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A Multi-band Multi-slot MIMO Antenna with Enhanced Isolation

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Abstract

In this correspondence a small low profile multiband multi-slot MIMO antenna is proposed. The proposed patch antenna covers five bands. Band I covers 2.71–2.82 GHz, band II covers 3.73–4.64 GHz, band III covers 5.14–6.72 GHz, band IV covers 7.52–8.53 GHz and band V covers 8.66–9.41 GHz. It combines many applications into a single device by designing a single antenna that can be operated in multi-bands. The proposed antenna consists of multi-slot radiator with defected ground plane. Proposed antenna is smaller in size 15×20 mm^2 ($0.14\lambda_0 \times 0.18\ \lambda_0$). It is extended to MIMO and mutual coupling is reduced in three bands (III, IV and V) using Defected Ground Structure (DGS). Mutual coupling in the first band (I, II) is minimized using a decoupling element. The proposed MIMO antenna is fabricated and tested. Simulation and measured results are found to be in good agreement.

Keywords Multiband antenna · Multiple input and multiple output (MIMO) · Envelope correlation coefficient (ECC) · Gain · Efficiency · Radiation pattern · Mutual coupling (MC) · Co-polarization (Co-pol) · Cross-polarization (X-pol)

1 Introduction

In microwave communication that requires large coverage antenna array plays vital role. For modern communication multiband transceivers are required. A mobile is used for multipurpose like voice communication, data transfer, global positioning system (GPS), blue tooth and Wi-Fi. If one antenna is used for one application then it consumes more space and also performance deteriorated. The solution for this is to use of identical antennas, which improves overall radiation performance. But the problem is the space allocated for antennas is very small in any electronic gadget. When more it is required to place more number of antennas in the close proximity electromagnetic interaction between radiation patterns takes place and this phenomena is called as mutual coupling (MC). Mutual coupling influences performance of MIMO antenna in pessimistic way. It changes many

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parameters of antenna like impedance, radiation pattern received voltages. Under these conditions, the antenna elements in the array are expected to operate independently with large isolation. Therefore it is required to mitigate the effect of MC.

In [1] fractal DGS is used to enhance isolation ultra-wideband (UWB) multiple input multiple output (MIMO). In [2] MC is reduced in dual bands by using defected ground structure (DGS). In [3] MC between two patches is reduced by using DGS. In [4] Electromagnetic band gap (EBG) structure is used to reduce the MC. In [5] MC is minimized using novel DGS shape. In [6] a novel L-shaped strips are used to reduce the MC. Diversity schemes are also used to reduce MC like polarization diversity, spatial diversity and pattern diversity. In [7] pattern diversity is used to minimize MC in portable devices. In [8] MC is reduced using neutralization line. In [9] MC is reduced between the two antennas by inserting parasitic element.

2 Antenna Configuration and Design Approach

The geometry and dimensions of proposed multiband antenna are shown in Fig. 1. It is developed on FR4 substrate of thickness 1.4 mm, relative permittivity of 4.3 and loss tangent of 0.02. The overall size of antenna is 15 × 20 mm^2 only or about 0.14 λ_0 × 0.18 λ_0 where λ_0 is free space wave length at 2.71 GHz. The proposed structure consists of multi slots on a square patch. The antenna design evolution process to achieve multiband as shown in Fig. 2. The parameters of the proposed antenna are shown in Table 1.

The proposed antenna obeys Eq. (1). The ε_{reff} for proposed antenna is 3.783. The lengths of surface currents responsible for resonant frequencies 2.76, 4.38, 6.73, 8.25 and 9 are L_{r1} = 27.55 mm L_{r2} = 16.99 mm, L_{r3} = 11.48 mm, L_{r4} = 8.98 mm, L_{r5} = 8.48 mm The surface current distributions are plotted at sample frequencies 2.76 GHz, 4.38 GHz, 6.73 GHz, 8.25 GHz and 9 GHz as shown in Fig. 3. Table 2 gives the difference between simulated and calculated resonant frequencies.

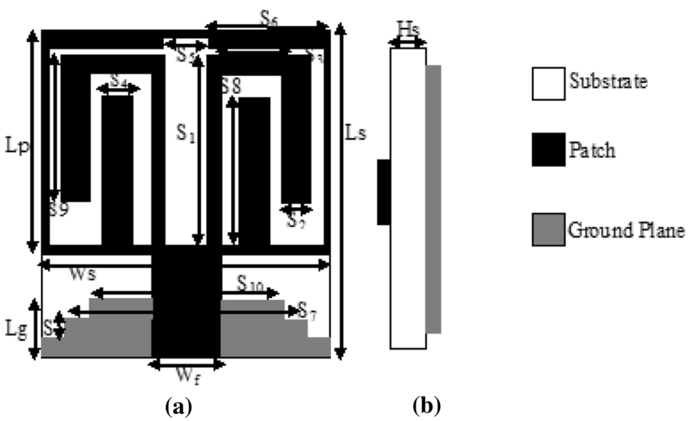

Fig. 1 Schematic Configuration of the proposed multiband Antenna **a** front view and **b** side view

$$\mathrm{f_r} = \frac{C}{2L_r\sqrt{\varepsilon reff}} \tag{1}$$

The lengths of currents responsible for sample resonating frequencies are shown in Eqs. (2)–(6).

$$\mathrm{L_{r1}} = \mathrm{S1 + S3 + S9 - S2} \tag{2}$$

$$\mathrm{L_{r2}} = \mathrm{S1 + (Ws - Wf)/3} \tag{3}$$

$$\mathrm{L_{r3}} = \mathrm{Lp + (Ws - Wf)/2 + Wf/2 - S9 + S2} \tag{4}$$

$$\mathrm{L_{r4}} = \mathrm{(Ws - Wf)/4 + S8/2} \tag{5}$$

$$\mathrm{L_{r5}} = \mathrm{2 * S8 + S4 - S9 - S3 - S5} \tag{6}$$

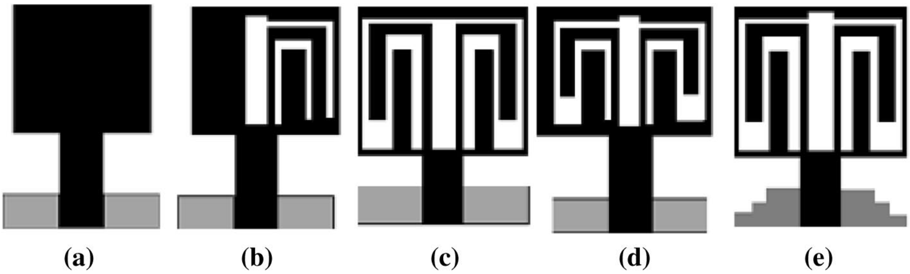

Fig. 2 Antenna geometry evolution for the proposed design

Table 1 Parameters of the proposed multiband antenna

Parameter	W_p	L_p	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	W_f	H_s	S	W_s	L_s
Unit (mm)	15	15	13	1.5	3.5	2.5	2	6	9	12	12.5	9	3	1.4	1	15	20

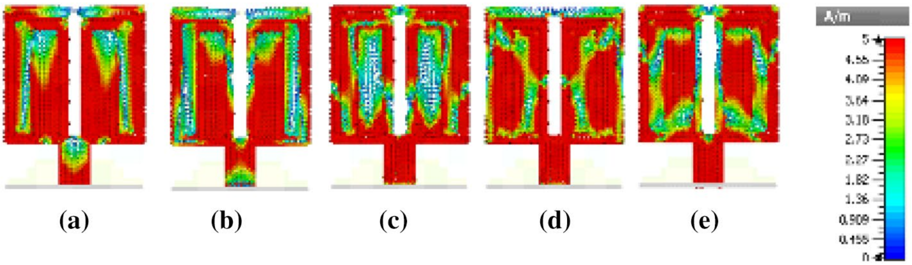

Fig. 3 Surface current distributions at sample frequencies **a** 2.76 GHz, **b** 4.38 GHz, **c** 6.73 GHz, **d** 8.25 GHz and **e** 9 GHz

Table 2 Comparison between design equation and full wave simulation

Resonant frequency (GHz)	Design equation	Full wave simulation	% difference
L_{r1}	2.8	2.76	1.4
L_{r2}	4.54	4.38	3.5
L_{r3}	6.72	6.73	0.1
L_{r4}	8.59	8.25	3.9
L_{r5}	9.09	9	0.1

2.1 Return Loss

The return loss curve (S_{11}) is shown in Fig. 4. It shows that proposed antenna resonates at five bands I from 2.71 to 2.82 GHz, II from 3.73 to 4.64 GHz, III from 5.14 to 6.72 GHz, IV from 7.52 to 8.53 GHz, and V from 8.66 to 9.41 GHz. The highest return loss in bands I, II, III, IV and V is −21 dB, −19.5 dB, −26 dB, −29 dB and −21 dB respectively.

The proposed antenna is compact in size. Table 3 shows the comparison of the proposed structure with the structures reported in the literature. Comparison is made in terms of size and number of bands.

3 MIMO Antenna Using DGS

A 2×1 MIMO antenna structure is shown in Fig. 5. The edge to edge distance (d) between two antennas is 4 mm or 0.035 $\lambda_{0.}$ The S-parameters (S_{11}, S_{21}) both simulated and measured are shown in Fig. 6. As it is symmetrical structure, the S-parameters of antenna1 (S_{12} and $S_{11)}$ are same as S-parameters of antenna2 (S_{21}, $S_{22)}$. The highest MC in band III, IV,

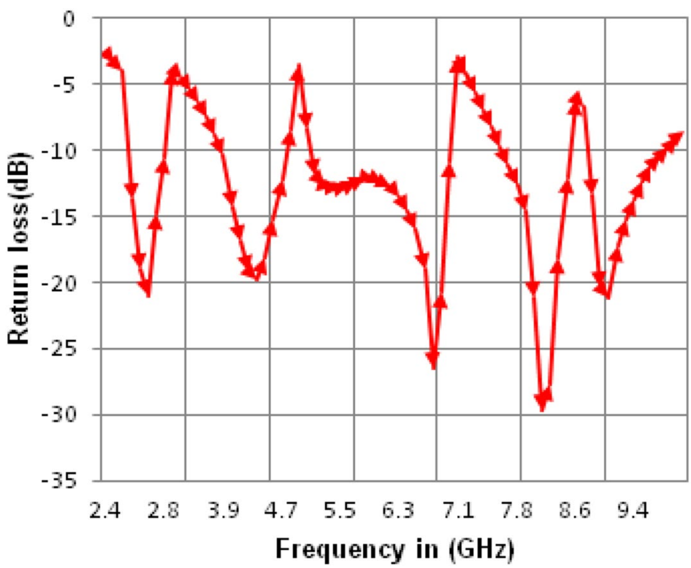

Fig. 4 Simulated return loss against frequency for proposed antenna

Table 3 Gain and Efficiency at the center frequencies of all five bands

Frequency/parameters	2.76 GHz	4.38 GHz	6.73 GHz	8.25 GHz	9 GHz
Gain	1	1.7	2.2	2.8	2.6
Efficiency (%)	88	91	94	89	96

and V is −27 dB, −24.7 dB, −37 dB achieved respectively. But in band I and II MC is −9 dB and −10 dB which is not acceptable.

The surface current distributions of the proposed MIMO antenna with stair case ground structure at sample frequencies 2.76 GHz, 4.38 GHz, 6.73 GHz, 8.25 GHz and 9 GHz are shown in Fig. 7. One of the primary reasons for the MC is surface currents propagating from one antenna to other. It is observed from Fig. 7 that surface currents are prevented from propagating antenna1 to antenna2 only in bands III, IV and V. Hence MC is reduced by greatly in bands III, IV and V. In Fig. 7a and b the large amount of surface currents propagating from antenna1 to antenna2, therefore the MC is not in acceptable range in bands I and II. The front view and rare view of fabricated MIMO antenna with staircase ground is as shown in Fig. 8.

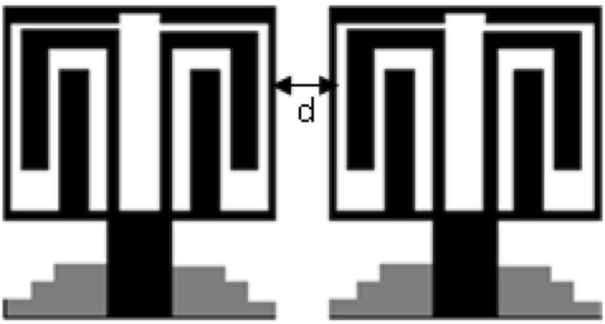

Fig. 5 Proposed MIMO antenna

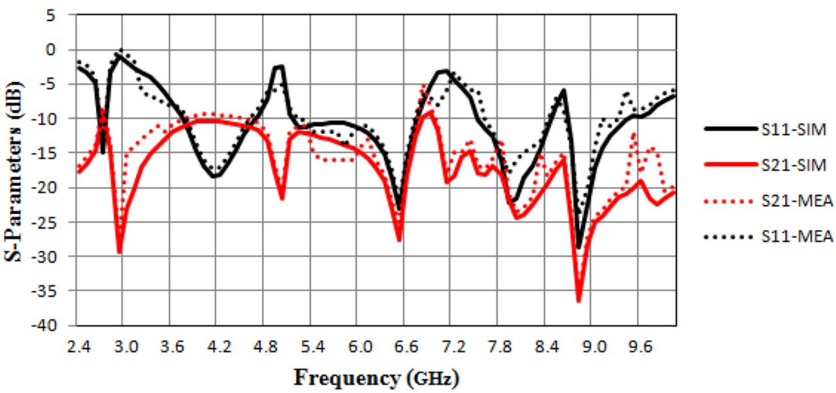

Fig. 6 S-Parameters for the proposed MIMO antenna

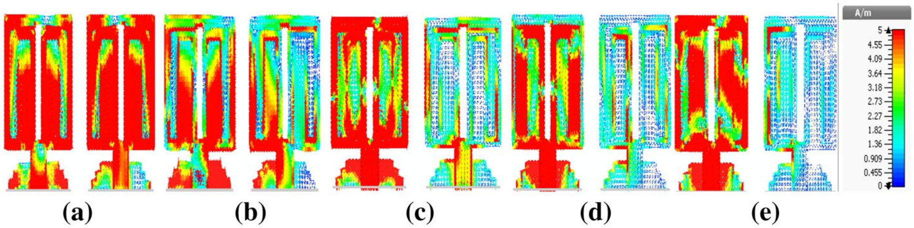

Fig. 7 Surface current distributions of MIMO antenna at sample frequencies **a** 2.76 GHz, **b** 4.38 GHz, **c** 6.73 GHz, **d** 8.25 GHz and **e** 9 GHz

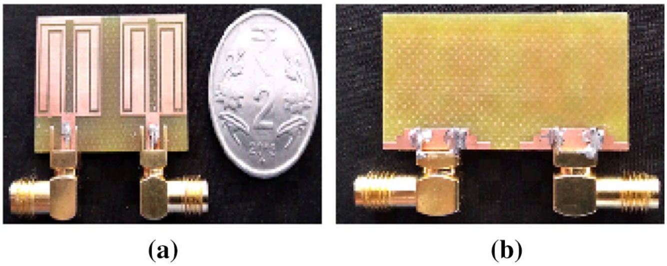

Fig. 8 Fabricated Proposed MIMO antenna **a** front view and **b** rare view

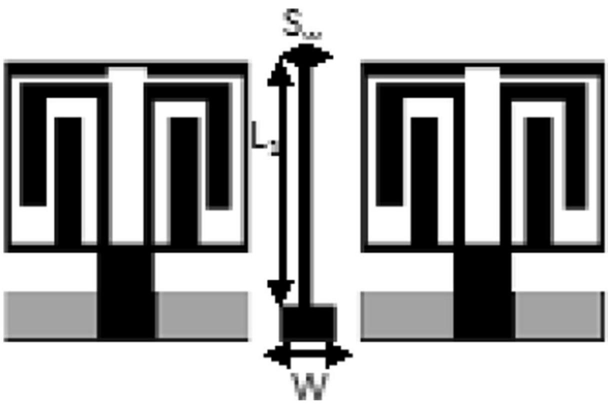

Fig. 9 MIMO antenna with decoupling element

4 MIMO Antenna with Decoupling Element

To increase the utility of MIMO antenna for many applications MIMO antenna with staircase ground structure is modified to reduce the mutual coupling in bands I and II. In the MIMO antenna with staircase ground structure, a decoupling element is inserted between two patches as shown in Fig. 9. Decoupling element is added to improve the isolation over bands I, and II. The dimensions of the decoupling element are $S_w = 1$ mm,

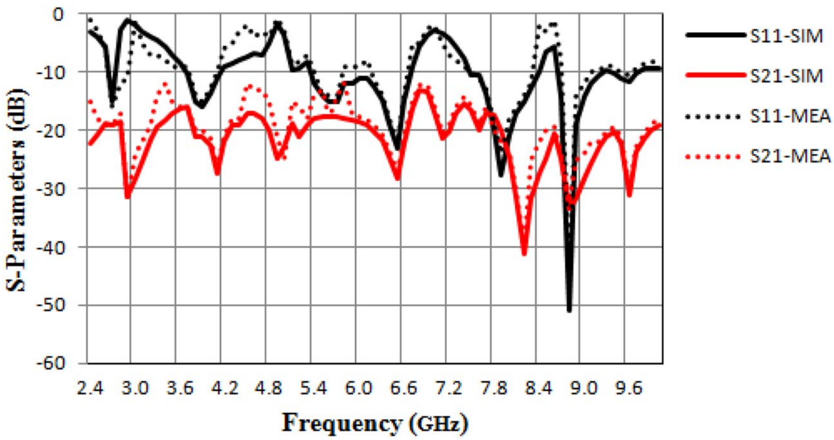

Fig. 10 S-parameters of the modified proposed MIMO antenna

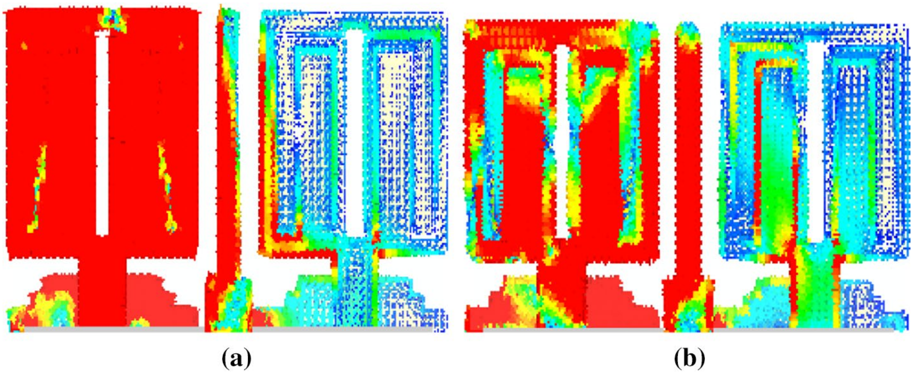

Fig. 11 Surface current distribution MIMO antenna at **a** 2.76 GHz and **b** 4.38 GHz

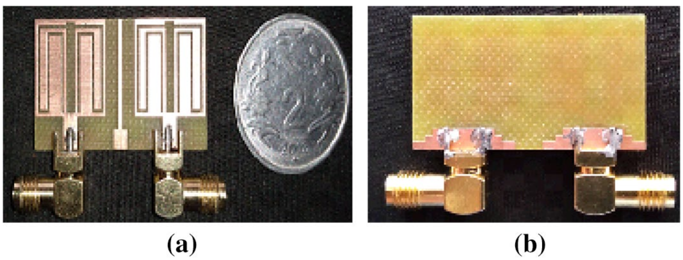

Fig. 12 Fabricated MIMO antenna with decoupling element (a) Front view (b) Rare view

$L_1 = 17$ mm, W = 3.5 mm. The S-parameters (S_{11}, S_{21}) both simulated and measured are shown in Fig. 10. It is evident that S_{21} is below − 15 dB in bands I and II.

The effect of decoupling element on the performance of MIMO antenna can be understood from surface current distribution at 2.76 GHz and 4.38 GHz as shown in

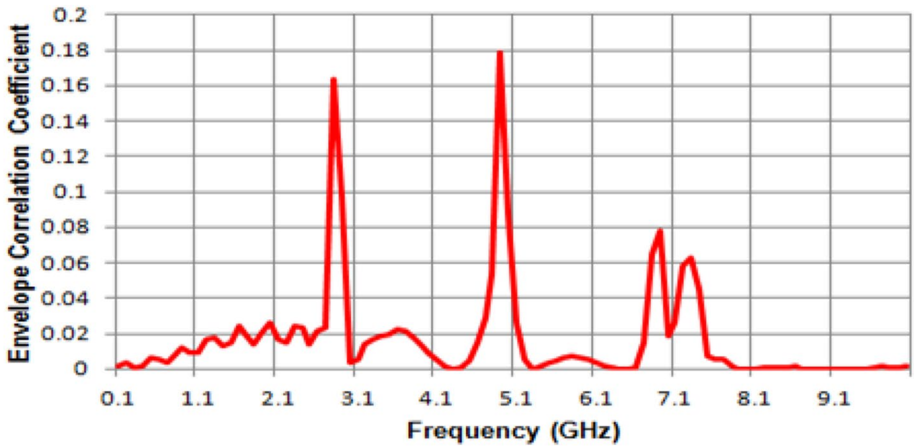

Fig. 13 ECC for the proposed design

Fig. 14 Radiation pattern measurement in Anechoic chamber

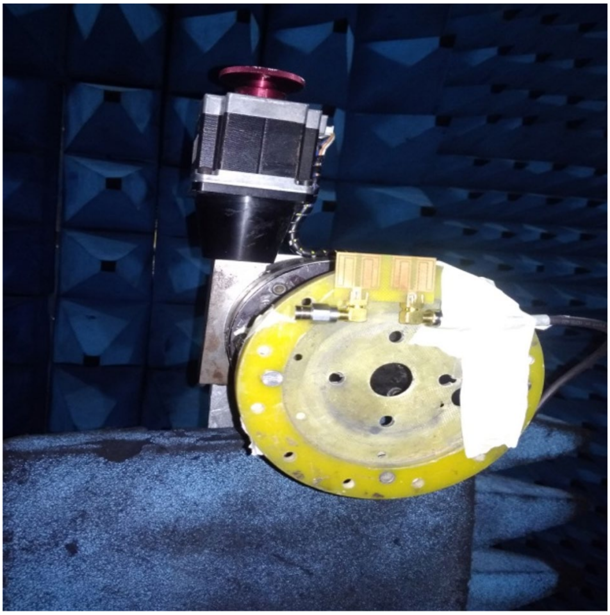

Fig. 12. The decoupling element traps the surface currents. It prevents surface currents propagating from one antenna to other and it can be understood from Fig. 7a, b and 11a, b. Front view and rare view of fabricated MIMO antenna with the decoupling element are shown in Fig. 12.

Another important parameter for evaluating the performance of MIMO antenna is ECC. The ECC curve is as shown in Fig. 13. Its value is below 0.02 in all five bands. The ECC and Diversity gain are reciprocally related. The smaller the ECC the higher the diversity gain.

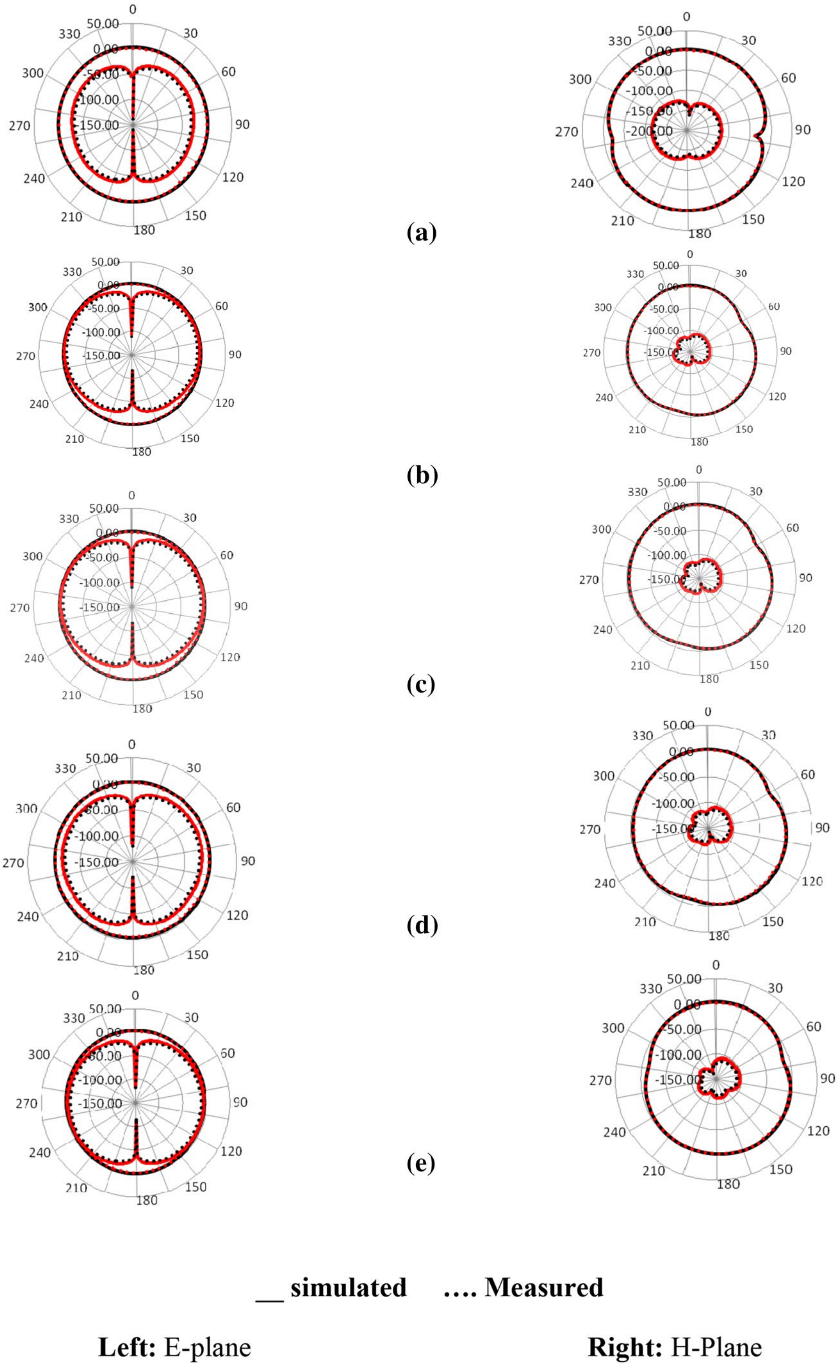

Fig. 15 Simulation and measured Radiation pattern at sample frequencies **a** 2.76 GHz, **b** 4.38 GHz, **c** 6.73 GHz, **d** 8.25 GHz and **e** 9 GHz

Table 4 Performance evaluation of proposed MIMO antenna in terms of ECC, DG, EDG and multiplexing efficiency

Frequency/parameter	2.76 GHz	4.38 GHz	6.73 GHz	8.25 GHz	9 GHz
Mutual coupling (dB)	≤ 15	≤ 15	− 27	− 24.7	− 37
Efficiency	88	91	94	89	96
Gain	1	1.7	2.2	2.8	2.6
ECC	0.001	0.002	0.003	0.0015	0.002
Diversity gain	9.99	9.97	9.98	9.98	9.96
Multiplexing efficiency	− 0.11	− 0.08	− 0.05	− 0.1	− 0.03
Effective diversity gain	0.88	1.55	2.1	2.5	2.5
CCL	0.16	0.25	0.25	0.27	0.23

Table 5 Comparison of proposed antenna with previous works

References	Size (mm^2)	Mutual coupling (dB)	Number of bands	ECC	Diversity gain	Efficiency
Ref. [10]	120 × 76	≤ 40	4	< 0.5	NA	NA
Ref. [11]	20 × 10	≤ 30	4	< 0.09	NA	> 82
Ref. [12]	120 × 60	− 20	4	0.01	NA	NA
Ref. [13]	80 × 80	≤ 20	2	< 0.2	5.31	> 70.8
Ref. [14]	136 × 68.8	≤ 20	6	< 0.08	NA	NA
Proposed	15 × 20	− 37	5	0.001	9.99	> 88

Co-pol indicates radiation in the desired direction whereas X-pol indicates radiation in the direction perpendicular to the desired direction. Radiation pattern measurement of proposed structure in anechoic chamber is shown in Fig. 14. Simulated and measured Co-pol and X-pol in both E-plane and H-plane are shown in Fig. 15. The X-pol component is very low. The gain and efficiency of MIMO antenna at sample frequencies in all five bands as shown in Table 4.

The performance of the proposed structure is evaluated further in terms of ECC, DG, EDG and multiplexing efficiency as shown in Table 5.

4.1 Diversity Gain

The diversity gain (DG) of the MIMO antenna is 9.99 dB at both 5.93 and 7.68 GHz.

$$DG = 10\sqrt{1 - |ECC|^2} \tag{7}$$

4.2 Multiplexing Efficiency

Multiplexing efficiency and total efficiency for two element antenna is

$$|\rho_e|^2 = 1 - \frac{\eta_{mux}}{\eta_1 \eta_2} \tag{8}$$

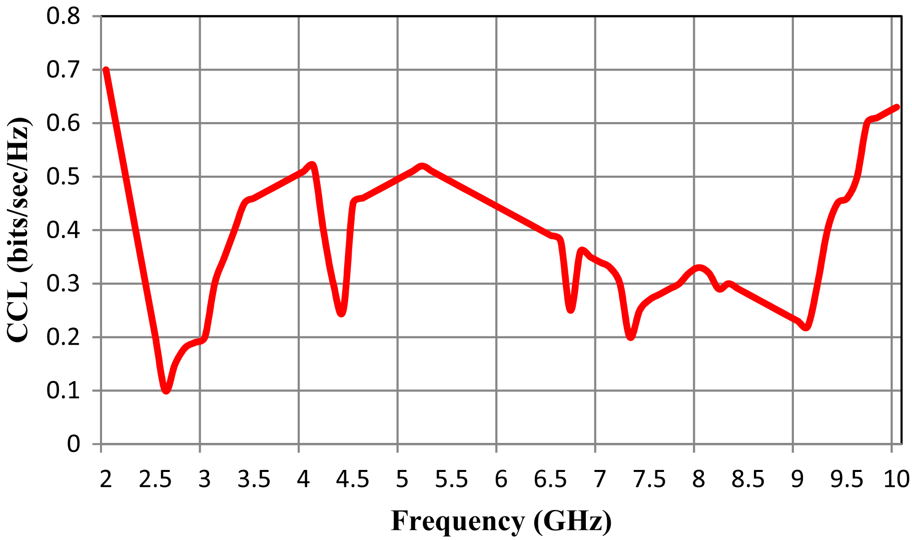

Fig. 16 Channel capacity loss of the MIMO antenna

η_1 and η_2 are total efficiency of antenna 1 and antenna 2, respectively. η_{mux} is multiplexing efficiency.

4.3 Effective Diversity Gain

The relation between antenna efficiency, DG, effective diversity gain (EDG). For the proposed MIMO antenna EDG is 8 dB.

$$\text{EDG} = \text{DG} \times \eta_{ant} \tag{9}$$

4.4 Channel Capacity Loss (CCL)

Channel capacity is one of the important performance index for MIMO antenna. The channel capacity loss plot is shown in Fig. 16. It is observed that CCL value at 2.76 GHz, 4.38 GHz, 6.76 GHz, 8.25 GHz and 9 GHz are 0.16, 0.25, 0.25, 0.27 and 0.23 bits/sec/Hz respectively.

$$\text{C}_{\text{loss}} = -\log_2 \det\left(\Psi^R\right) \tag{10}$$

$$\Psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix}$$

$$\rho_e = \frac{\left|s_{11}^{*}s_{12} + s_{21}^{*}s_{22}\right|^2}{\left(1 - \left|s_{11}\right|^2 - \left|s_{21}\right|^2\right)\left(1 - \left|s_{22}\right|^2 - \left|s_{12}\right|^2\right)}$$

With $\rho_{ii} = \left(1 - \left(\left|S_{ii}\right|^2 + \left|S_{ij}\right|^2\right)\right)$ and $\rho_{ij} = -\left(S_{ii}^{*}S_{ij} + S_{ji}^{*}S_{jj}\right)$ for i, j = 1 or 2.

5 Conclusions

A Compact multi-band multi-slot MIMO antenna is proposed. MIMO antenna with stair case ground and MIMO antenna with decoupling element are fabricated and tested. It is clear that for the proposed MIMO antenna simulation and measurement results are found in good agreement. The proposed MIMO antenna features are compact size, multiband and stable radiation pattern indicating that it can be a good candidate for several applications in S, C and X bands.

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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