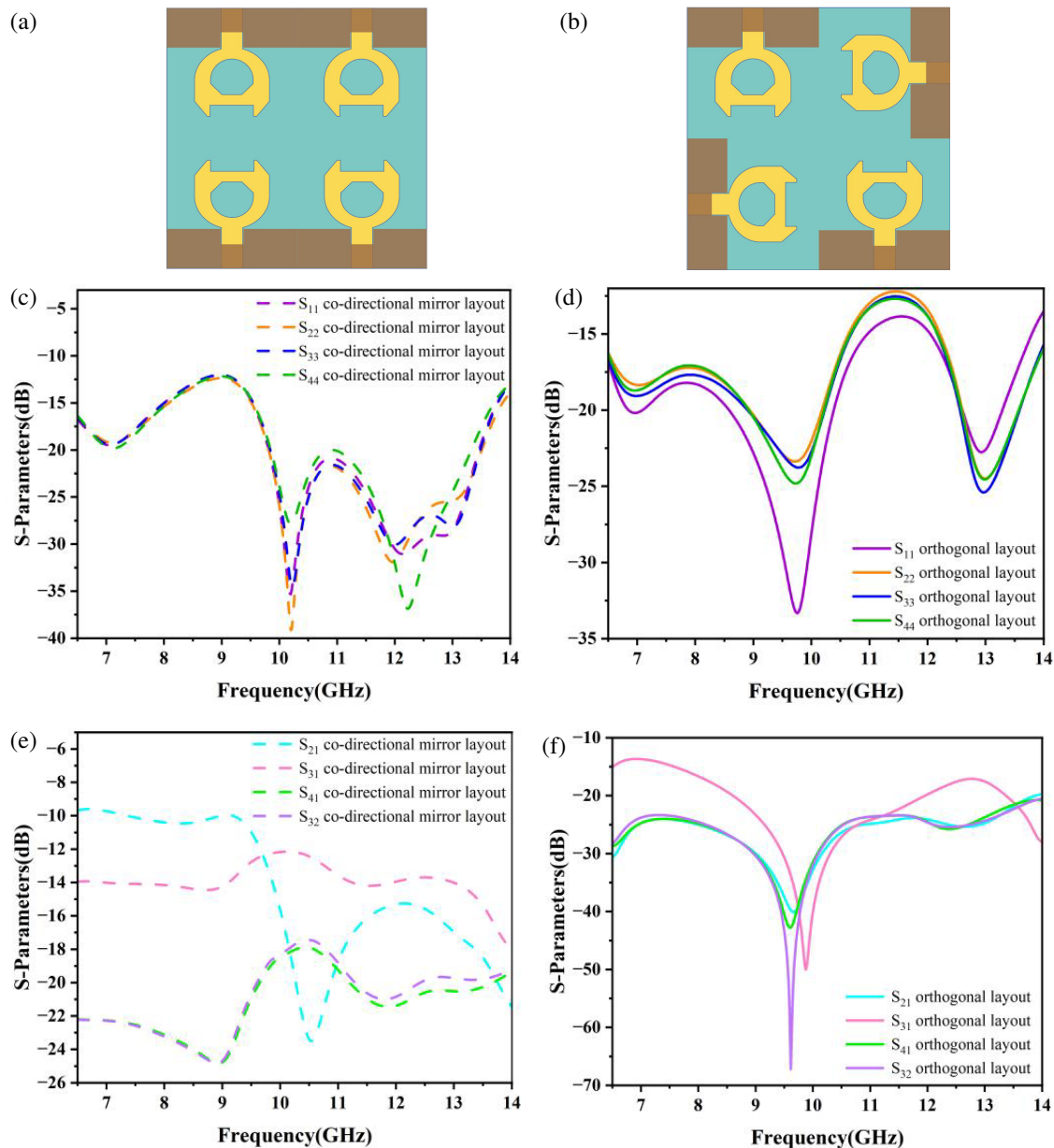


FIGURE 4. Comparison of four-element MIMO configurations and S -parameters: (a) co-directional layout, (b) orthogonal layout, (c), (e) S -parameters of co-directional layout, and (d), (f) S -parameters of orthogonal layout.

The parameter r_2 mainly affects the effective current path length of the radiating element, which influences the resonant behavior and impedance matching characteristics. Meanwhile, L_3 affects the ground-current distribution and the coupling behavior between the radiating element and the ground plane. Therefore, parametric studies of r_2 and L_3 were conducted to investigate their influences on impedance characteristics. Based on the simulation results, Figure 3 shows the optimized dimensions of the radiating element, and the corresponding parametric analyses.

2.2. Four-Element MIMO Antenna

After obtaining the optimized UWB monopole antenna element, a 2×2 mirror-symmetrical arrangement was established

as a reference configuration. Subsequently, the antenna elements were placed orthogonally and symmetrically at the four corners of the FR4 dielectric substrate, as shown in Figure 4. Compared with the co-directional arrangement, the orthogonal configuration modifies electromagnetic coupling between adjacent radiating elements, providing a preliminary enhancement of port isolation performance. It serves as the foundation for the subsequent design of the proposed composite decoupling structure.

Figure 4 shows simulated reflection coefficients (S_{11} , S_{22} , S_{33} , and S_{44}) in the four ports when no decoupling structure is introduced. The reflection coefficients (S_{11} , S_{22} , S_{33} , and S_{44}) remain below -10 dB in the 6.5–14 GHz operating band, indicating acceptable impedance matching. Although the antenna elements show structural symmetry, slight differences

among reflection coefficients can still be observed due to different feeding orientations, current return paths, and local electromagnetic coupling environments.

Isolation results show that the orthogonal arrangement provides lower mutual coupling than the co-directional configuration; however, residual coupling remains in some frequency regions due to the limited element spacing required for compact integration. Consequently, a composite decoupling structure is introduced to further enhance inter-port isolation performance.

2.3. Composite Decoupling Design

The four-element MIMO antenna achieved the required wide-band impedance matching performance. However, due to the limited spacing between adjacent radiating elements, strong mutual coupling occurs between antenna elements. Therefore, a decoupling structure is required to further enhance port-isolation performance.

To enhance isolation performance in the 6.5–14 GHz band, this study proposes a composite decoupling structure consisting of a non-through isolation slot, an embedded metal patch, and a cross-shaped defected ground structure (cross-DGS), as shown in Figure 5. The proposed structure combines near-field coupling suppression, local electromagnetic response adjustment, and ground-plane current redistribution, achieving broadband mutual-coupling reduction over the operating frequency range.

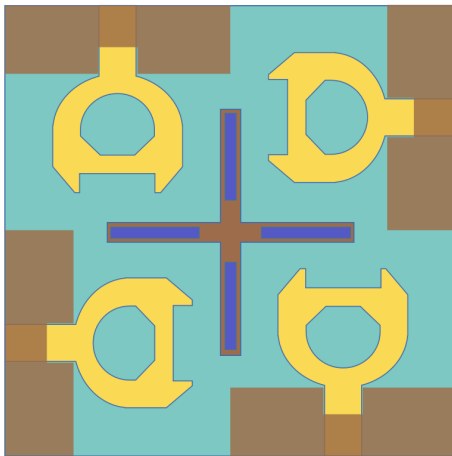


FIGURE 5. Antenna structure.

To further analyze the proposed decoupling structure, a simplified equivalent LC model is established to provide a qualitative explanation of the decoupling mechanism. The non-through isolation slot extends the coupling current path and introduces an equivalent inductive effect, while the embedded metallic patch provides additional capacitive loading in the coupling region. Meanwhile, cross-DGS regulates the ground-current distribution and modifies coupling paths. The corresponding resonant behavior can be described by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where L and C represent the equivalent inductance and capacitance associated with the proposed decoupling structure, re-

spectively. By adjusting the geometrical parameters, the induced current distribution and coupling paths between adjacent antenna elements can be modified, resulting in enhanced isolation performance.

First, a non-through isolation slot is introduced near the substrate's geometrical symmetry axis. By modifying the coupling current propagation path between adjacent radiating elements, the slot reduces coupling intensity in the near-field region and provides an initial improvement in isolation performance. However, due to its localized effect, isolation enhancement remains limited across the entire operating band.

Second, an embedded metal patch is incorporated into the slot to further adjust the electromagnetic distribution in the transducer's coupling region. The introduced metal patch improves isolation in the low-frequency and part of the mid-frequency regions, while degradation is observed in the 10–12 GHz range. This phenomenon indicates that the electromagnetic response introduced by the metal patch is frequency-dependent, and the resulting isolation variation may be associated with changes in induced currents and coupling-field distribution around the patch. Therefore, the metal patch alone cannot guarantee continuous isolation enhancement across the entire operating band; instead, it provides a local electromagnetic tuning effect for the subsequent composite decoupling design.

Finally, a cross-shaped defected ground structure (cross-DGS) is introduced in the corresponding region of the ground plane. By regulating the ground-plane current distribution, the cross-DGS improves isolation performance in the higher-frequency region and compensates for the degradation caused by the metal patch. Consequently, the combined decoupling structure enables the antenna to maintain a relatively stable isolation performance over the entire 6.5–14 GHz operating band.

The three components provide complementary electromagnetic effects and collectively contribute to suppressing mutual coupling. Specifically, the non-through isolation slot primarily modifies the coupling current path between adjacent elements, the embedded metal patch adjusts the local electromagnetic response in the coupling region, and the cross-DGS further regulates the ground-plane current distribution. By the combined effects of these three mechanisms, the proposed structure improves isolation in frequency regions with relatively strong coupling and maintains stable isolation across the target frequency band.

2.4. Decoupling Performance Analysis

To further analyze the decoupling mechanism of the proposed composite structure, Figure 6 compares surface-current distributions at 7, 10, and 13.5 GHz under Port 1 excitation. These three frequencies were selected to represent the low-, middle-, and high-frequency regions of the operating band, respectively. Four configurations, including the antenna without a decoupling structure, the antenna with only the non-through isolation slot, the antenna with the embedded metallic patch inside the slot, and the antenna with the complete composite decoupling structure, are compared to investigate the contribution of each decoupling component. The non-through isolation slot extends the coupling current path between adjacent antenna ele-

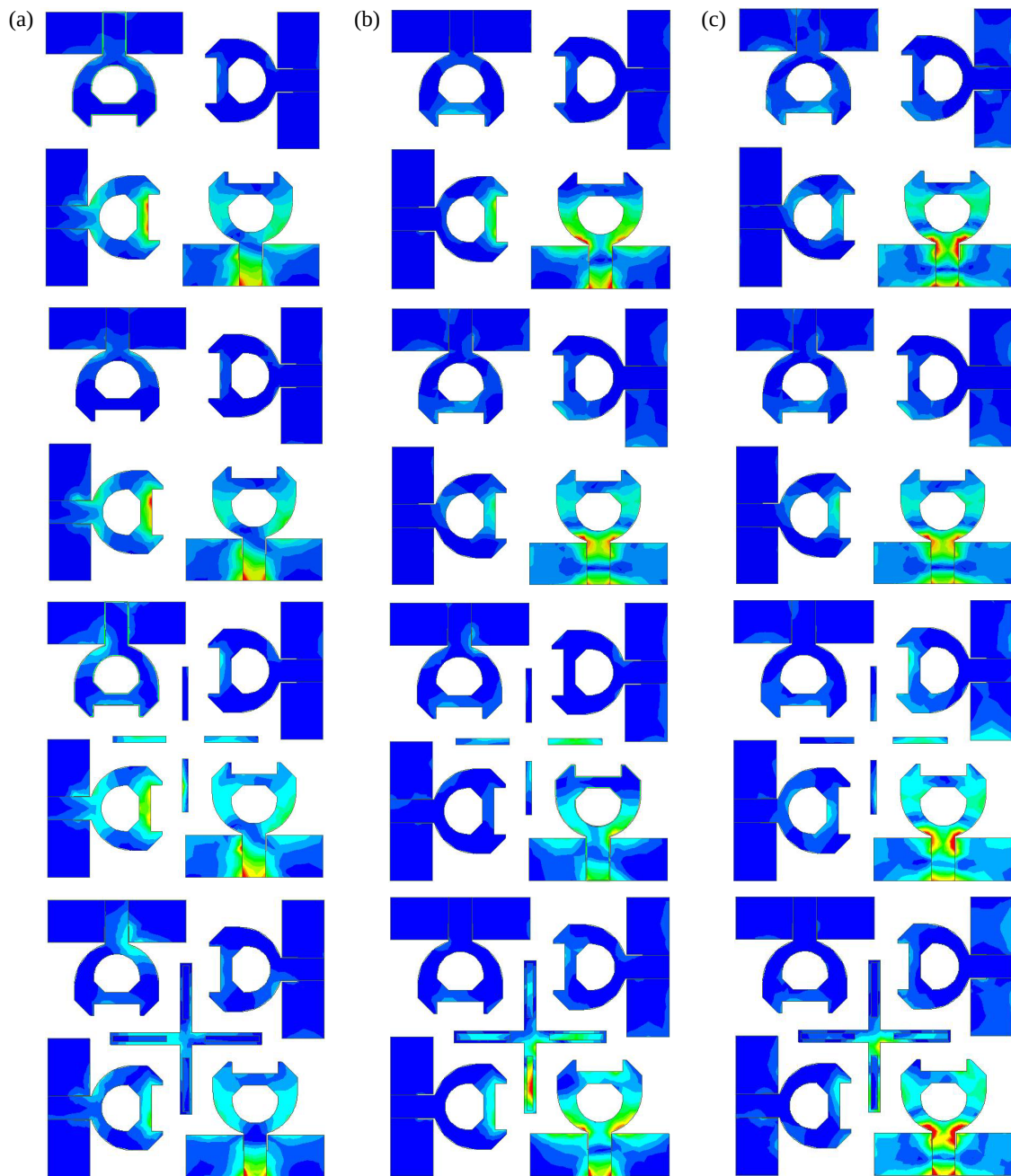


FIGURE 6. Surface current distributions for different stages of the proposed decoupling structure: (a) $f = 7$ GHz, (b) $f = 10$ GHz, and (c) $f = 13.5$ GHz.

ments, thereby introducing an additional equivalent inductive effect and reducing the direct near-field coupling. The embedded metallic patch provides capacitive loading in the coupling region and further adjusts the local electromagnetic field distribution and the coupling response within part of the operating band. Meanwhile, the cross-DGS regulates the ground-current distribution and reduces the propagation of coupling currents on the ground plane. Without the decoupling structure, the surface current on the excited element flows along the edges of the radiating element and ground plane, resulting in current concentration around adjacent elements and forming coupling paths. Consequently, induced currents were observed on non-

excited elements owing to mutual coupling. After introducing the composite decoupling structure, the induced currents on adjacent elements were reduced, and the surface current distribution around the decoupling region was modified. This redistribution indicates that the proposed structure alters original coupling paths and improves port isolation. The observed current variation further demonstrates the role of the composite decoupling structure in reducing mutual coupling over the operating band.

Figure 7 presents the effects of cross-DGS dimensions L_4 and W_4 on isolation performance. L_4 mainly determines the effective current path length of the Cross-DGS, and W_4 af-

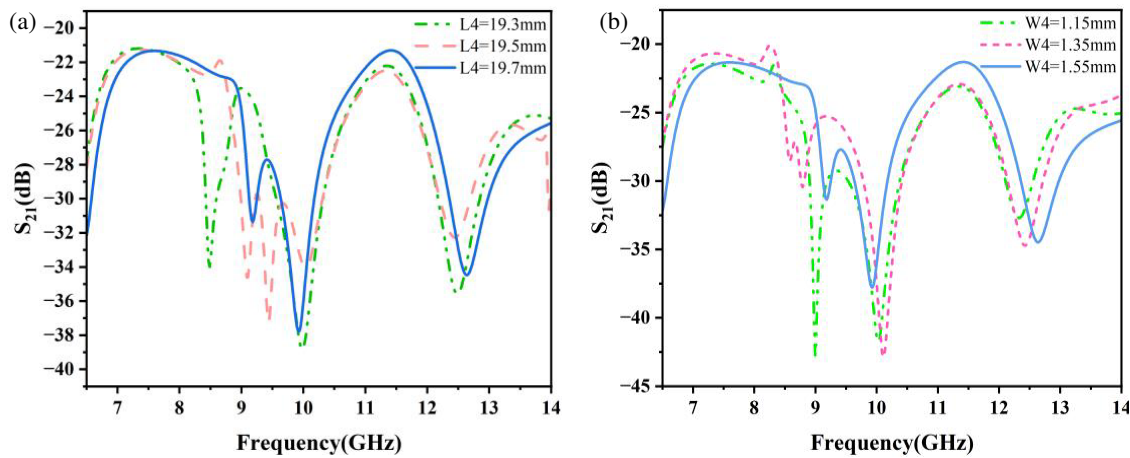


FIGURE 7. S_{21} curves versus L_4 and W_4 variations.

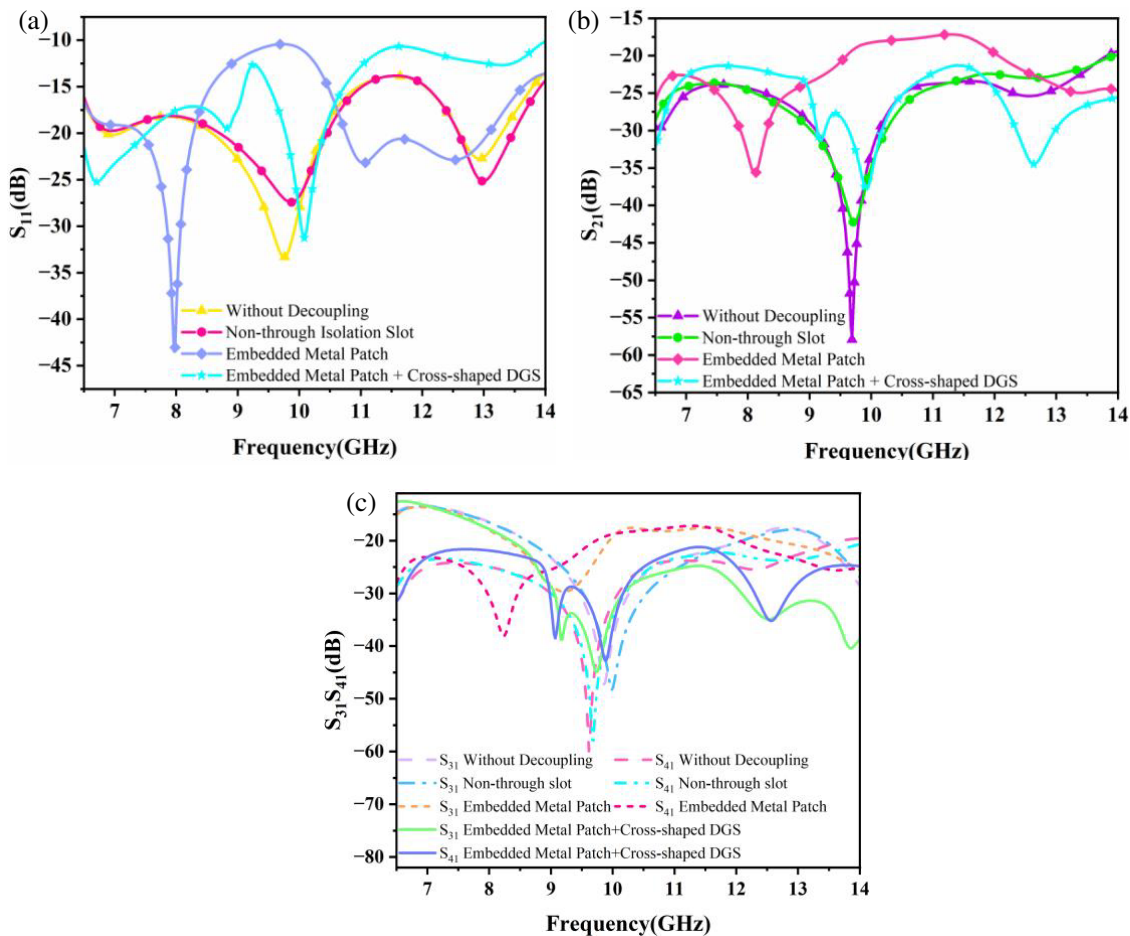


FIGURE 8. Simulated S -parameter comparison of different decoupling structures.

affects the current distribution on the ground plane, thereby influencing the coupling suppression capability. Considering the isolation performance and impedance matching over the 6.5–14 GHz band, the optimized dimensions are determined as $L_4 = 19.7$ mm and $W_4 = 1.55$ mm.

Figure 8 presents a comparison of the antenna's S -parameters under different decoupling configurations. As shown in Figure 8(a), introducing decoupling structures

slightly modifies the antenna's impedance-matching characteristics; however, all configurations maintain the required impedance-matching performance over the 6.5–14 GHz operating band. This result indicates that the proposed decoupling structure influences the impedance response while preserving the antenna's original broadband impedance matching characteristics.

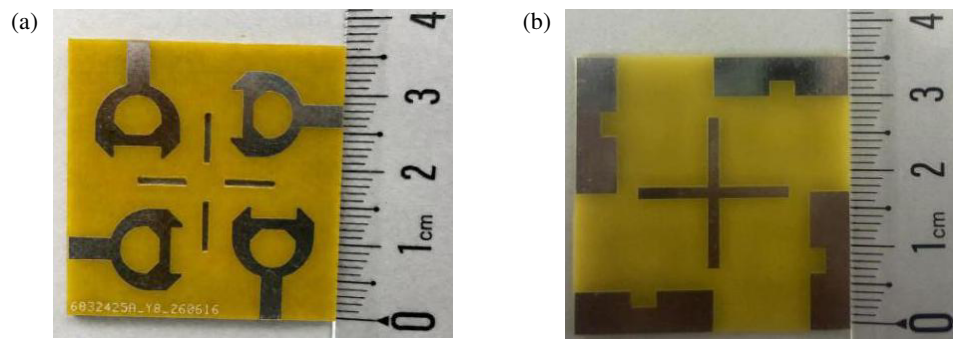


FIGURE 9. Prototype of the fabricated MIMO antenna: (a) Top view and (b) bottom view.

Figure 8(b) compares port isolation characteristics for different decoupling configurations. Without the decoupling structure, the S_{21} curve varies across the operating frequency range, with a local isolation improvement at approximately 9.7 GHz, and higher coupling levels remain in other frequency regions. The lower S_{21} value at this frequency is mainly attributed to frequency-dependent coupling between adjacent radiating elements. However, this improvement occurs only in a narrow frequency range and cannot provide stable broadband isolation. By introducing the proposed decoupling structures, the coupling paths between adjacent elements are modified, and electromagnetic interaction is suppressed, leading to more consistent isolation enhancement over the operating band. After introducing the non-through isolation slot, the isolation performance improved in some frequency ranges, indicating that the slot modified the coupling current path between adjacent radiating elements.

After embedding the metal patch, the port isolation response was further adjusted. As observed from Figure 8(b), the metal patch improves isolation in the low- and mid-frequency regions, whereas the isolation level decreases in the 10–12 GHz range. This behavior is mainly attributed to the electromagnetic loading effect introduced by the embedded metallic patch. The additional capacitive loading introduced by the patch changes the equivalent electrical length and resonant characteristics of the coupling path. As a result, the induced current on the metallic patch varies with frequency. Around 10–12 GHz, this induced current cannot effectively counteract the original coupling current between adjacent antenna elements, resulting in increased mutual coupling and reduced isolation. After introducing the cross-DGS, the ground-current distribution is further redistributed, which suppresses the remaining ground-current coupling and compensates for the isolation degradation caused by the metallic patch.

Therefore, the metal patch alone cannot provide consistent isolation enhancement over the entire frequency band; instead, it provides local electromagnetic tuning effect for subsequent composite decoupling designs. When the cross-DGS is further introduced, isolation performance in the 10–12 GHz range is improved, resulting in a more balanced isolation response over the operating band. This result indicates that the cross-DGS compensates for the isolation degradation introduced by the metal patch in the frequency range. Ultimately, the com-

bined effect of the isolation slot, embedded metal patch, and Cross-DGS improves the port isolation performance across the entire 6.5–14 GHz band.

Figure 8(c) compares the isolation performance of four configurations via simulated S_{31} and S_{41} characteristics during the evolution of the proposed composite decoupling structure. The results show that the composite decoupling structure effectively suppresses mutual coupling between adjacent antenna elements and improves the isolation of other port pairs.

3. EXPERIMENTAL RESULTS

3.1. S-Parameter Analysis

Figure 9 shows the fabricated prototype of the proposed four-port MIMO antenna. The fabricated antenna was measured using a vector network analyzer (VNA). During S -parameter measurements, the excited port was connected to a Vector Network Analyzer (VNA) through an SMA connector, while the remaining ports were terminated with 50 Ω matched loads. Measured S -parameters were compared with simulated results to validate antenna performance.

Figure 10 shows a comparison between simulated and measured S -parameters. As shown in Figure 10, in the 6.5–14 GHz operating band, all port reflection coefficients remain below -10 dB, and the adjacent-port isolation exceeds 20 dB. The results demonstrate that the fabricated antenna achieved the required impedance matching and isolation performance within the target operating band.

The isolation performance varies among different port combinations. The proposed decoupling structure is mainly designed to reduce the strong coupling between adjacent antenna elements, where near-field coupling and ground-current coupling have a major influence. Therefore, S_{21} maintains an isolation level better than 20 dB in the operating band. For non-adjacent ports, such as S_{13} , the coupling behavior is mainly related to the overall radiation field distribution and the relative positions of the antenna elements. As a result, relatively higher coupling occurs in the lower-frequency region. Nevertheless, the obtained isolation performance, combined with the low ECC and high DG, demonstrates the suitability of the proposed antenna for compact UWB-MIMO applications.

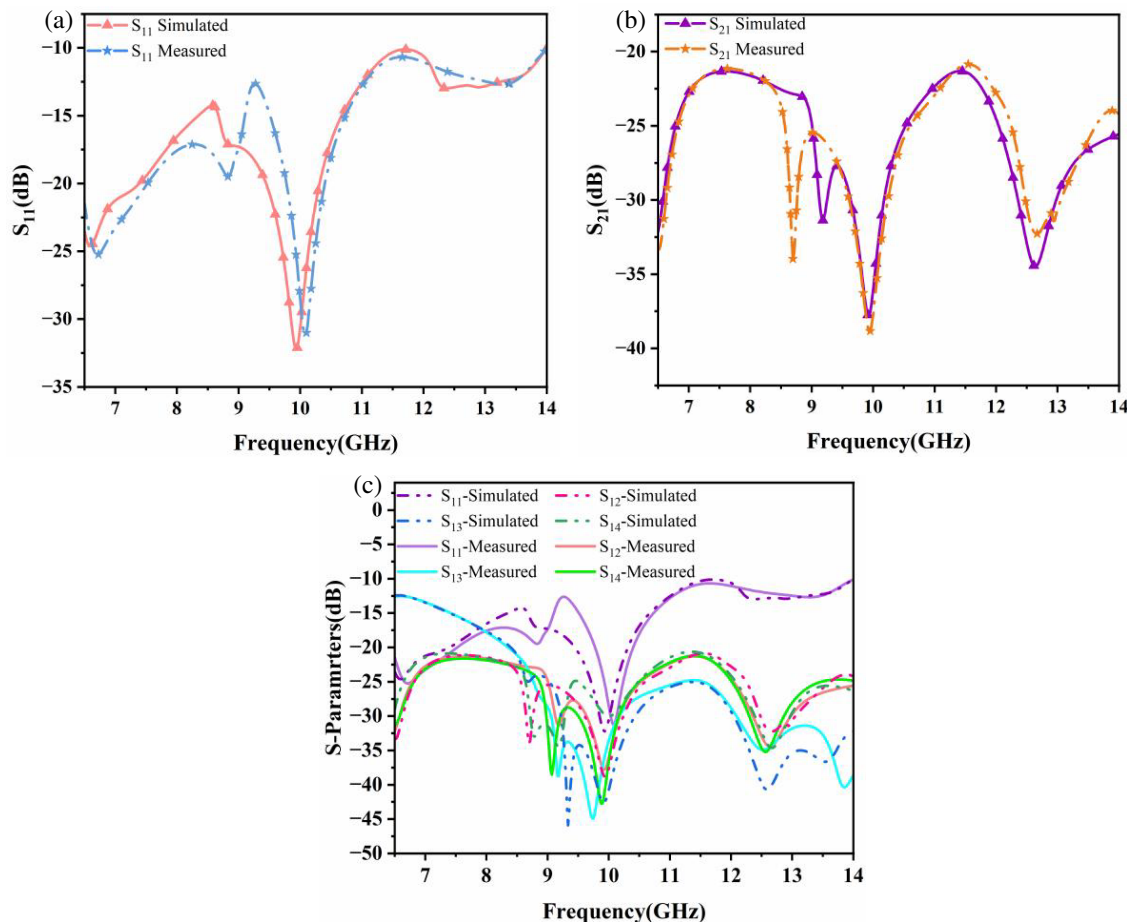


FIGURE 10. Simulated and measured S -parameters of the MIMO antenna.

3.2. Radiation Characteristics

Figure 11 presents simulated and measured two-dimensional radiation patterns of the proposed UWB-MIMO antenna in the E -plane ($\phi = 0^\circ$) and H -plane ($\phi = 90^\circ$) at 6.5, 9, 11.5, and 14 GHz. The radiation characteristics were measured in a standard microwave anechoic chamber under far-field conditions. Measured radiation patterns are compared with simulated results, and measured results generally follow simulated trends, although some discrepancies can be observed in certain angular regions. The results show that H -plane radiation patterns have quasi-omnidirectional radiation characteristics, whereas the E -plane patterns have dipole-like radiation characteristics.

Figure 12(a) presents simulated and measured gains of the proposed antenna. In the 6.5–14 GHz frequency range, the measured gain varies from 2.0 to 4.1 dBi.

It is worth noting that the proposed decoupling structure enhances isolation without introducing additional absorptive materials. The isolation improvement is achieved via current redistribution rather than energy dissipation. By maintaining the dominant radiation current distribution of the antenna elements, the proposed structure maintains stable gain and radiation efficiency while achieving adjacent-port isolation exceeding 20 dB over the 6.5–14 GHz operating band.

The radiation efficiency of the proposed antenna is defined as the ratio of the radiated power to the accepted input power, which can be expressed as

$$\eta_r = \frac{P_{rad}}{P_{acc}} \quad (2)$$

where P_{rad} represents the radiated power, and P_{acc} denotes the accepted input power.

As shown in Figure 12(b), the radiation efficiencies maintain relatively high values over the 6.5–14 GHz operating band. A reduction in efficiency is observed around 9 GHz, where the minimum efficiency is approximately 77%, which is mainly related to impedance matching characteristics and surface-current redistribution at this frequency.

The discrepancies between simulated and experimental results of the radiation pattern, gain, and radiation efficiency may be attributed to fabrication tolerances and measurement uncertainties.

3.3. Diversity Performance Analysis

The performance of MIMO antennas is typically assessed using several key parameters, including envelope correlation coefficient (ECC), diversity gain (DG), radiation efficiency, and total active reflection coefficient (TARC).

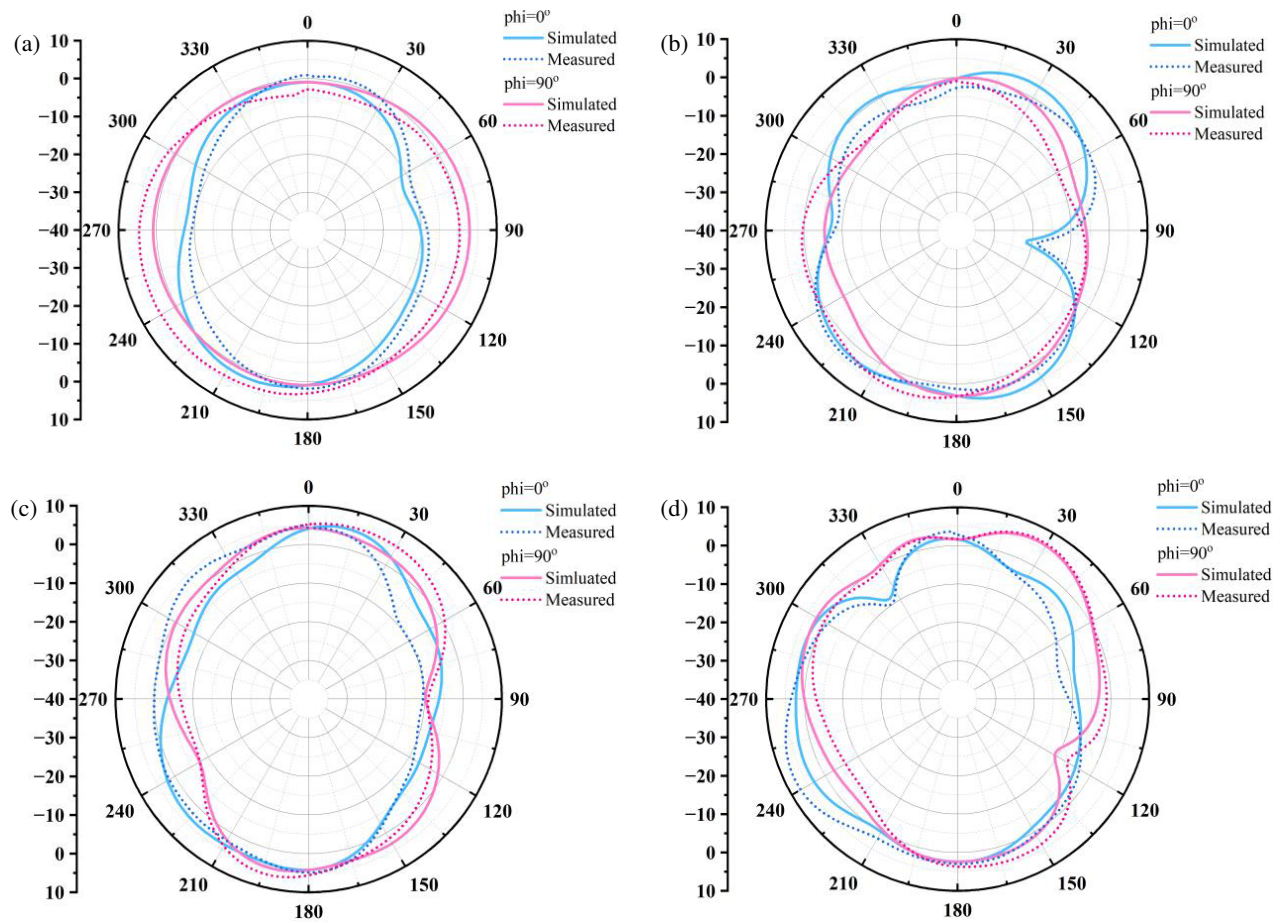


FIGURE 11. Radiation patterns at (a) 6.5 GHz, (b) 9 GHz, (c) 11.5 GHz, and (d) 14 GHz.

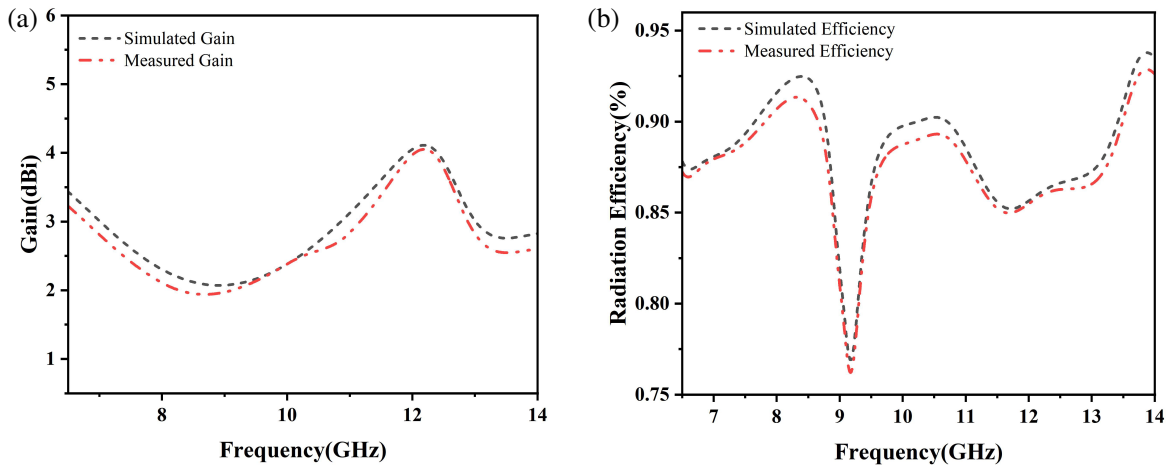


FIGURE 12. Simulated and measured radiation characteristics of the proposed antenna: (a) gain and (b) radiation efficiency.

Envelope correlation coefficient (ECC) and diversity gain (DG) are key parameters for evaluating the diversity performance of MIMO antennas. ECC characterizes the correlation between signals received by different antenna elements, where a lower ECC value indicates weaker correlation and better diversity performance. DG represents the improvement in diversity performance provided by spatial diversity. In practical MIMO applications, the ECC is generally required to be below

0.5. In this work, ECC is calculated using the S -parameter-based formulation for the proposed four-port MIMO antenna.

The corresponding expressions for calculating ECC and DG are given in Equations (3) and (4) [14], respectively.

$$|\rho_e(i, j, N)| = \frac{\sum_{n=1}^N S_{i,n}^* S_{n,j}}{\prod_{k=(i,j)} \left[\sum_{n=1}^N S_{i,n}^* S_{n,k} \right]} \quad (3)$$

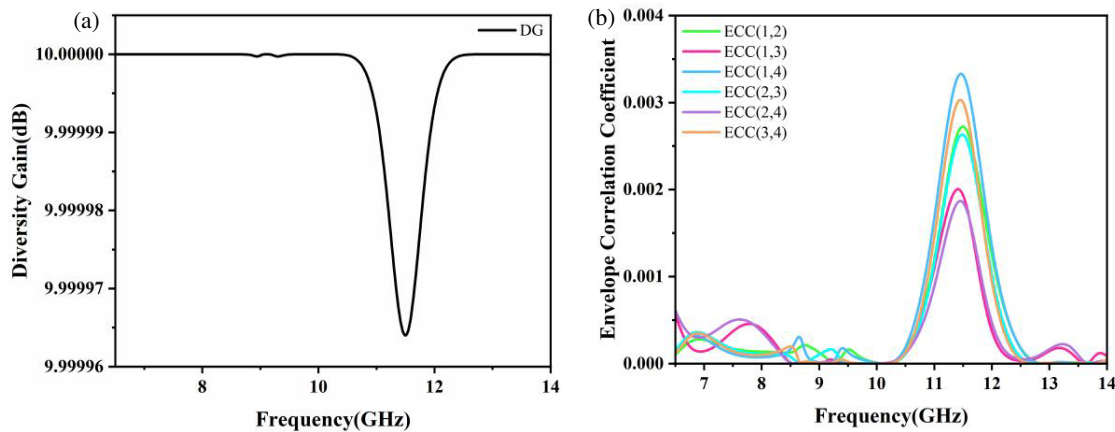


FIGURE 13. Envelope correlation coefficient and diversity gain of the proposed antenna.

TABLE 2. Comparative analysis of the proposed antenna with conventional designs.

Ref	Size (mm)	Bandwidth (GHz)	Isolation (dB)	Gain (dBi)	ECC
[1]	$36 \times 36 \times 0.8$	2–11.08	> 15	6.5	< 0.13
[4]	$45 \times 45 \times 1.6$	4.5–16.4	> 20	7.6	< 0.002
[10]	$65 \times 65 \times 1.6$	2.57–11.81	> 20	5.8	< 0.0095
[13]	$42 \times 42 \times 1$	3.09–12	> 16.4	5.1	< 0.02
[18]	$38 \times 38 \times 1.6$	2.71–19.70	> 19	8.9	< 0.08
[19]	$40 \times 48 \times 0.8$	5.6–6.1/8.7–10.8	> 25	4.8	< 0.05
[20]	$40 \times 32 \times 1.2$	4.24–19.70	> 22	8.5	< 0.02
This Work	$36 \times 36 \times 1.6$	6.5–14	> 20	4.1	< 0.0035

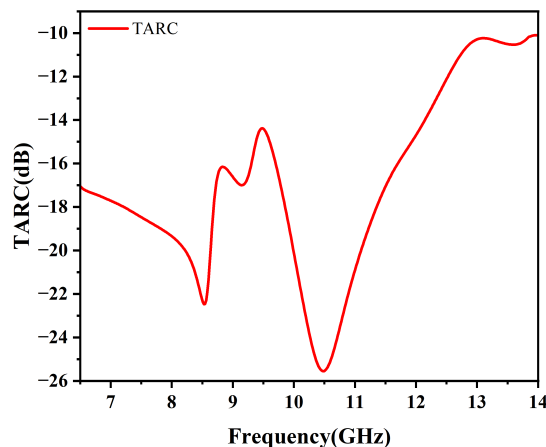


FIGURE 14. Simulated TARC characteristics of the proposed four-port MIMO antenna.

Here, consider the values of i , j , and $N = 1$ to 4 (for four elements).

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

Figure 13 shows simulated ECC and DG results for the proposed antenna. The ECC remains below 0.0035, and the DG is close to 10 dB across the operating band, demonstrating the good diversity of the proposed MIMO antenna.

TARC is calculated using the S -parameter-based formulation for the proposed four-port MIMO antenna under multi-port ex-

citations [10].

$$TARC = \frac{\sqrt{\sum_{i=1}^4 |S_{i1} + \sum_{n=2}^4 S_{in} e^{j\theta_{n-1}}|^2}}{2} \quad (5)$$

where S_{ij} denotes the S -parameter from port j to port i ; i and j are the port indices; n represents the excited port; and θ_{n-1} is the relative phase difference with respect to port 1. For the four-port MIMO antenna, $i, j = 1, 2, 3, 4$, and $n = 2, 3, 4$.

As shown in Figure 14, the simulated TARC remains below 10 dB over the operating band, indicating stable active impedance matching performance under different excitation phases.

3.4. Performance Comparison

Table 2 presents a performance comparison between the proposed four-port wideband MIMO antenna and previously reported MIMO antennas. Although the proposed antenna shows a slightly lower peak gain than some reported designs, it still achieves a gain of approximately 4.1 dBi over the operating band. The reduced gain is mainly related to the compact antenna size and the integration of the composite decoupling structure, which modifies the surface-current distribution to suppress mutual coupling.

Compared with designs optimized for a single parameter, the proposed antenna achieves a balanced trade-off among size,

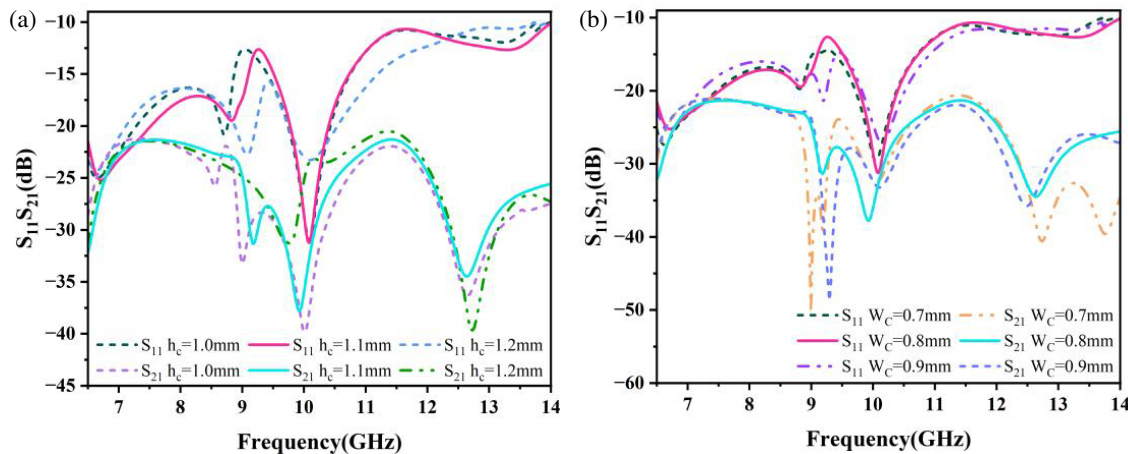


FIGURE 15. Simulated effects of fabrication tolerances on the impedance matching and isolation performance with variations of (a) h_C and (b) W_C .

bandwidth, isolation, diversity characteristics, and gain. The composite decoupling structure enhances isolation by regulating multiple coupling paths without increasing the antenna footprint, making the proposed design suitable for compact UWB-MIMO applications.

4. PRACTICAL CONSIDERATIONS

4.1. Ground Configuration and Integration Issues

The proposed four-element MIMO antenna uses separated ground configurations instead of a conventional common ground plane. This configuration provides additional flexibility in controlling current distribution and reduces coupling currents associated with shared ground-current propagation, resulting in improved isolation. Together with the proposed composite decoupling structure, the separated ground configuration contributes to suppressing multiple coupling paths while maintaining compact antenna size and acceptable radiation performance.

Compared with MIMO antennas using a common ground plane, the separated ground configuration requires additional considerations during practical implementation. The interface between the antenna and RF front-end circuits needs to be properly designed to maintain stable current return paths. Moreover, the influence of the device chassis, feeding network, and surrounding components should be taken into account in practical MIMO terminals, which may require further optimization at the system level.

4.2. Fabrication Tolerance Analysis

The fabrication tolerance of the proposed composite decoupling structure was analyzed by varying critical dimensions (h_C and W_C) of the non-through isolation slot, which simultaneously determines the corresponding configuration of the embedded metallic patch. Figure 15 presents variations of h_C and W_C and their effects on impedance matching and isolation performance.

Only slight changes are observed in simulated isolation curves with dimensional variations, while isolation performance and impedance matching remain stable over the

6.5–14 GHz operating band. Therefore, $h_C = 1.1$ mm and $W_C = 0.8$ mm are selected as final design values by considering both broadband performance and fabrication tolerance. In particular, the antenna maintains relatively stable performance under approximately ± 0.1 mm dimensional variations of both h_C and W_C , which is suitable for practical PCB fabrication.

5. CONCLUSION

This paper proposes a four-element high-isolation ultra-wideband MIMO antenna with overall dimensions of $36 \text{ mm} \times 36 \text{ mm} \times 1.6 \text{ mm}$. A composite decoupling structure integrating a non-through isolation slot, an embedded metallic patch, and a cross-DGS is proposed to regulate multiple coupling paths, including direct near-field coupling and ground-current coupling. The proposed structure enhances port isolation while preserving compact antenna configuration and radiation characteristics. Simulated and measured results demonstrate that the antenna operates over the 6.5–14 GHz frequency band, with the adjacent-port isolation exceeding 20 dB, an ECC below 0.0035, and a DG close to 10 dB. With its wide operating bandwidth, compact configuration, enhanced isolation, and good diversity performance, the proposed antenna shows potential for compact UWB-MIMO terminals requiring low mutual coupling.

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