(Received 6 March 2024, Accepted 19 May 2024, Scheduled 20 June 2024)

Interconnected Ground Plane Structure Based High Isolation, Dual Band Quad-Element MIMO Antenna for C-Band, and X-Band Applications

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ABSTRACT: This paper presents a dual band orthogonal quad-element multiple input multiple output (MIMO) antenna for C-band and X-band applications. Each antenna element of the proposed MIMO antenna contains a deformed rectangle-shaped radiating patch etched with two circular slots of different radii on the top surface and partial ground plane in the bottom surface. The modified partial ground structure is used in the bottom to enhance the bandwidth of the antenna. The orthogonal arrangement of the proposed quad-element MIMO antenna is designed and fabricated with a distinct gap of $d > \lambda/2$ between individual antenna elements. The interconnected ground plane was introduced in the bottom of the proposed quad-element MIMO antenna for high isolation. The proposed MIMO antenna has an overall size of $1.69\lambda \times 1.69\lambda \times 0.022\lambda$ (at 4.23 GHz) and exhibits the measured double operating bands ($S_{11} < -10$) covering 4.23–4.55 GHz and 6.30–10.22 GHz with the high isolation of > 27 dB and > 32 dB, respectively. Both the operating bands have simulated peak gain of 5.73 dBi and peak efficiency of 72% over the entire operating range. Furthermore, the presented antenna has good diversity performance with envelope correlation coefficient (ECC) < 0.001, diversity gain (DG) of 9.996 dB, and total active reflection coefficient (TARC) < -10 dB. The simulated and measured results of proposed MIMO antenna are in good agreement.

1. INTRODUCTION

Over the last decade, the deployment from wired to wireless communication is growing with the requirement of high data rate, more reliable and secure communication in electromagnetic scattering environment. Various factors such as multipath fading, signal deviation with obstructed path, flexible and high signal transfer speed have major attention from researchers and academicians [1]. As per user's requirement for future communication, MIMO technique is widely adopted to increase the reliability and efficiency of spectrum in comparison of single antenna. In MIMO technique, multiple antennas are used at both the transmitter and receiver to work simultaneously with minimum coupling. When two or more radiating elements are located near each other, mutual coupling occurs due to electromagnetic (EM) interaction between the elements [2, 3]. Hence, MIMO antennas are analysed with diversity parameters such as low envelope correlation coefficient (ECC), high isolation, and good diversity gain (DG). In recent years, numerous MIMO antennas have been presented in literature to enhance the antenna performance based on defected ground structure (DGS) [4, 5], electronic band gap (EBG) elements [6, 7], antenna placement [8], dielectric resonator (DR) [9], artificial magnetic conductor (AMC) surface [10, 11], neutralization techniques [12–14], and lumped circuit networks [15]. A two-port fractal shaped MIMO antenna with interconnected ground plane is designed to enhance the isolation [16].

In the past years, the great interest of researchers has been intended to design multiband antennas. A novel dual-band MIMO antenna is demonstrated in [17], for WiMAX applications. Two rings are used in antenna design to operate in two bands as 2.3–2.4 GHz and 3.3–3.7 GHz. In [18], a compact dual-band MIMO antenna with reactive dummy loaded element array is reported to achieve isolation > 20 dB at lower band and > 25 dB at higher band. A modified H-shaped dual-band MIMO design is presented and operates in 3.6 GHz and 4.1 GHz frequency bands [19]. The decoupling surface is used to enhance the isolation. A CPW-fed dual-band MIMO antenna with two orthogonal slotted patches is designed in [20], which operates in frequency bands of 2.25–3.15 GHz. The isolation (> 15 dB) can be achieved by using defected ground plane with rectangular strips. Another, dual-band MIMO antenna is proposed for 5G mobile applications. The common ground plane between the radiating elements plays an important role to improve isolation [21]. A similar concept is used in [22], to obtain the isolation > 15 dB using quarter circular rings and a neutral line. Based on the concise study, several dual-band MIMO antennas are designed with DGS and common ground techniques to increase the isolation.

In this article, a quad-element orthogonal MIMO antenna is presented for C-band and X-band applications. Initially, the unit cell antenna is designed by implementing two circular slots

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in radiating patch on top surface and a partial ground structure on back surface to achieve dual bands covering 4.27–4.52 GHz and 6.47–10.15 GHz bandwidths. Further, a proposed interconnected ground plane quad-element MIMO antenna is designed and fabricated in orthogonal manner by putting the four radiating elements with the spacing of $d > \lambda/2$ between individual antenna elements to achieve high isolation and high diversity performance. The novelty of the proposed MIMO design is discussed in terms of simple design geometry and good diversity performance. The proposed quad-element MIMO antenna has good isolation without any complex decoupling techniques. By using partial ground and connected ground, wide band and better impedance matching are achieved. The proposed interconnected ground plane quad-element MIMO antenna configuration provides dual bands of 4.29–4.54 GHz and 6.40–10.40 GHz, with high isolation of > 27 dB and > 32 dB, respectively. The proposed MIMO antenna has simulated peak gain about 5.73 dBi, high diversity performance especially ECC < 0.001, DG > 9.996 dB, and TARC < -10 dB over the entire dual frequency bands. It is a favourable candidate for C-band and X-band future applications.

The entire paper is structured as follows. Section 2 elaborates the design and study of a single element antenna loaded with a partial ground surface. Section 3 presents the configuration of a quad-element MIMO antenna. The measured results and diversity performance of quad element orthogonal MIMO antenna are presented in Section 4. Section 5 concludes the outcomes of the presented study.

2. SINGLE-ELEMENT ANTENNA WITH PARTIAL GROUND DESIGN AND ANALYSIS

The schematic of the proposed partial ground loaded single-element antenna with front side and back side is illustrated in Fig. 1. The microstrip line feeding technique with $50\,\Omega$ impedance is used to excite the proposed modified rectangular patch single element antenna. The rectangular patch antenna is modified by removing two circular slots with different radii and position coordinates $R1(-14, -6)$ and $R2(-8.5, -6)$, respectively. By changing the current direction mechanism, the concept of partial ground is very popular in literature to enhance the impedance bandwidth of the radiating element. An FR-4 lossy substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) with thickness of 1.6 mm is used to fabricate the proposed prototype. The overall dimension of the proposed single element antenna is $60 \times 60 \times 1.6\,\text{mm}^3$. The simulation and optimization of the proposed geometry are implemented on 3D EM simulator CST Micro Studio. The design parameter values of the proposed modified rectangular single radiating element are demonstrated in Table 1.

TABLE 1. Optimized dimensions of the proposed single radiating element.

Parameter	L	W	Lp	Wp	Wf
Value (mm)	60	60	32	35	3.0
Parameter	Lf	$R1$	$R2$	$L1$	$L2$
Value (mm)	17	5.9	4.15	26.6	33.4

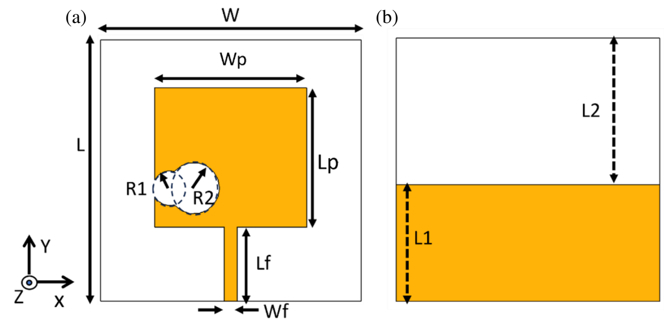

FIGURE 1. Single radiating element structure: (a) front side, (b) back side.

The proposed modified rectangular patch antenna is designed in four step-by-step processes. These design processes named as Ant. 1, Ant. 2, Ant. 3, and Ant. 4 are shown in Fig. 2. Initially, Ant. 1 is a rectangular patch antenna using a microstrip line feed that resonates at 5.15 GHz with narrow frequency band from 4.85 to 5.32 GHz. A circle with radius $R1$ is etched from rectangular patch which provides an additional resonance with narrow frequency band as first at 4.85 GHz and second at 6.58 GHz, respectively. In Ant. 3, another circular cut with radius $R2$ is embedded with first circular cut radius $R1$ in rectangular patch, then the lower band shifts towards lower side at about 4.6 GHz, and at upper side wide band is achieved from 6.72 to 8.92 GHz. From the literature study, it is found that the partial ground surface is used in bottom of the antenna geometry to improve the radiation characteristics of the antenna. Finally, a partial ground surface with length $L1$ is used in Ant. 4, then lower frequency band resonates at about 4.32 GHz, and the upper frequency band becomes wider from 6.47 to 10.15 GHz. The stepwise improvement in simulated reflection coefficient of the single radiating element is depicted in Fig. 3, and optimized results are summarized in Table 2.

3. PROPOSED ORTHOGONAL QUAD-ELEMENT MIMO ANTENNA

This section evaluates the design structure of overall MIMO antenna. The geometries of proposed interconnected ground plane quad-element MIMO antenna's front and back views are shown in Fig. 4. In the proposed MIMO antenna, four radiating elements are placed in orthogonal manner with a distinct gap of $d > \lambda/2$ among each other single radiating element. The final prototype is fabricated on a 1.6 mm thick FR4 epoxy substrate ($\varepsilon_r = 4.4$), and the overall size of proposed MIMO antenna is $120 \times 120 \times 1.6\,\text{mm}^3$. The orthogonal placement approach is useful to provide a gap between individual radiating elements which decreases the coupling between adjacent antenna radiating elements, thus the isolation of the proposed quad-element MIMO antenna configuration is improved. In this configuration, bottom ground plane with interconnected ground strips acts as decoupling and matching network. The decoupling mechanism is a useful technique in MIMO antenna design which relies on embedding additional structure to minimize the mutual coupling or to improve the isolation between radiating elements. In MIMO antenna concept, the spacing

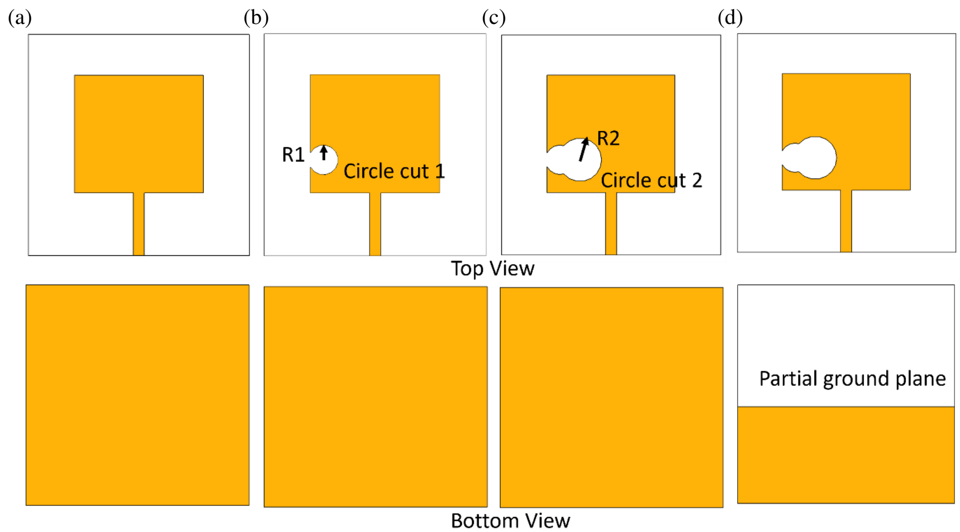

FIGURE 2. Step-by-step design process of the proposed antenna: (a) Ant. 1, (b) Ant. 2, (c) Ant. 3, and (d) Ant. 4.

S.No.	Antenna Structures	Impedance Bandwidth (GHz, $f_{span\|GHz}$, $f_{c\|GHz}$, %)
1.	Ant. 1	4.85–5.32, 0.47, 5.08, 9.25
2.	Ant. 2	4.57–5.04, 0.47, 4.80, 9.79 6.22– 6.62, 0.40, 6.42, 6.23
3.	Ant. 3	4.43–4.72, 0.29, 4.57, 6.34 6.72–8.92, 2.20, 7.82, 28.13
4.	Ant. 4	4.27–4.52, 0.25, 4.40, 5.68 6.47–10.15, 3.68, 8.31, 44.28

TABLE 2. Step-by-step reflection coefficient improvement of proposed single element antenna.

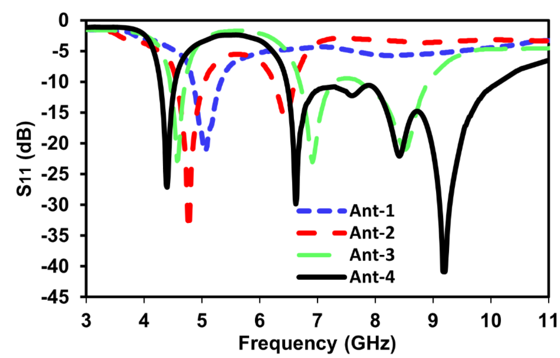

FIGURE 3. Effect of circular cut and partial ground surface on reflection coefficient.

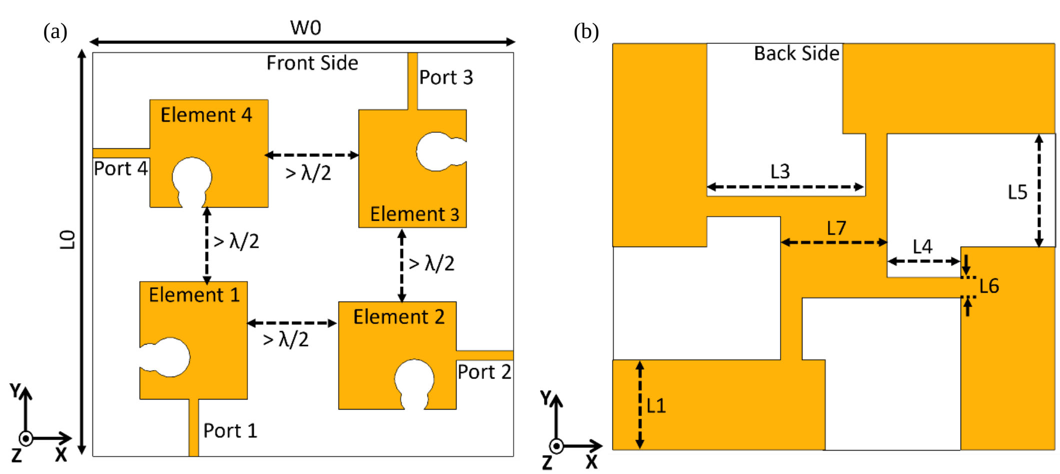

FIGURE 4. Structure of proposed quad-element interconnected ground-based MIMO antenna: (a) front side, (b) back side. Dimensions ($L0 = W0 =$ 120 mm, $L1 = 26.60$ mm, $L3 = 44.90$ mm, $L4 = 20.90$ mm, $L5 = 33.40$ mm, $L6 = 6.0$ mm, $L7 = 30$ mm.

between radiating elements should be greater than half wavelength ($> \lambda/2$) for minimum coupling.

The reason for considering orthogonal placement approach for the proposed MIMO antenna design is to improve the radiation characteristic and diversity parameters over the covered frequency band. The simulated transmission coefficient parameters (S_{11} and S_{12}) of the proposed quad-element MIMO antenna array are shown in Fig. 5. It can be analysed that the

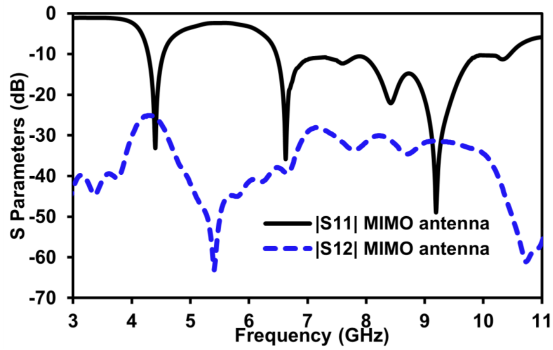

FIGURE 5. Optimized results of the proposed interconnected ground-based quad-element MIMO antenna: transmission coefficient parameters.

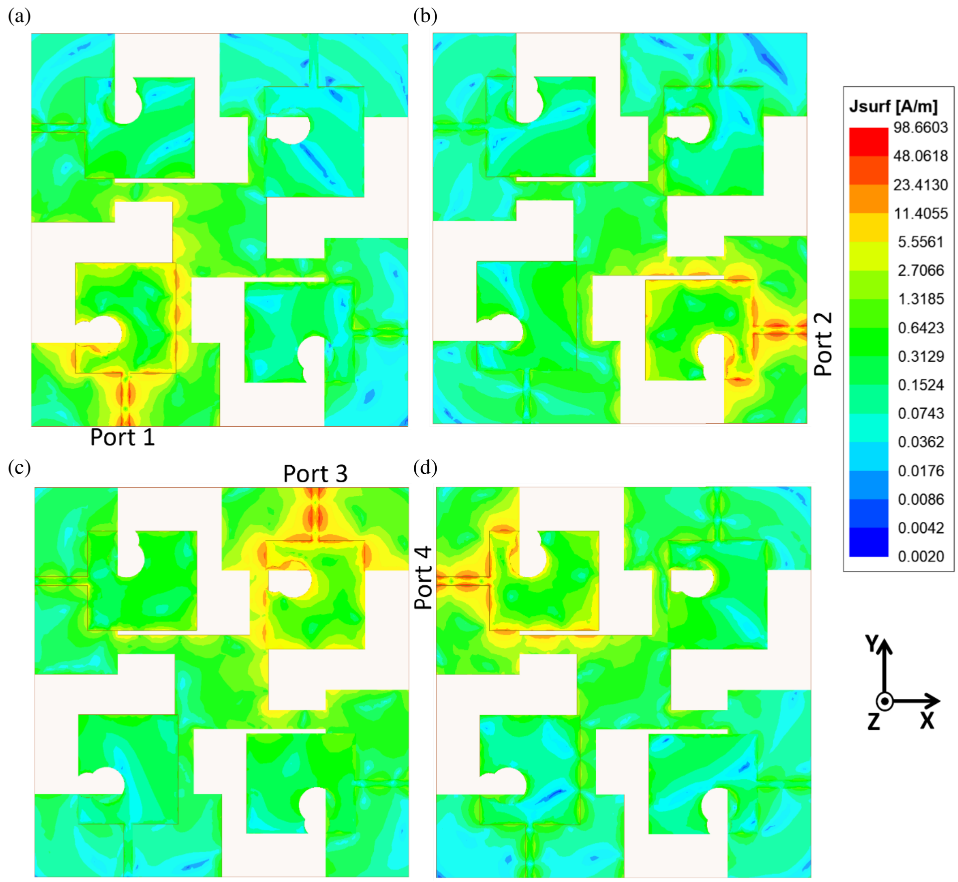

FIGURE 6. Current density of the proposed quad-element MIMO antenna at 4.40 GHz when (a) port-1 excited, (b) port-2 excited, (c) port-3 excited, (d) port-4 excited.

isolation between two adjacent elements 1–2 is about > 27 dB in the first frequency band and > 32 dB in the second frequency band, as transmission coefficient is below −27 dB and −32 dB.

To further analyse the electromagnetic mechanism of decoupling structure, the effect of current density at 4.40 GHz frequency is illustrated in Fig. 6. If port 1 is excited and remaining ports 2, 3, and 4 matched with 50 Ω load impedance of the designed quad-element MIMO antenna, then current distribution is maximum at port 1 as shown in Fig. 6(a). Similarly, if remaining ports are excited one by one and other ports matched through 50 Ω load, then current distribution is maximum on the excited port as illustrated in Figs. 6(b), 6(c), and 6(d), respectively. Finally, it is analysed that by using decoupling structure the excited port has minimum effect on the remaining radiating elements hence leads to high isolation.

4. RESULTS AND DISCUSSION

This section illustrates the simulated and measured results with diversity parameters of the interconnected ground quad-

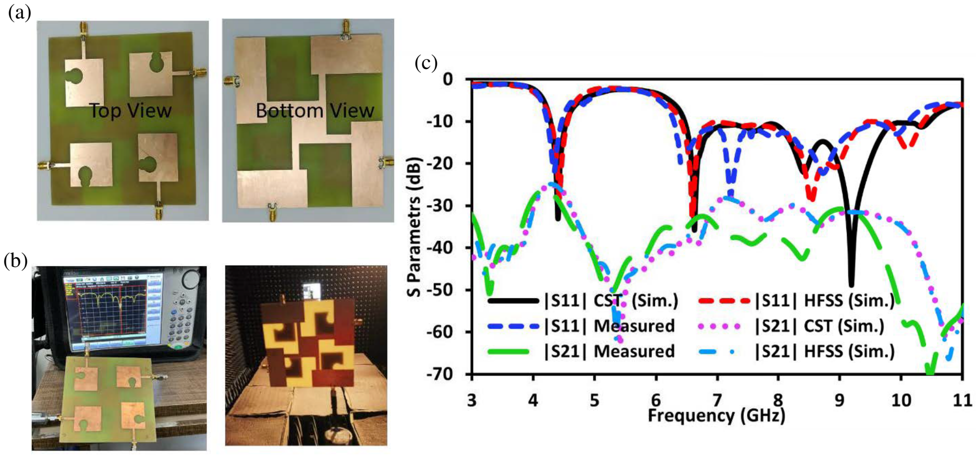

FIGURE 7. (a) Fabricated geometry of quad-element MIMO antenna. (b) Measurement setup with VNA and in anechoic chamber. (c) S-parameters (Simulated and measured).

element MIMO antenna. To validate the simulated results, 3D EM simulator as Ansys HFSS (High Frequency Structure Simulator) and CST Microwave Studio (MWS) are used in this article.

4.1. Results Analysis of Proposed MIMO Antenna

To inspect and verify the scheme of the proposed interconnected ground, a dual-band quad-element MIMO antenna prototype is fabricated on an FR4 substrate with size of $120 \times 120 \times 1.6\,\text{mm}^3$ ($1.69\lambda \times 1.69\lambda \times 0.022\lambda$, where λ is wavelength at 4.23 GHz) as shown in Fig. 7(a). Four RF SMA $50\,\Omega$ connectors are used to excite the proposed MIMO configuration. The fabricated prototype measurement setup in an anechoic chamber is shown in Fig. 7(b). Fig. 7(c) describes the simulated S-parameters of the proposed quad-element MIMO antenna by using full wave simulator CST Micro Studio, Ansys HFSS, which are compared with measured S-parameters using Anritsu S820E vector network analyzer (VNA).

The measured impedance bandwidth of proposed dual-band quad-element MIMO antenna has ranges of 4.23–4.55 GHz and 6.30–10.22 GHz with fractional bandwidth of 7.2% and 45.47%, respectively, while simulated -10 dB impedance bandwidth in double operating bands using CST MWS covers ranges of 4.29–4.54 GHz and 6.40–10.40 GHz and of 4.28–4.56 GHz and 6.40–10.36 GHz with CST and HFSS MWS, respectively. The simulated isolation between port 1 and port 2 is achieved > 27 dB in lower band and > 32 dB in upper band, respectively. The minor deviation between measured and simulated results is due to the SMA connector loss, hardware parts position, prototype boundary conditions, and error in fabrication.

The combined peak gain and radiation efficiency (η) of the proposed dual-band quad-element MIMO antenna are depicted in Fig. 8. The modified rectangular patch radiating element with partial ground has peak gain around 3.40 dBi, and orthogonally arranged interconnected ground plane quad-element MIMO antenna has peak gains around 5.73 dBi with CST micro studio and 5.67 dBi with Ansys HFSS software. The fabricated prototype of the proposed quad-element MIMO antenna has measured peak gain about 5.66 dBi over the operating frequency band. From Fig. 8, it is perceived that the peak gain is increased about 51.04% (CST), 50.11% (HFSS), and 49.88% (measured), respectively, of the quad-element MIMO configuration in comparison to single radiating element. The simulated efficiency (η) by using CST Micro Studio and Ansys HFSS is more than 72% over the entire frequency band. The simulated and measured results of the proposed quad-element MIMO antenna with single radiating element are summarized in Table 3.

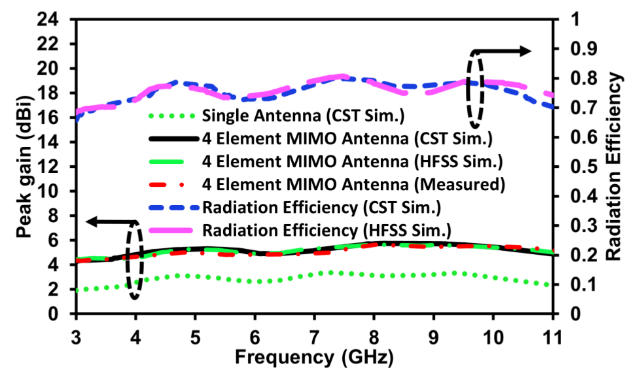

FIGURE 8. Peak gain and radiation efficiency of the proposed quad-element MIMO antenna.

Figures 9(a) and (b) illustrate the simulated and measured far-field radiation patterns (normalized) of the proposed interconnected ground plane quad-element MIMO configuration in two principal planes, i.e., XZ-plane ($\phi = 0°$) and YZ-plane ($\phi = 90°$) at 4.40 and 8.40 GHz resonance frequencies. By using full wave simulators CST Micro Studio and Ansys HFSS simulation software, the measured and simulated co-pol and cross-pol results have good matching. Due to arranging the four-antenna element and interconnected ground plane, satisfactory co-to-cross polar isolation > 20 dB is achieved. The proposed MIMO configuration has almost omnidirectional co-polarized radiation patterns in the XZ-plane. It is also analysed

TABLE 3. Simulated and measured results comparison of proposed quad-element MIMO configuration.

S. No.	Antenna Type	IBW (GHz, $f_{span\|GHz}$, $f_{c\|GHz}$, %)	Peak Gain (dBi)	η (%)
1.	Simple element antenna with partial ground	4.27–4.52, 0.25, 4.40, 5.68 6.47–10.15, 3.68, 8.31, 44.28	3.40	—
2.	Quad-element MIMO antenna array (CST)	4.29–4.54, 0.25, 4.41, 5.66 6.40–10.40, 4.0, 8.40, 47.61	5.73	> 73
3.	Quad-element MIMO antenna array (HFSS)	4.28–4.56, 0.28, 4.42, 6.33 6.40–10.36, 3.96, 8.38, 47.25	5.67	> 72
4.	Quad-element MIMO antenna array (Measured)	4.23–4.55, 0.32, 4.39, 7.2 6.30–10.22, 3.92, 8.26, 47.45	5.66	—

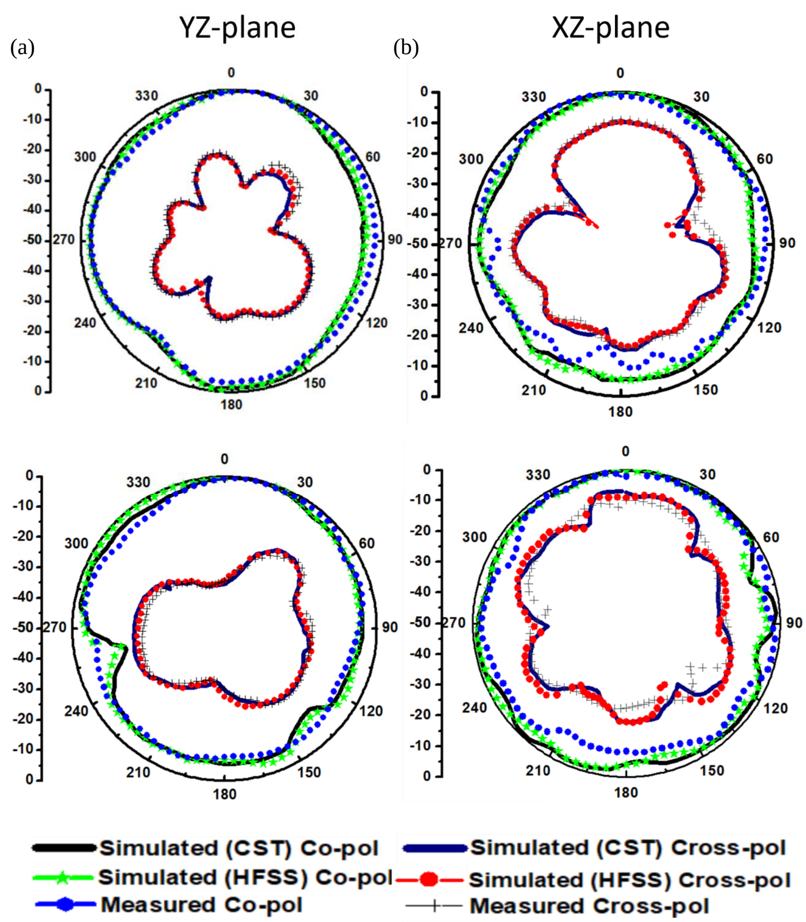

FIGURE 9. Far-field radiation patterns of proposed quad-element MIMO antenna, (a) at 4.40 GHz and (b) at 8.40 GHz.

that in the XZ-plane, the proposed MIMO antenna maintains nearly omnidirectional co-polarized patterns.

4.2. Diversity Performance of Orthogonal MIMO Antenna Array

This section analyses the diversity characteristic of the proposed quad-element interconnected ground plane MIMO antenna. It is evaluated through MIMO diversity key parameters such as envelope correlation coefficient (ECC) and diversity gain (DG). ECC parameter is the correlation between antenna elements, and for good diversity performance it should be low (ECC < 0.5). It can be calculated from scattering parameters through Eq. (1) [23].

$$\rho_{eij} = |\rho_{eij}|^2 = \left| \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|}{\left| \left(1-|S_{ii}|^2-|S_{ji}|^2\right)\left(1-|S_{jj}|^2-|S_{ij}|^2\right)\eta_{rad_i}\eta_{rad_j} \right|^{1/2}} \right|^2 \quad (1)$$

where i and j are the port serial number; ρ denotes the calculated ECC parameter; S represents the scattering parameters of

TABLE 4. Comparison of the proposed quad-element MIMO antenna with published 2-/4-element MIMO works.

S. No.	No. of elements	Impedance Bandwidth (GHz, $f_{span|GHz}$, %)	Isolation (dB)	Peak Gain (dBi)	ρ
[20]	2	2.25–3.15, 0.90, 33.30 4.89–5.95, 1.06, 19.60	> 15	5.59 5.63	< 0.003 < 0.01
[22]	2	2.99–3.61, 0.62, 18.80 4.53–4.92, 0.39, 8.30	> 16	3.14 3.84	< 0.002
[24]	2	2.4–2.5, 0.1, 4.08 5.15–5.82, 0.67, 12.30	> 15 > 22	2.0	< 0.29 < 0.12
[25]	4	3.28–4.15, 0.87, 23.40 4.69–6.01, 1.32, 24.70	> 19	4.0	< 0.0025
[26]	4	7.58–8.04, 0.46, 5.90 9.23–10.79, 1.56, 15.6	> 20	2.5	< 0.003
[27]	4	2.47–3.38, 0.91, 31.16 4.94–7.24, 2.30, 37.76	> 15	1.62 4.50	< 0.064
[28]	2	2.20–5.09, 2.89, 79.28 6.20–8.10, 1.90, 26.57	> 15	2.0 5.4	< 0.01 < 0.1
This Work	**4**	**4.29–4.54, 0.25, 5.66** **6.40–10.40, 4.0, 47.61**	$\mathbf{> 27}$ $\mathbf{> 32}$	**5.73**	$\mathbf{< 0.001}$ **0.0009**

i and j port number; and η is the radiation efficiency with i and j port, respectively. DG (dB) parameter can be evaluated from ECC parameter through Eq. (2) [23].

$$\text{DG} = 10 * \sqrt{1 - |\text{ECC}|^2} \tag{2}$$

From the literature, it is analysed that the diversity gain (DG) parameter should be near 10 dB over the operating frequency band.

The MIMO diversity parameters ECC and DG are evaluated by exciting port 1 and keeping other ports matched with 50 Ω load impedance. The simulated ECC and DG (dB) by using full wave simulator CST Micro Studio and Ansys HFSS are shown in Fig. 10. Diversity performance is achieved from S-parameters as ECC < 0.001 and DG almost 10 dB ($>$ 9.996 dB) over the operating frequency band. Total active reflection coefficient (TARC) is another important parameter for MIMO diversity characteristic analysis. The simulated TARC (dB) of the proposed quad-element MIMO is shown in Fig. 11, and it is observed that the plots are < -10 dB over both functioning bands of 4.29–4.54 GHz and 6.40–10.40 GHz.

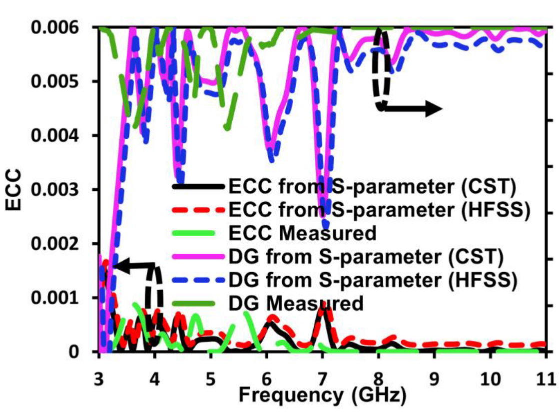

FIGURE 10. Simulated ECC and Diversity Gain (dB) of the proposed MIMO antenna.

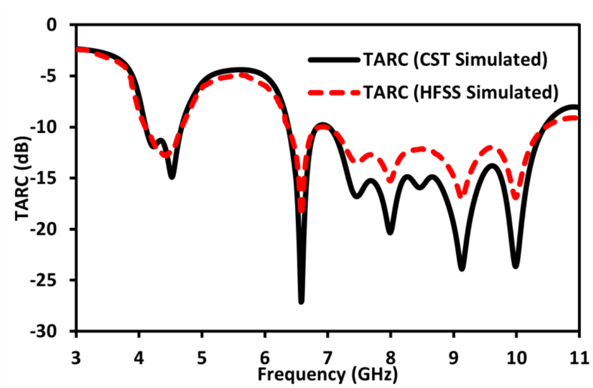

FIGURE 11. Simulated TARC (dB) of the proposed MIMO antenna.

4.3. Performance Comparison with Other Dual-band Antennas

The performance comparison of the quad-element MIMO configuration with existing dual-band antennas is demonstrated in Table 4. The comparison is analysed based on the key parameters for number of radiating elements used, impedance bandwidth, coupling between radiating elements, and peak gain of the antennas. From the published work it is analysed that the proposed antenna with an FR-4 substrate and common ground surface has better impedance bandwidth with simulated peak gain of 5.73 dBi, good isolation, and lower ECC (ρ) over the operating band.

5. CONCLUSION

In this article, a low-cost FR4-based quad-element dual-band MIMO configuration has been proposed. A modified rectangular patch antenna is embedded with partial ground plane offering dual frequency bands. The proposed interconnected ground plane quad-element MIMO configuration is designed and fabricated in orthogonal manner with spacing of $d > \lambda/2$ between individual antenna elements. The proposed MIMO antenna has an overall size of $1.69\lambda \times 1.69\lambda$ and exhibits the measured double operating bands ($S_{11} < -10$) covering 4.23–4.55 GHz and 6.30–10.22 GHz with high isolation of > 27 dB and > 32 dB, respectively. Both the operating bands have simulated peak gain of 5.73 dBi and peak efficiency of 72% over the entire operating band. Furthermore, the presented antenna has good diversity performance with envelope correlation coefficient (ECC) < 0.001, diversity gain (DG) of 9.996 dB, and total active reflection coefficient (TARC) < -10 dB. To provide many benefits including planar geometry, dual band, high isolation, and minimum value of ECC over the operating frequency band, the quad-element MIMO antenna is suitable for C band light weight wireless broadband applications and X-band (Satellite communications, Radar) applications.

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