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Hybrid Mutual Coupling Reduction Techniques In Multiple Input And Multiple Output Antenna For X-Band Applications

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ARTICLE INFO **ABSTRACT**

In recent years, Multiple Input and Multiple Output antennas (MIMO) used for high-bandwidth communications where it's important to not have interference from microwave or RF systems. The MIMO antenna offers good matching with stable gain and desired radiation patterns but it suffers on mutual coupling effects. The spacing between antenna elements is less than half the wavelength, and then mutual coupling effects are more. This paper provides a review on different mutual coupling reduction techniques in MIMO antenna. In this letter, a hybrid mutual coupling reduction technique such as substrate integrated waveguide (SIW) and defected ground structure (DGS) in MIMO antennas for X-band applications. The developed MIMO antenna has dimensions as 25 x 36 mm over a FR4 1.6 mm substrate. The MIMO antenna has formed by combining two fractal-shaped structures. Here, the antenna element spacing is taken as minimum of 5.62mm. To reduce the mutual coupling effect and enhance gain, hybrid techniques are used. By adding 24 hollow cylindrical SIW is placed in between a MIMO element and six rectangular DGS slots placed at the bottom of the antenna for reducing the mutual coupling and enhance the gain. The proposed antenna operates at resonating frequencies of 10.04 GHz, 11.14 GHz, and 11.69 GHz for measurement. The mutual coupling or isolation loss was observed around <-25 dB. The envelope correlation coefficient (ECC) and diversity gain (DG) of the proposed antenna are 0.0016 and >9 dB, respectively. The gain observed for the proposed design is 5.2 dB. The ANSYS High-Frequency Structure Simulator (HFSS) tool is used for antenna simulation.

Keywords: MIMO, mutual coupling, SIW, DGS, ECC, DG, X-band applications

1. INTRODUCTION

Multiple-input multiple-output (MIMO) communication is a useful technique for enhancing the capability and performance of wireless communications networks. These days, wireless networking relies heavily on MIMO antennas. MIMO antennas find widespread applications in various wireless communication standards, such as Wi-Fi, LTE, and 5G [1]-[2]. The advantages of MIMO technology increase with the number of antennas, yet it can be difficult to get additional antennas into the small, ever-shrinking devices. While designing a compact MIMO design, mutual coupling problem can happen if antenna elements are adjacent to one another, despite the MIMO antenna's struggles with mutual coupling and separation. To reducing the mutual coupling effect, several techniques are used [3]. Firstly, a metamaterial structure is used between antenna array elements to reduce isolation to less than 15 dB. A wideband, two-port MIMO antenna with a metamaterial structure enhances the mutual coupling to a maximum of 75 dB [4]-[5]. However, a metamaterial used antenna fabrication process can be technically challenging. Next a different type of mutual coupling reduction technique is used in MIMO by using the defected ground structure (DGS) and parasitic structure, eight port antennas with c-shaped parasitic structure achieves a gain of 1.4 dB to 4 dB [6]-[8]. A crossed-dipole

MIMO antenna with circular polarization suffers from high mutual coupling. Adding a metallic post or neutralization line in the middle reduces this coupling by 13 dB [9]. A two-port CPW-fed MIMO antenna achieves an improved gain of 5.63 dB [10] with fabrication difficulties. A quad-port MIMO antenna with Defected ground Structure in bottom plane is increases the isolation by more than 20 dB [11]. A novel half-mode substrate integrated a waveguide and slots to improve the isolation by 10 dB [12]. The antenna uses a neutralization line and a half-mode substrate integrated wave guide for decoupling, and the peak gain of the element is 7.93 dB [13]. A metamaterial and SIW-inspired isolating fence introduced MIMO antenna for lateral decoupling in space wave and surface wave radiation [14]. A newly introduced fractal antenna is used for X-band wireless applications; it achieves an impedance bandwidth of 494 MHz and a gain of 6.98 dBi [15]. A monopole antenna with dual polarization is suitable for X-band applications, and the antenna achieves a bandwidth of 4.69 GHz and a peak gain of 5.71 dB [16] with low isolation effects.
Review on literature, a hybrid mutual coupling reduction technique in a fractal MIMO antenna suitable for X-band applications is presented in this paper. This antenna uses special fractal-shaped elements for better performance across different frequencies. It also has DGS slots in the ground structure to improve its efficiency and reduce mutual coupling. And it has a 24-hollow cylindrical substrate-integrated waveguide between its elements to minimize interference between them. The combined method of DGS slots and SIW will reduce the mutual coupling and give a better result during simulation and measurement.

2. PROPOSED WORK

2.1 Design of fractal structure

The design of the patch is packed in five steps shown in figure1. The single fractal design was in five steps. The first step A is for initiate five circles with the radius r = 4.02mm. Keep the intersection of these circles which is in four oval shaped format.

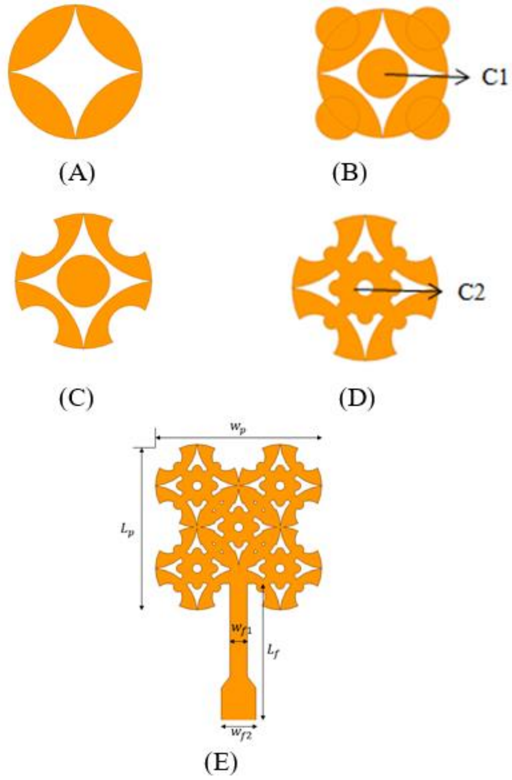


Fig 1: (A) Step1, (B) Step2, (C) Step3, (D) Step4, (E) Step5: single fractal design.

The second step B is for scaled down the radius of the circle by 30% and fit it into 4 corners and center of the four oval shaped format named as C1. Step three C is for subtract the four corners from the step2. Step four D is for the 13 circles scaled down from the radius of the circle in step 2 by 30% named as C2. In the 13 circles 12 circles are fitted around the C1 and 1 circle is subtracted from the middle of C1. Repeat the above steps fiver times and place the four of these at the four corners around the one in the middle and merge these. The single fractal dimensions are shown in Table 1.

2.2 Design calculation of fractal structure

Initially, the Circular patch radius is determined from the below expression

$$R = \frac{F}{\{1+\frac{2h}{\Pi \varepsilon_r F}[\ln(\frac{\Pi F}{2h})+1.7726]\}^2} \quad (1)$$

Where,

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} = 4.19 \times 10^{-3} \quad (2)$$

Substrate thickness h =1.6mm

$\pi = 3.14$

Resonate frequency f_r = 10GHz

Dielectric constant ε_r = 4.4

Diameter of the circle a= $2\times R$ (3)

Length of the substrate $L_s = 2\times2\times a$ (4)

Width of the substrate $W_s = 2\times2\times a$ (5)

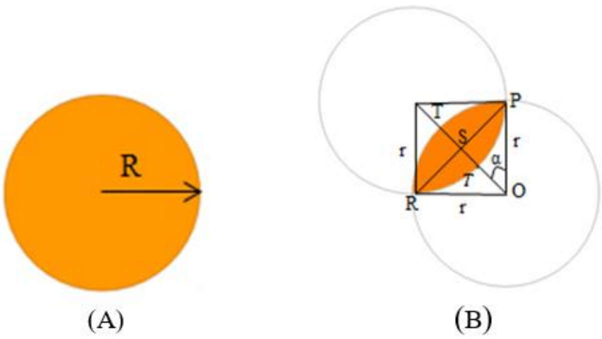


Fig 2: (A) Initial circle, (B) oval dimensions

From figure 2(B) the perimeter of oval shape is:

$$P_{oval} = 4\times 2\Pi r\times(\frac{\alpha}{360^0}) \quad (6)$$

Where, $\alpha = COS^{-1}(\frac{OS}{OP})$ (7)

From figure 2 (B) $\triangle$ORP is:

$$RP^2 = OR^2 + OP^2 = 32.32\text{mm} \quad (8)$$

Length of the oval shape RP = 5.68 mm

Width of the oval shape TT' = 2.4 mm

and $P_{oval} = 12.75mm$

From figure 2(B) the perimeter of four oval shapes is computed as

$$P_B = 4\times P_{oval} \quad (9)$$

The perimeter of figure 1(C) is calculated as

$$P_C = P_B - 4(\Pi C_1/2) + (\Pi C_1) \quad (10)$$

Where, C_1 =2.68mm

The perimeter of figure 1(D) is calculated as

$$P_D = P_C + 12(\frac{\Pi C_2}{2}) - (\Pi C_2) \qquad (11)$$

The total perimeter of a fractal 1(E) is calculated as

$$P_T = \frac{5 \times p_D}{4} \qquad (12)$$

The length of the fractal patch $L_P = p_T / 4$ (13)

The width of the fractal patch $w_p = p_T / 4$ (14)

Table 1: Structural dimensions of fractal structure

parameter	Value (mm)
Length of fractal antenna	$L_P = 14.4$
Width of fractal antenna	$W_P = 14.4$
Microstrip line length	$L_P = 12.07$
Microstrip line width	$W_{f1} = 1.5$, $W_{f2} = 3$
Length of the substrate	$L_s = 25$
Width of the substrate	$W_s = 36$
Height of the substrate	h= 1.6 mm

2.3 Fractal MIMO structure [proposed design]

The proposed MIMO antenna has a compact size of 25 mm x 36 mm and it was printed on FR-4 substrate with the substrate thickness of h = 1.6 mm as shown in figure 4. The flowchart for proposed design has shown in the figure 3. First the single fractal antenna is designed then adding two elements with a separation of a elements s_p is 5.2mm. The spacing between the antennas elements is less than $\lambda_0 / 2$, than the mutual coupling can occur. For the proposed antenna, the spacing of 5.2 mm is less than half of wavelength.

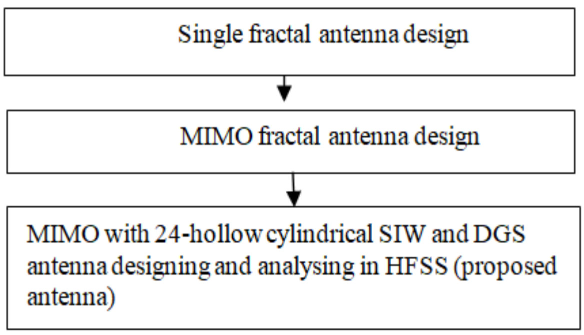
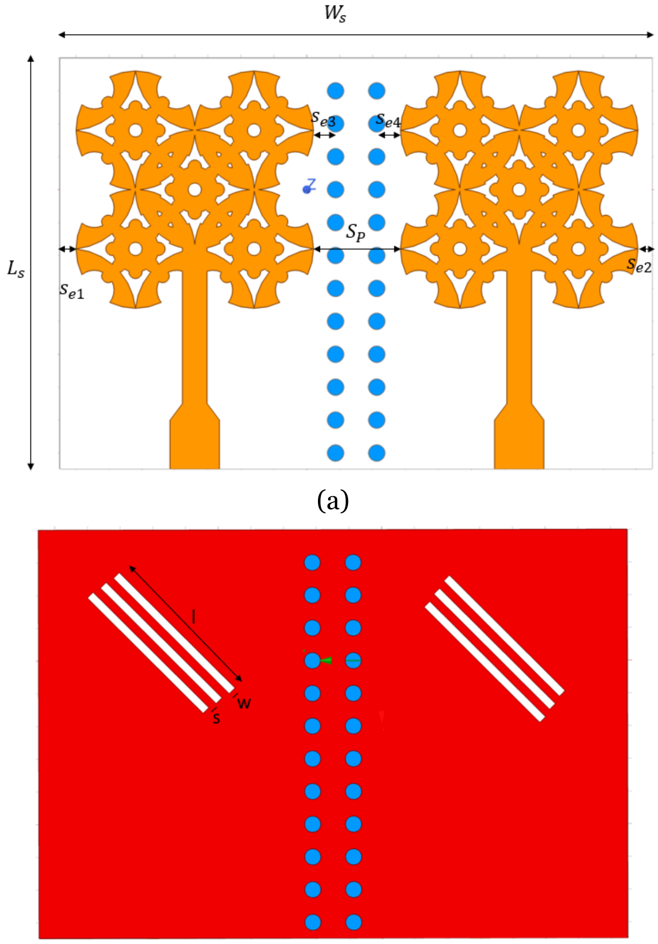


Fig 3. Flow chart for proposed antenna

By reducing this mutual coupling effect a hybrid method such as substrate integrated waveguide and defected ground structure is used in proposed design. The 24-hollow cylindrical SIW is used in between a antenna element is for increase the isolation.



(b)

Fig 4: Proposed MIMO antenna (a) front view (b) back view

The incorporation of SIW technology within MIMO elements yields several advantages. These include enhanced performance, expanded coverage, increased capacity, and diminished interference, all within a compact form factor.

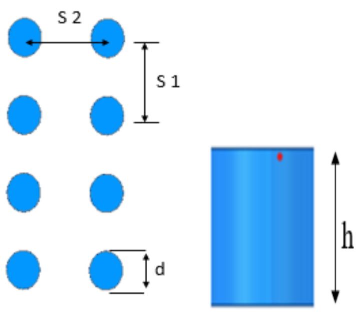


Fig 5: SIW Design.

These benefits make SIW an invaluable tool for constructing efficient and dependable MIMO systems across diverse wireless communication applications. The design and dimensions of the SIW is shown in figure 5. A single line consists of 12 hollow cylindrical SIW. The SIW is made as follows: a 1-mm hollow copper cylinder is inserted into the 1-mm hole on the substrate. The ground plane has six DGS slots to increase the isolation and gain of the antenna. The design and

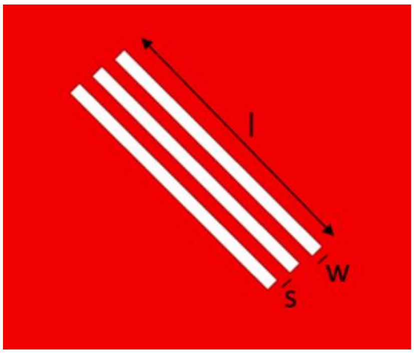


Fig 6: DGS slots on ground plane

dimensions of the six rectangular slots on the ground plane are shown in figure 6. The length (l), width (w) and Space (s) of the slot are 10 mm, 0.5 mm and 0.5 mm, respectively.

3. Results and discussions:

The proposed fractal MIMO antenna was simulated using ANSYS HFSS simulation tool. The antenna was tested and measured in an anechoic chamber shown in figure 7. The proposed fractal MIMO antenna simulated and measured results are shown below. The design effectiveness of the antenna is determined by simulating and analyzing its design parameters, which include radiation characteristics, MIMO diversity parameters, and scattering parameters. The radiation pattern of the antenna and gain of the antenna has been analyzed using isotropic horn antenna in the anechoic chamber.

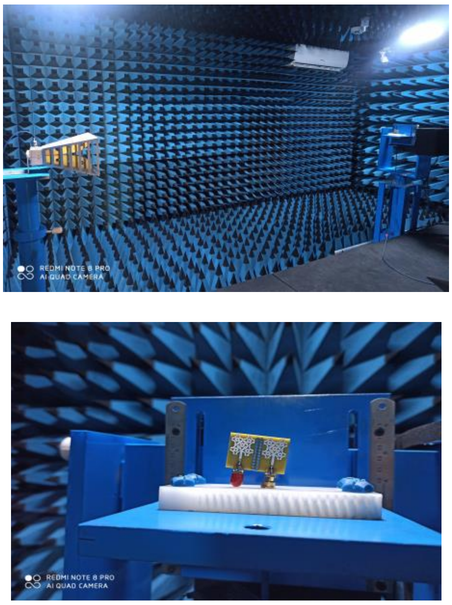
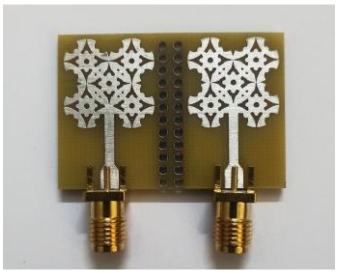
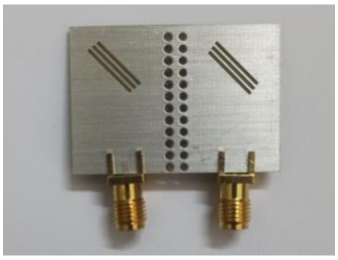


Fig 7: Experimental setup in anechoic chamber



(a)



(b)

Fig 8: prototype model of proposed antenna (a). Front view (b). Back view.

The figure 8 illustrates the prototype model of the proposed antenna. The simulated and measured results of the reflection coefficient (s_{11} & s_{22}) shown in figure 9. The reflection coefficient as -23 dB at 10.02 GHz and -16 dB at 11.55 GHz for simulation and -28 dB at 10.04 GHz and -21dB at 11.69 GHz for measurement.

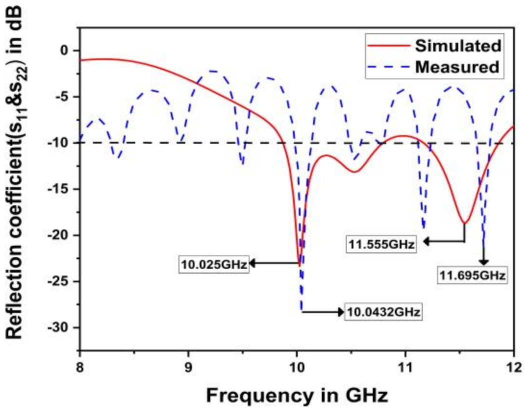


Fig 9: Simulated and measured reflection coefficient (s_{11} & s_{22}) of developed antenna.

The resonating frequencies are better improvement in a measurement. The frequencies are well suitable for X-band frequency applications.

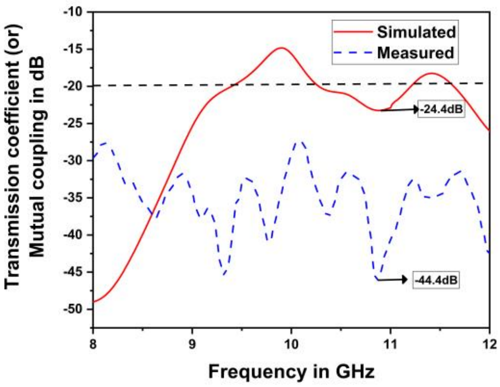


Fig 10: Simulated and measured transmission coefficient (mutual coupling) (s_{12} & s_{21}) of proposed antenna.

The simulated transmission coefficient (s_{12} & s_{21}) are shown in Figure 10. The process of dividing coexisting antennas so that there is only allowable interference between systems is known as antenna isolation. A minimum mutual coupling level of 16–20 dB on the antenna is required for a successful MIMO characteristic. The simulated and measured mutual coupling is minimum of around 24 dB and 44dB respectively. For the mutual coupling measured results the antenna isolation was improved and the interference between the antenna radiations is less.

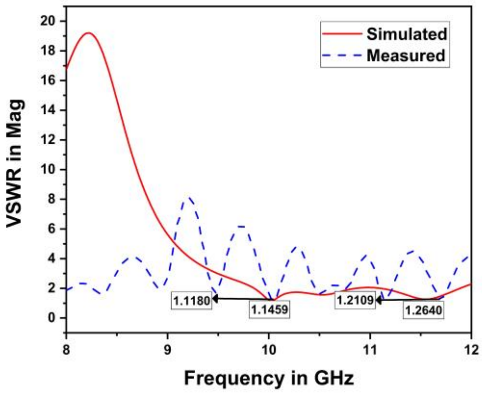


Fig 11: Simulated and measured VSWR for proposed antenna.

The simulated and measured antenna exhibits voltage standing wave ratio (VSWR) values of 1.1459 at 10.02 GHz and 1.1180 at 10.04 GHz are shown in Figure 11. The Voltage Standing Wave Ratio (VSWR) is an indication of the amount of mismatch between an antenna and the feed line connecting to it. For most antenna applications, a VSWR value of less than two is considered optimal. One could characterize the antenna as having a Good Match.

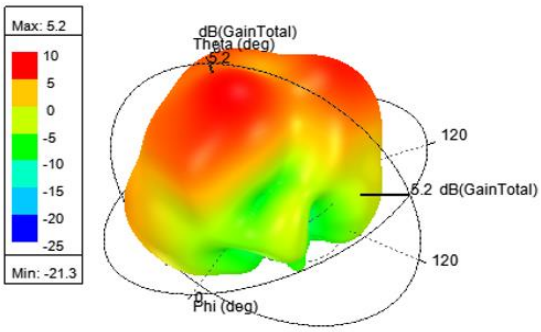


Fig 12: Gain of the proposed antenna

The figure 12 illustrates the simulated gain value of the proposed antenna. Antenna gain is a measure of the maximum effectiveness with which the antenna can radiate the power delivered to it by the transmitter towards a target. The gain of an antenna is more than 3 dB, which is good for an antenna. In the proposed simulated antenna, the highest simulated gain recorded was 5.2 dB.

The envelope correlation coefficient and diversity gain of the proposed fractal MIMO antenna is shown in Figure 13. The simulated ECC and diversity gain values are 0.0016 and 9.9996 dB respectively. The ECC and DG are calculated using the equation 15 and 16.

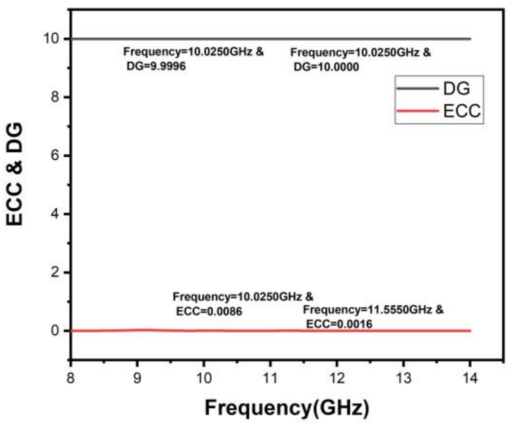


Fig 13: DG and ECC of proposed antenna

$$DG = 10(\sqrt{1-|ECC|^2}) \quad (15)$$

$$ECC = \frac{|s_{11}^{*}s_{12} + s_{21}^{*}s_{22}|^2}{(1-|s_{11}|^2-|s_{21}|^2)(1-|s_{22}|^2-|s_{12}|^2)} \quad (16)$$

Where, $|S_{11}|$ and $|S_{22}|$ are reflection coefficients of port 1 and port 2. $|S_{12}|$ and $|S_{21}|$ are other transmission coefficients of port 1 and port 2. The envelope correlation coefficient value of <0.004 is good for MIMO antennas. For this characteristic, our design achieves ECC values less than 0.004 for the corresponding frequencies. The diversity gain for a MIMO antenna is >9.98 dB. The design achieves an improved diversity gain of over 9.98 dB. This demonstrates that the suggested MIMO antenna performs well in real-world environments. The simulated and measured radiation pattern of the antenna is shown in figure 14 and 15 from these figures, it is understood that the antenna radiates in omnidirectional.

Table 2: Comparison between existing work and proposed work

Ref	Techniques used	Size (mm)	Frequency (GHz)	Gain (dB)	Isolation (dB)	ECC	DG
[4]	Metamaterial	40 x 30 x 1.6	5.3	3	<-15	<0.002	>9
[5]	SIW based bow tie	-	28.6	11	<-75	<0.0005	>9.9
[7]	C-shaped parasitic structure	$0.8\lambda \times 1.33\lambda$	4.5-16.4	7.8	<-20	<0.002	>9
[10]	Rectangular Microstrip strip	50 x 50 x 1.59	2.45l, 5.5	5.59	<-15	<0.003	>9
[11]	HMSIW	31.4 x 15.7 x 1.5	5.035	6	<-36	<0.003	>9
[14]	SIW , DGS and Metamaterial	35 x 36 x 1.6	2-16	3.7	<-20	<0.4	>9
[17]	MPS radiator	36 x 27	7.9-9.59	3.55	<-18	<0.01	>9.9
This work	SIW and DGS	25 x 36 x 1.6	10.04, 11.14, 11.69	5.2	<-44	<0.0016	>9

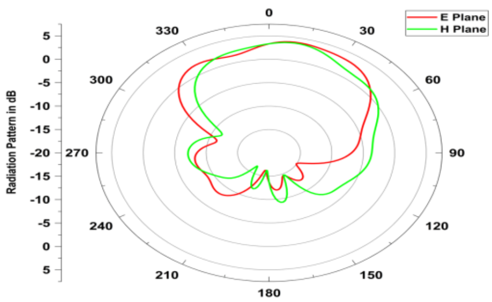


Fig 14: Normalized radiation pattern at 10GHz

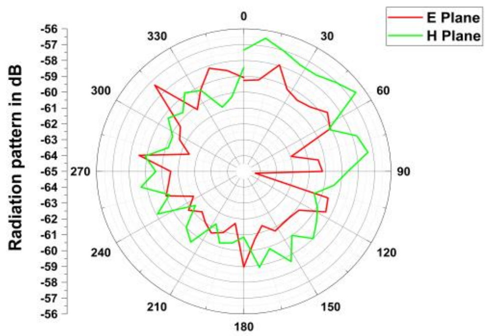


Fig 15: Measured radiation pattern.

The gain, isolation loss, Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) were compared with existing work in various papers shown in table 2. From table 2, ref [4] a metamaterial structure is used for reducing the mutual coupling by 15dB. In ref [7] a C- shaped parasitic structure is used for reduce mutual coupling and increase the gain by 7.8dB. From ref [14] the SIW, DGS and metamaterial structures are used for reduce the radiation interference in MIMO. For the above comparisons the proposed antenna was exhibits improved gain and mutual coupling reduction. The proposed work exhibits good gain, isolation loss, ECC and DG which can be very well utilized for X-band applications. In addition, using the hybrid decoupling methods such as using slots and Substrate Integrated Waveguide (SIW), the antenna gain, and efficiency, as well as radiation patterns are all improved, which is very desirable.

Table 3. Comparison table for simulated and measured results of the proposed antenna.

Parameters of proposed antenna	**Simulated results**	**Measured results**
Reflection coefficient	-23dB	-28dB
Mutual coupling (dB)	-24.4 dB	-44.4 dB
VSWR	1.1459	1.1180
GAIN	5.2 dB	5.2dB
ECC	0.0016	0.0016
Diversity Gain	>9	>9

In table 3 the simulated and measured results are compared for developed antenna. From the table we can infer that the mutual coupling, VSWR and gain of the proposed antenna are significantly improved as compared with the other works referred.

4. Conclusion

A fractal shaped MIMO antenna including SIW and DGS to reduce the mutual coupling and enhance the gain. The proposed antenna size of 25 x 36 x 1.6 mm is made of FR4 substrate material with the resonating frequencies of 10.04 GHz, 11.14 GHz and 11.69GHz. By adding a 24-hollow cylindrical SIW in between a MIMO and six DGS slots on a ground plane to reduce the mutual coupling by around 44 dB. The improved VSWR of 1.18 are obtained at 10.04 GHz. The ECC and DG of the proposed antenna are 0.0016 and >9 respectively. The gain observed for the proposed design is 5.2 dB. For the above results and discussions, the antenna was well suitable for X-band frequency application like satellite communication, radar application and whether monitoring.

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