

A HIGH-ISOLATION WIDEBAND MIMO ANTENNA WITH HYBRID DGS–EBG DECOUPLING FOR SUB-6 GHz 5G APPLICATIONS

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Abstract - This study proposes a wideband four-port MIMO antenna for sub-6 GHz wireless communication systems. The antenna employs four elliptical-slotted radiating elements arranged orthogonally on a 0.762-mm-thick Rogers RO4350B substrate and a hybrid decoupling structure combining a T-shaped defected ground structure with a via-loaded electromagnetic bandgap structure. Six prototypes with overall dimensions of $118 \times 118 \times 0.762 \text{ mm}^3$ were fabricated and measured to evaluate antenna performance and fabrication repeatability. The six prototypes exhibit a mean operating frequency range of 2.25 – 6.82 GHz and a mean minimum isolation of 26.9 dB. The antenna achieves a realized gain of 2.7 – 5.9 dBi, a total radiation efficiency exceeding 85%, and an envelope correlation coefficient below 0.002. These results demonstrate that the antenna is well suited for sub-6 GHz wireless communication applications.

Key words - Wideband MIMO antenna; hybrid DGS–EBG decoupling; high isolation; sub-6 GHz wireless systems

1. Introduction

The rapid development of next-generation wireless communication systems has imposed increasingly stringent requirements on MIMO antennas in terms of operating bandwidth, inter-element isolation, and radiation performance. Technologies such as 5G, 5G-Advanced, Wi-Fi 6/6E/7, private 5G, and small-cell networks operate in the sub-6 GHz frequency range and require a single antenna platform capable of supporting multiple communication standards [1] – [3]. Consequently, wideband MIMO antennas have become an attractive solution for improving spectrum utilization, channel capacity, and link reliability.

When multiple antenna elements are placed in close proximity, strong mutual coupling degrades the input impedance, radiation efficiency, diversity performance, and inter-element isolation. Therefore, suppressing mutual coupling remains one of the primary challenges in wideband MIMO antenna design.

Several decoupling techniques have been reported, including orthogonal element arrangement, defected ground structures (DGS), electromagnetic bandgap (EBG) structures, metasurfaces, and hybrid decoupling approaches [4] – [8]. Although these methods improve isolation, they often involve trade-offs among operating bandwidth, antenna size, gain, radiation efficiency, and fabrication complexity. Consequently, achieving wide bandwidth, high isolation, and stable MIMO performance

over the continuous sub-6 GHz frequency range remains challenging.

Instead of pursuing highly compact configurations, some recent studies have adopted larger antenna apertures to achieve both wide bandwidth and high gain. For example, Rakluea et al. [9] reported a four-port MIMO antenna operating from 0.7 to 7 GHz with a peak gain of approximately 10 dBi. However, its overall dimensions of $500 \times 500 \text{ mm}^2$ limit its applicability to fixed wireless infrastructure.

Building upon our previous 2×2 UWB MIMO antenna for sub-6 GHz 5G applications [10], this work introduces an elliptical slot to extend the upper operating frequency for Wi-Fi 6E/7 coverage and develops a hybrid decoupling structure combining a T-shaped DGS with centrally located via-loaded EBG cells. Six prototypes were fabricated and experimentally characterized to validate both the antenna performance and fabrication repeatability. In addition, the decoupling mechanism is investigated through surface current and electric-field distributions, providing physical insight into the achieved isolation enhancement.

2. Single Antenna Element Design

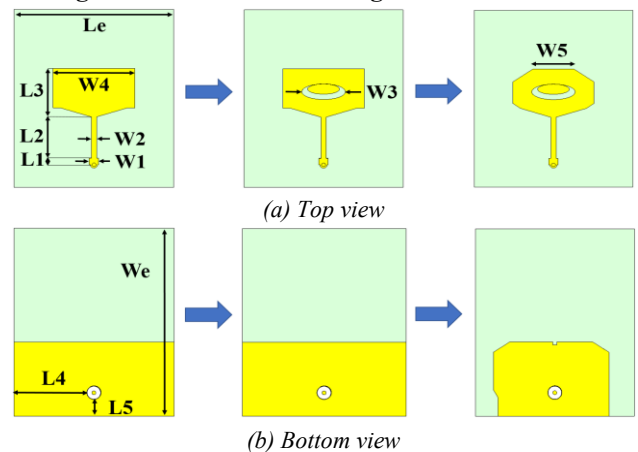


Figure 1. Evolution of the proposed single antenna element

The four-port MIMO antenna is developed from a single wideband monopole fabricated on a 0.762-mm-thick RO4350B substrate ($\epsilon_r=3.66$). Figure 1 shows its design evolution, and the optimized dimensions are listed in Table 1. The initial resonant frequency is determined from the geometrical parameters according to [11]:

$$f_r = \frac{15.3}{11 + 12 + b + \frac{R_1}{2\pi\sqrt{\epsilon_r + 1}} + \frac{R_2}{2\pi\sqrt{\epsilon_r + 1}}} \quad (1)$$

where, R_1 and R_2 are the ground and patch areas, respectively; b is their separation; and l_1 and l_2 are the corresponding lengths.

The antenna is excited through a vertically mounted 50 Ω SMA connector. A two-section microstrip feed line provides impedance matching, with its characteristic impedance determined using the Hammerstad equations [12]:

$$Z = \frac{120\pi}{\sqrt{\epsilon_{\text{eff}}} \times \left[\frac{W}{h} + 1.393 + \frac{2}{3} \times \ln\left(\frac{W}{h} + 1.444\right) \right]} \quad (2)$$

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \times \left(1 + 12 \times \frac{h}{W} \right)^{-\frac{1}{2}} \quad (3)$$

where, W is the width of the microstrip line and h is the substrate thickness.

Figure 2 shows the reflection-coefficient evolution. The initial monopole operates from 2.5 to 6.1 GHz. Introducing the elliptical slot creates an additional resonance near 6 GHz, while corner chamfering further improves impedance matching, extending the operating band to 2.5–6.64 GHz.

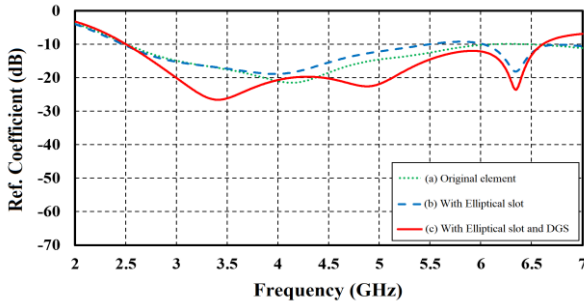


Figure 2. Simulated reflection coefficients during the evolution of the single antenna element

Figure 3 shows typical monopole radiation characteristics at 5 GHz, with a realized gain of 4.32 dBi and a radiation efficiency of 97.8%.

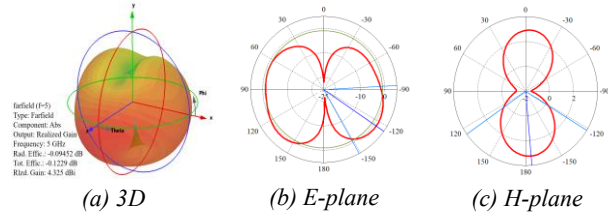


Figure 3. Simulated 3D and 2D radiation patterns of the optimized single antenna element at 5 GHz

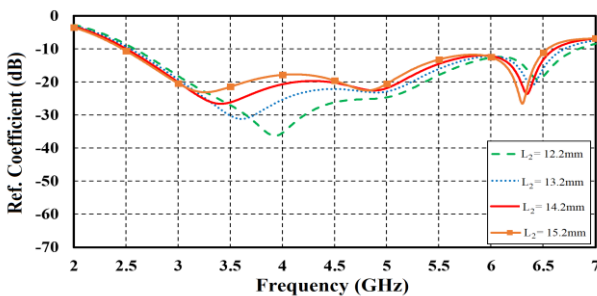


Figure 4. Effect of L_2 on the reflection coefficient

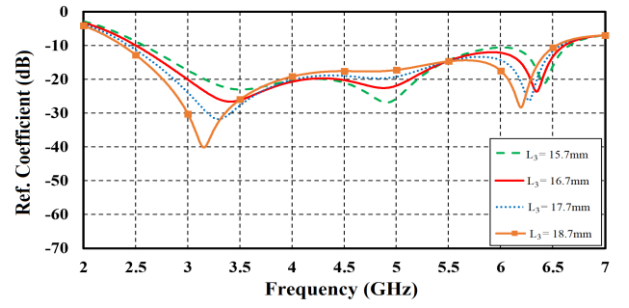


Figure 5. Effect of L_3 on the reflection coefficient

Figure 4 and Figure 5 show the influence of parameters L_2 and L_3 . Increasing L_2 mainly shifts the resonance toward lower frequencies and slightly reduces the impedance bandwidth, whereas increasing L_3 extends the operating band toward lower frequencies. Based on the parametric analysis, the optimized dimensions listed in Table 1 are selected.

Table 1. Optimized design dimensions

Parameter	Value (mm)	Parameter	Value (mm)
Le	50	We	61.15
L1	2.27	W1	2.92
L2	14.2	W2	1.62
L3	16.7	W3	13.7
L4	22.8	W4	25.6
L5	5.53	W5	12.9
L6	30.4	W6	16.1
L7	50	W7	8
L	118	-	-

3. Proposed 4-port MIMO Antenna Design

3.1. Antenna Configuration and Isolation Structure

Figure 6 illustrates the geometry of the proposed 4-port MIMO antenna, which occupies an overall size of $118 \times 118 \times 0.762$ mm³. The antenna is developed by arranging four identical broadband monopole elements, introduced in Section 2, in an orthogonal configuration. This arrangement inherently improves polarization diversity while providing sufficient spacing for the integration of the decoupling structure.

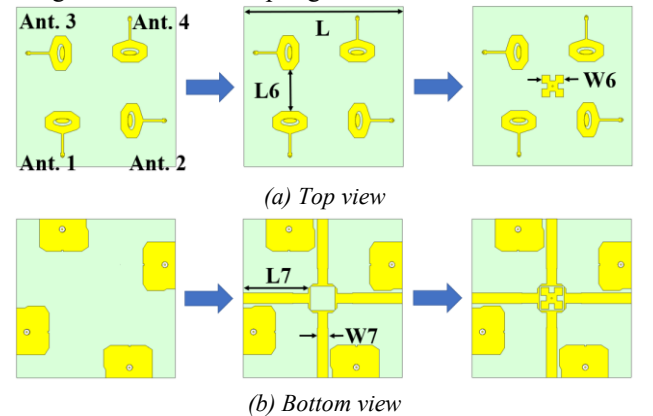


Figure 6. Geometry of the proposed 4-port MIMO antenna

To further suppress mutual coupling between adjacent antenna elements, a hybrid isolation structure combining a DGS and a via-loaded EBG structure is employed. As

shown in Figure 6(b), four T-shaped DGS sections are symmetrically etched on the ground plane beneath the antenna elements. These structures modify the surface current distribution and increase the effective current path, thereby reducing electromagnetic coupling through the ground plane.

To enhance the isolation over the entire operating band, a square EBG cell with truncated corners is placed at the center of the antenna. A metallic via connects the EBG patch to the ground plane, forming a resonant structure that suppresses surface-wave propagation around its operating frequency. The DGS primarily mitigates coupling between adjacent elements, whereas the centrally located via-loaded EBG further suppresses coupling between diagonally positioned elements. The combination of these two mechanisms forms a hybrid decoupling structure that improves isolation while maintaining the impedance bandwidth of the antenna.

3.2. Simulated S-Parameters and Isolation Performance

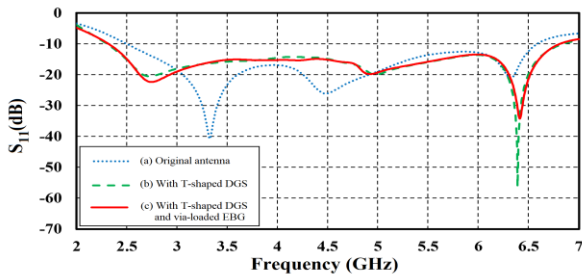


Figure 7. Simulated reflection coefficients during the design evolution

Figure 7 shows the simulated reflection coefficients during the design evolution. The four-element antenna without the isolation structure maintains the 2.50–6.64 GHz bandwidth of the single element. After incorporating the hybrid decoupling structure, the operating band extends to 2.32–6.81 GHz, with a minimum reflection coefficient of –37.4 dB at 6.41 GHz.

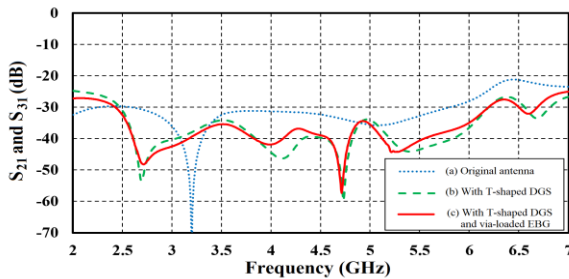


Figure 8. Simulated S_{21} and S_{31} responses

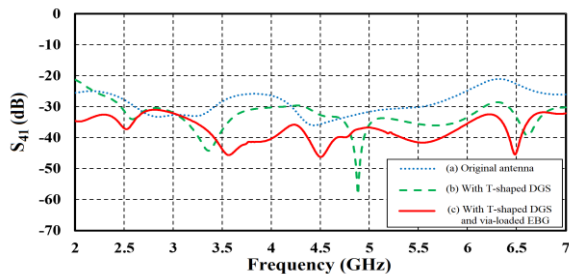


Figure 9. Simulated S_{41} response

The simulated isolation characteristics are illustrated in Figures 8 and 9. Owing to the orthogonal arrangement of Antennas 2 and 3 with respect to Antenna 1, the transmission coefficients S_{21} and S_{31} exhibit nearly identical responses throughout the operating band. The optimized antenna achieves a minimum isolation better than 27.63 dB for all antenna pairs.

The contribution of each decoupling component is evaluated at three design stages. The orthogonal configuration alone provides approximately 21 dB isolation. Adding the T-shaped DGS improves S_{21} and S_{31} by about 6–7 dB, while the via-loaded EBG provides an additional 2–14 dB improvement in S_{41} over 3–6.5 GHz.

3.3. Isolation Mechanism and Parametric Analysis

Figure 10 illustrates the simulated surface current distributions at different design stages. Strong induced currents are observed on adjacent elements in the reference structure. The T-shaped DGS suppresses current propagation through the common ground, while the via-loaded EBG further reduces the residual current toward the diagonally positioned elements. Consequently, the hybrid structure effectively suppresses mutual coupling over the operating band.

The corresponding electric-field distributions in Figure 10 further clarify this mechanism. Without the decoupling structure, strong fields extend from the excited element toward the other radiators. After introducing the DGS–EBG structure, the field intensity around the non-excited elements is substantially reduced, confirming the suppression of the dominant coupling paths.

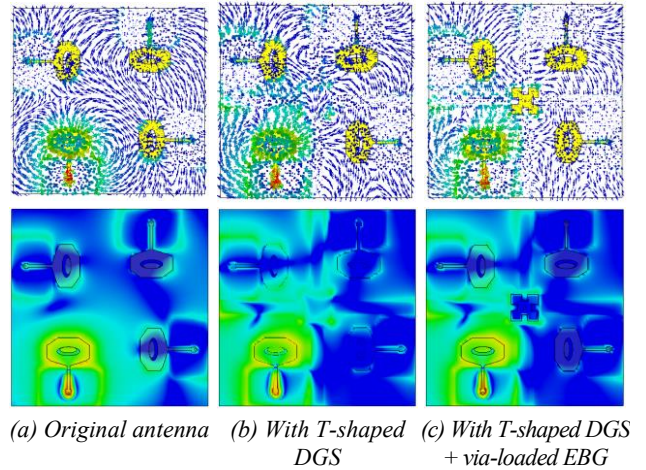


Figure 10. Simulated surface current and electric-field distributions

To further investigate the influence of the isolation structure, a parametric analysis is performed for the key dimensions L_7 and W_7 , which determine the electrical length and width of the T-shaped DGS. The simulated transmission coefficients corresponding to different parameter values are presented in Figures 11–14.

As shown in Figures 11 and 12, reducing L_7 from 50 mm to 47 mm weakens the isolation performance, particularly in the 3.5–6.0 GHz band for S_{21}/S_{31} and the 4.5–6.0 GHz band for S_{41} . In addition, the isolation peaks gradually shift toward lower frequencies, indicating

that L_7 mainly controls the resonant frequency of the isolation structure.

The influence of the parameter W_7 is illustrated in Figures 13 and 14. Increasing W_7 from 5 mm to 8 mm improves the isolation level within the upper operating band, while simultaneously shifting the isolation peaks toward lower frequencies. These results indicate that W_7 mainly affects the coupling strength and impedance characteristics of the hybrid decoupling network. Based on the parametric investigation, the optimized dimensions listed in Table 1 are selected for the final antenna design.

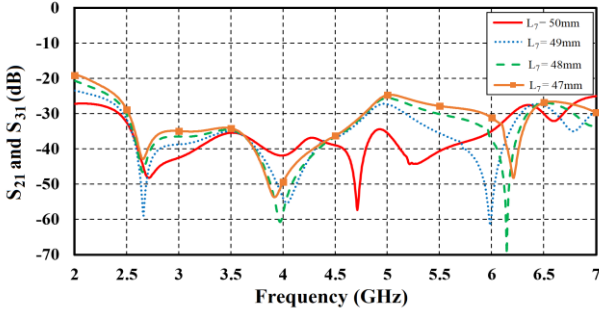


Figure 11. Effect of the parameter L_7 on S_{21} and S_{31}

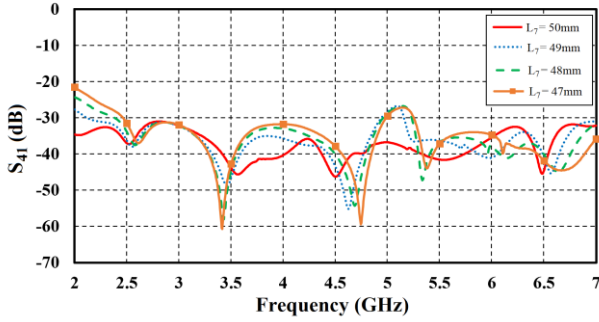


Figure 12. Effect of the parameter L_7 on S_{41}

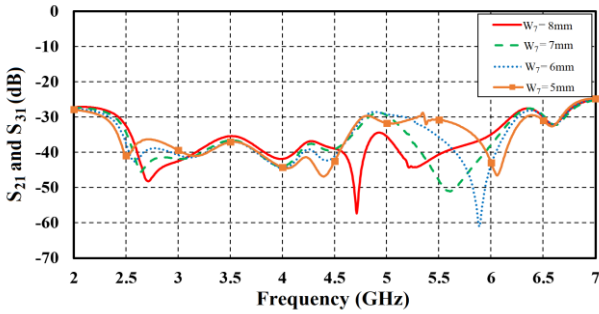


Figure 13. Effect of the parameter W_7 on S_{21} and S_{31}

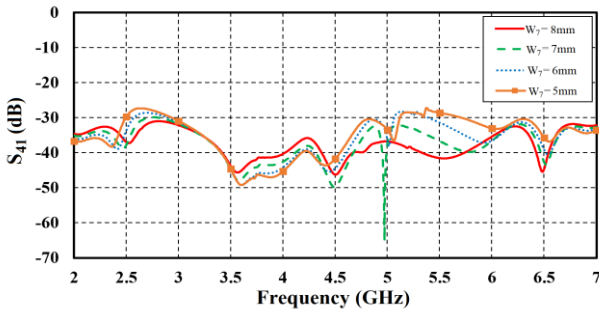


Figure 14. Effect of the parameter W_7 on S_{41}

3.4. Simulated Radiation and MIMO Characteristics

The MIMO performance of the proposed antenna is further evaluated in terms of the envelope correlation coefficient (ECC) [13], realized gain, radiation efficiency, and radiation characteristics. These parameters are widely used to assess the diversity capability and radiation performance of MIMO antennas. The ECC is evaluated from the simulated three-dimensional far-field radiation patterns, while the realized gain and radiation efficiency are obtained directly from the full-wave electromagnetic simulations.

Figure 15 presents the simulated ECC of the antenna. Owing to the combined effects of the orthogonal antenna arrangement and the proposed hybrid isolation structure, the correlation between antenna elements remains extremely low throughout the operating band. The maximum ECC is lower than 0.002, which is significantly below the commonly accepted criterion of 0.5, indicating excellent diversity performance and negligible mutual correlation between antenna elements.

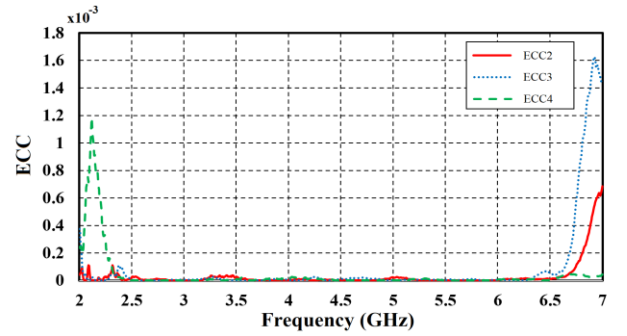


Figure 15. ECC of the proposed 4-port MIMO antenna

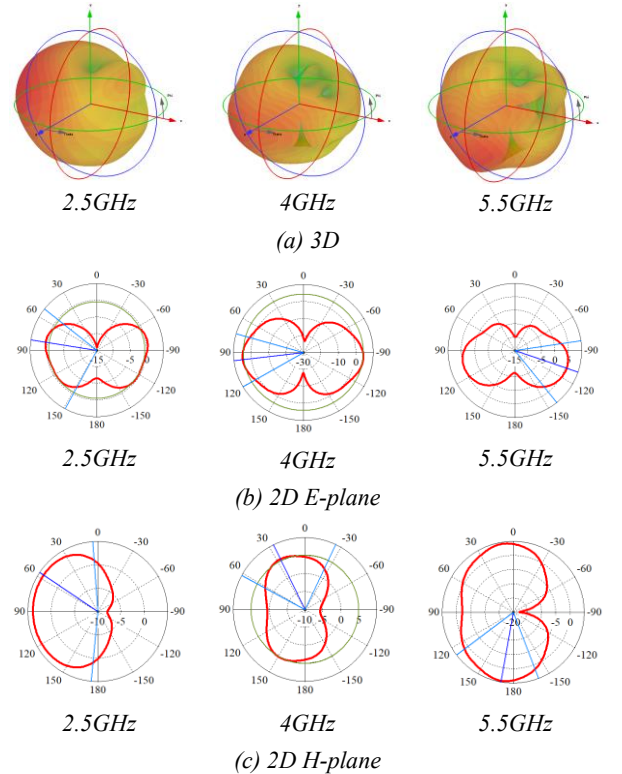


Figure 16. Simulated 3D and 2D radiation patterns

The simulated radiation characteristics at representative Sub-6 GHz frequencies are illustrated in Figure 16. The radiation patterns remain stable over the operating band. On the E-plane, the main radiation is concentrated in the forward and backward directions with beamwidths ranging from 46° to 100°, whereas the H-plane exhibits the typical bidirectional radiation behavior of monopole antennas. These results indicate that the hybrid isolation structure has negligible influence on the antenna radiation characteristics.

The simulated realized gain and antenna efficiencies are presented in Figure 17 and Figure 18, respectively.

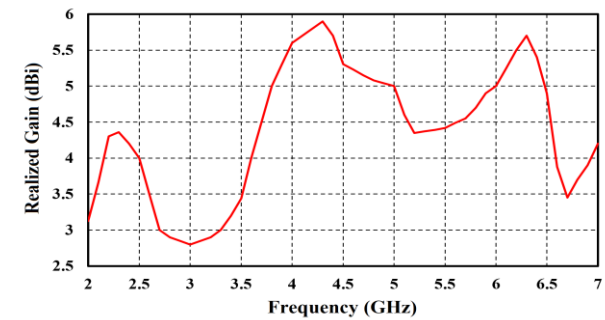


Figure 17. Realized gain characteristics

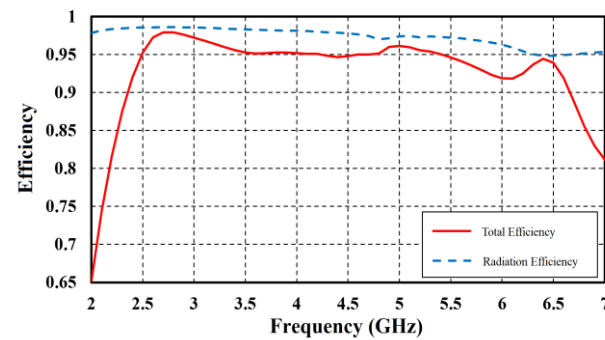


Figure 18. Radiation and total efficiency

Over the operating band of 2.32–6.81 GHz, the realized gain varies from 2.7 dBi to 5.9 dBi, reaching its maximum value at 4.25 GHz. Meanwhile, the radiation efficiency remains between 95% and 98.6%, whereas the total efficiency varies from 85.6% to 98%.

The above results are obtained from full-wave electromagnetic simulations. Experimental validation of the developed antenna, including the measured S-parameters and comparison with the simulated results, is presented in the following section.

4. Experimental Validation and Discussion

4.1. Prototype Fabrication and Measurement Setup

The fabricated prototypes and measurement setup are shown in Figure 19. The outer conductor of each SMA connector is soldered directly to the ground plane, while the inner conductor is connected to the corresponding microstrip feed line. The S-parameters were measured using a Rohde & Schwarz ZNB20 VNA calibrated over the frequency range of interest, with the remaining ports terminated by matched 50 Ω loads.

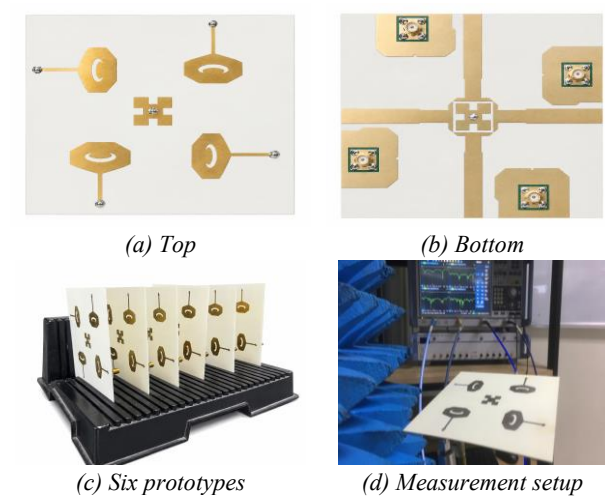


Figure 19. Fabricated prototypes and measurement setup

4.2. Measured S-Parameters

4.2.1. Repeatability

To evaluate fabrication repeatability, six independent prototypes were fabricated and measured under the same conditions. The measured results are presented in Figure 20, and the corresponding characteristic parameters are summarized in Table 2.

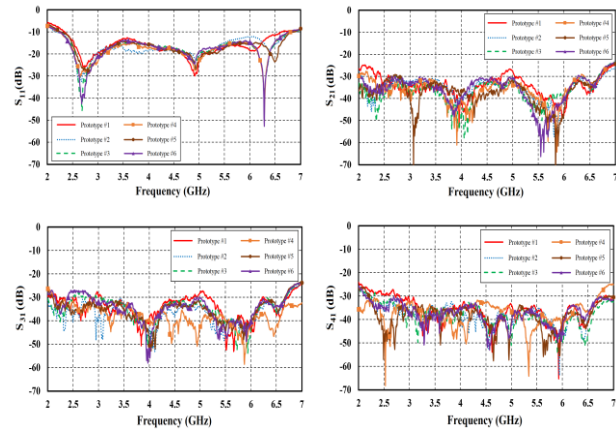


Figure 20. Repeatability evaluation of the six prototypes

Figure 20 shows that the reflection responses of the six prototypes nearly overlap across the operating band, with only small deviations around the resonant frequencies. The transmission coefficients S_{21} , S_{31} , and S_{41} maintain an isolation level greater than 26.6 dB throughout the operating band.

Table 2. Characteristic parameters of the six prototypes

Prototype	f_L (GHz)	f_H (GHz)	FBW (%)	Min. Iso. (dB)
#1	2.32	6.81	98.36	27.6
#2	2.19	6.78	102.34	27.1
#3	2.25	6.84	100.99	26.6
#4	2.23	6.81	101.33	26.7
#5	2.26	6.88	101.09	26.6
#6	2.23	6.79	101.11	26.8
Mean (μ)	2.25	6.82	100.87	26.9
Standard deviation (S)	0.043	0.037	1.33	0.39
Coefficient of variation (%)	1.92	0.54	1.32	1.45

As summarized in Table 2, the coefficients of variation are below 2% for all evaluated parameters. The lower and upper operating frequencies show standard deviations of 0.043 and 0.037 GHz, respectively, while the minimum isolation averages 26.9 dB with a standard deviation of 0.39 dB. The small variations may result from PCB fabrication tolerances, substrate dielectric variations, and SMA connector assembly errors, confirming good fabrication repeatability. Prototype #1 is used for the detailed simulation–measurement comparison below.

4.2.2. Reflection Coefficient

Figure 21 compares the simulated and measured reflection coefficients of Prototype #1. The measured 2.32–6.81 GHz bandwidth ($S_{11} < -10$ dB) agrees well with the simulated result, with only minor variations in impedance matching.

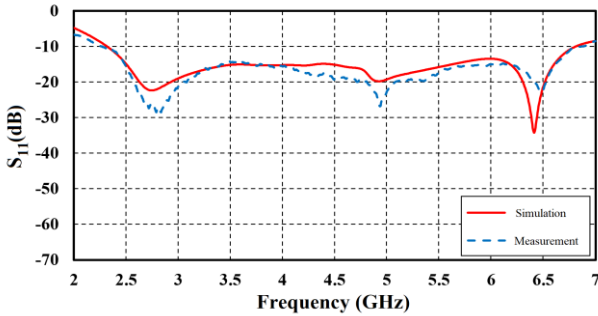


Figure 21. Simulated and measured reflection coefficients

4.2.3. Isolation Characteristics

The measured transmission coefficients of Prototype #1 are compared with the simulated results in Figures 22–24. Similar trends are observed throughout the operating band, with the measured isolation remaining above 27.6 dB over most of the frequency range and showing only slight degradation in the 2.5–3.5 and 4.3–5.5 GHz regions.

In particular, the measured S_{41} response closely follows the simulated isolation peaks, confirming the effectiveness of the DGS–EBG structure for diagonal-element decoupling. The remaining discrepancies can be attributed

to PCB fabrication tolerances, substrate-property variations, SMA soldering, and measurement uncertainties.

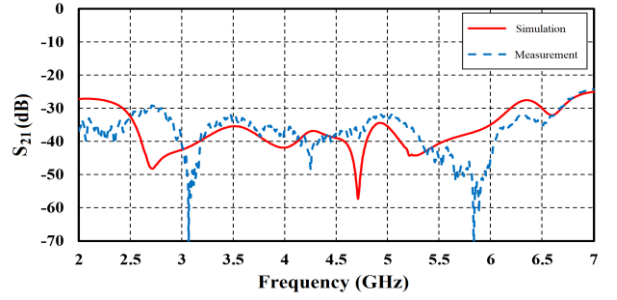


Figure 22. Simulated and measured S_{21} parameters

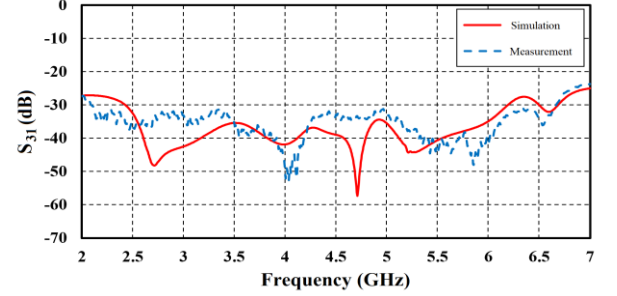


Figure 23. Simulated and measured S_{31} parameters

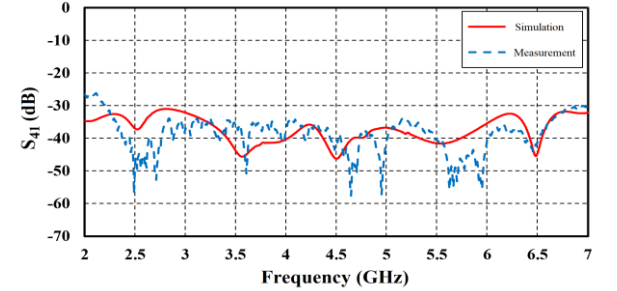


Figure 24. Simulated and measured S_{41} parameters

4.3. Discussion and Comparison with Previous Works

Table 3 compares the developed antenna with recently reported wideband MIMO antennas for sub-6 GHz wireless communications.

Table 3. Comparison with recently reported wideband MIMO antennas for sub-6 GHz wireless communications

Ref.	Ports	Overall Dimensions (mm × mm)	Operating Band (GHz)	Min. Isolation (dB)	Peak Gain (dBi)	ECC	Isolation Technique	Design Complexity (Low/ Moderate/ High)
[7]	2	31 × 50	2.76–5.32	20	3.5	<0.005	Metamaterial + Neutralization Line	High
[9]	4	500 × 500	0.7–7.0	15	10	<0.005	Large-aperture array	Moderate
[14]	4	54 × 54	3.50–11.00	17	5.0	<0.030	Orthogonal arrangement	Low
[15]	2	150 × 100	2.47–2.55	20	6.1	<0.003	Grounded Stubs + DGS	Moderate
[16]	2	40 × 21	2.94–11.61	18	4.21	<0.002	Self-Isolated DGS	Moderate
[17]	4	34 × 34	1.82–6.50	20	7.03	<0.004	Isolation Branches	Low
[18]	4	40.5 × 60	3.11–7.67	18.5	3.7	<0.015	Filtering Monopole + SRR + Inverted L-Stub	High
[19]	2	60 × 28	3.95–13.60	19	5.65	<0.023	Triple-T DNG Metamaterial Wall	High
This work	4	118 × 118	2.25–6.82*	26.9*	5.9	<0.002	T-Shaped DGS + Via-Loaded EBG	Moderate

*Mean values obtained from six independently fabricated prototypes.

The design complexity in Table 3 is qualitatively evaluated considering the substrate configuration, isolation technique, feeding network, additional components, and fabrication requirements. Compared with the reported designs, the developed antenna achieves the highest minimum isolation while maintaining wideband operation, low ECC, and a realized gain of 5.9 dBi. Although its $118 \times 118 \text{ mm}^2$ footprint is larger than several compact designs, the size accommodates four elements operating from 2.25 GHz without aggressive miniaturization. The antenna is implemented on a standard two-layer RO4350B PCB using a T-shaped DGS and a centrally located via-loaded EBG, without multilayer substrates, external decoupling circuits, or lumped RF components. This configuration results in moderate design complexity and conventional PCB fabrication requirements, providing a practical compromise among bandwidth, isolation, manufacturability, and implementation cost.

5. Conclusion

This paper presents a wideband four-port MIMO antenna employing a hybrid decoupling structure consisting of an orthogonal element arrangement, a T-shaped DGS, and a via-loaded EBG structure. Measurements of six independently fabricated prototypes yield a mean operating frequency range of 2.25–6.82 GHz and a mean minimum isolation of 26.9 dB, demonstrating good fabrication repeatability. The antenna exhibits an envelope correlation coefficient below 0.002, a peak realized gain of 5.9 dBi, and a total efficiency exceeding 85%. Good agreement between the simulated and measured results validates the proposed design. Owing to its balanced performance, simple planar structure, and standard two-layer PCB implementation, the antenna is a promising candidate for practical sub-6 GHz multi-antenna wireless communication systems.

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