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Dual Band Notched Orthogonal 4-Element MIMO Antenna With Isolation for UWB Applications

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ABSTRACT A Novel dual notched 4-element MIMO (Multi-Input-Multi-Output) antenna with gap sleeves and H-slot is proposed and fabricated for UWB (ultra wide-band) applications. The proposed antenna is CPW (Co-Planar Waveguide) fed and consists of four orthogonal elements with good isolation. It has low profile and small dimensions of $80 \times 80 \times 1.6\text{mm}^3$. The proposed MIMO antenna achieved an impedance bandwidth (S11 < -10dB) from 2.1GHz - 20GHz with notches from 3.3GHz - 4.1GHz and 8.2GHz - 8.6GHz frequency bands. These achieved notches can filter the interference of WiMAX(3.3GHz - 3.7GHz), and military/radar applications band (8.2GHz - 8.6GHz). Mutual coupling among the elements is also below -25dB. The performance parameters of proposed MIMO antenna are relatively good with very low ECC (Envelop Correlation Coefficient) less than 0.02 except at notches and DG (Diversity Gain) nearly 10. Peak gain of 5.8dB is achieved by the proposed antenna and the radiation efficiency is also above 80% except at notches.The computer-generated and experimental results are in accord and therefore, the proposed four element MIMO antenna can be suggested as a suitable aspirant for UWB applications with stop bands for WiMAX and military/radar applications.

INDEX TERMS Co-planar waveguide (CPW) fed, diversity gain (DG), envelop correlation coefficient (ECC), isolation, multi input multi output (MIMO) antenna, mutual coupling, orthogonal elements.

I. INTRODUCTION

Ultra wideband (UWB) antennas have become a trend from the past few years because of their low cost, high data rates and large communication capacity. Multipath fading and reliability are the practical limitations of UWB antennas. The convergence of MIMO technology and UWB antenna can overcome these limitations with suppressed multipath effect, enhanced capacity, improved data transmission efficiency and increased communications quality. Various MIMO antennas with improved isolation for UWB applications are presented in [1]–[5]. Many narrowband communication systems operating at WiMAX (3.3-3.8GHz), WLAN (5.15-5.85GHz), and X-band communication satellites (7.99-8.4GHz) frequency bands are in existence and therefore, notch band UWB MIMO antenna is desirable to reject such existing frequency bands in UWB communication system. UWB MIMO antennas with dual and triple band notch characteristics are presented in [6]–[19]. Two element UWB MIMO antenna with notches at WLAN and WiMAX is proposed with couplingless than -15dB [6]. Four element differential pair UWB polarization diversity MIMO antenna is proposed in [7] with dual notch characteristics at WiMAX and WLAN bands. It achieved a good isolation of greater than 40dB in operating band. Single notched band Ultra-wideband MIMO antennas are proposed in [8]–[13] for WiMAX and WLAN frequency bands. Dual notched band UWB MIMO antennas and triple notched band characteristics are proposed in [14]–[16] and [17]–[19] respectively with low mutual coupling. In [4], [20]–[22], authors had proposed MIMO antenna arrays with dual notches for impulse radio UWB wireless applications, EBG structures and F-shaped stubs with better isolation for UWB applications.

In this paper, a dual notch band monopole antenna, 2-element MIMO array antenna with collinear and orthogonal elements and a 4-element orthogonal MIMO antenna

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with [23] is proposed with dual notched characteristics at WiMAX and military/radar applications frequency bands. The 4- elements of proposed MIMO antenna are symmetrical and identical. Section-II illustrates the single element design with its geometrical specifications. Two element MIMO antenna configurations and four element orthogonal MIMO antenna configurations with their respective S-parameter characteristics are presented in Section-III. Proposed MIMO antenna characteristics, performance parameters and comparison with recent existing UWB MIMO antennas are discussed in the Section-IV.

II. SINGLE ELEMENT

A monopole antenna with gap sleeve [23] and truncated edges is designed in iteration-1 as given in figure 1(i). The monopole antenna is a micro-strip patch antenna with coplanar waveguide (CPW) feeding. Basic design equations of CPW fed micro-strip patch antenna are used to design the monopole antenna as given in equations (1)-(4).

Effective dielectric constant of CPW can be calculated as:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2}\left\{tanh\left[0.775ln\left({}^{h}/_{G}\right) + 1.75\right] + \frac{kG}{h} \times \left[0.004 - 0.7k + 0.01\left(1 - 0.1\epsilon_r\right)\left(0.25 + k\right)\right]\right\} \quad (1)$$

where,

$$k = \frac{W}{W + 2G} \quad (2)$$

W = width of the centre conductor,
h is thickness of substrate,
G is the gap between signal conductor and the ground.

The analytical expression to compute characteristic impedance of CPW line which is derived from the conformal mapping can be expressed in terms of elliptic function of the 1st kind $K(k)$ (ratio of complete elliptic integral of first kind and its complement) as:

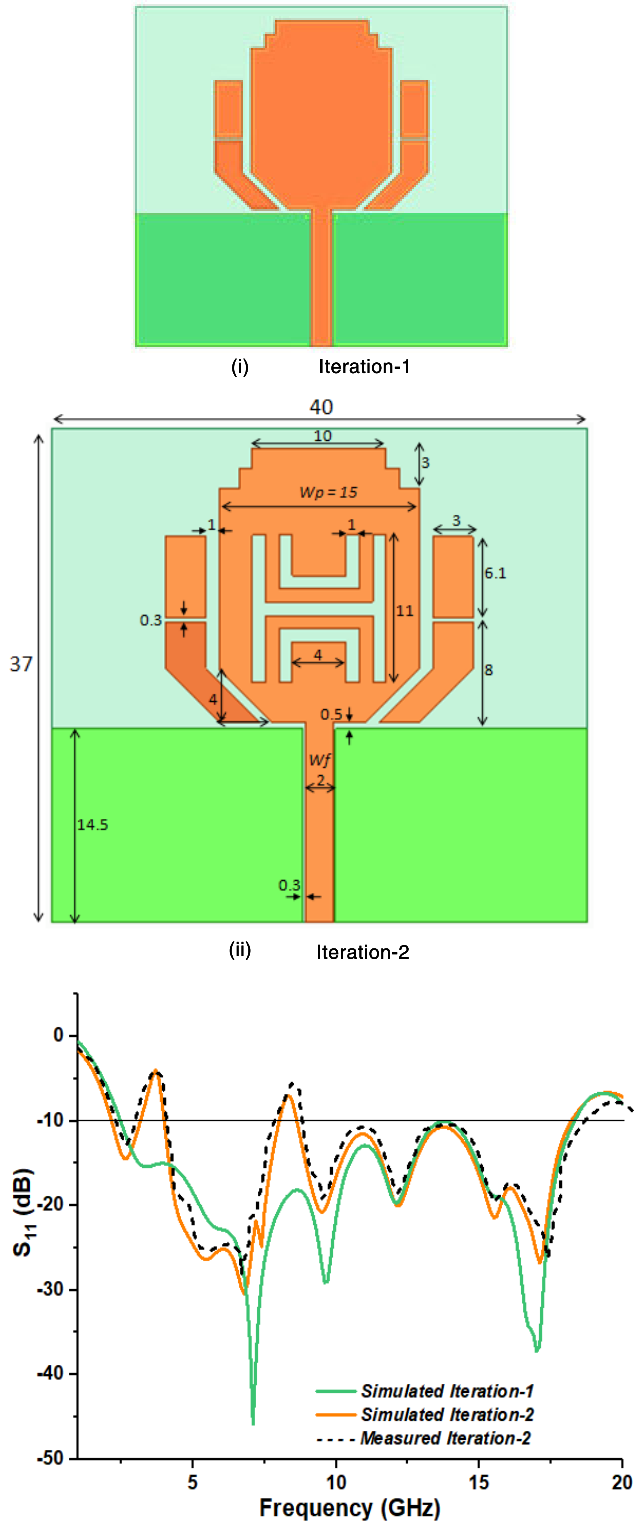
$$Z_{0CPW} = \frac{20\pi}{\sqrt{\epsilon_{reff}}}\frac{K'(k)}{K(k)} \quad (3)$$

$$\frac{K'(k)}{K(k)} = \left[\frac{\pi}{ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)}\right] \quad \text{if } 0 < k < 0.707$$

$$= \left[\frac{ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)}{\pi}\right] \quad \text{if } 0.707 < k < 1 \quad (4)$$

where, $k' = \sqrt{1-k^2}$ and $K'(k) = K(k')$.

From these equations, the theoretical values obtained are $\epsilon_{reff} = 2.809$, $Z_{0CPW} \cong 48$ohms for the design parameters W = 2mm, h = 1.6mm, G = 0.3mm and $\epsilon_r = 4.4$. It achieved ultra wideband from 2.5GHz to 18.3GHz with a wide bandwidth of 15.8GHz. To obtain dual notched band characteristics, H-slot with dual U-slots is incorporated in the radiating element rectangular patch. The total length of the H-shaped and U-shaped stubs at the central band notched frequency can be calculated using equations (5) and (6).



(iii) S11 characteristics of UWB antenna.

FIGURE 1. Single element dual notched UWB antenna.

$$L_s = \frac{\lambda_g}{4} \quad (5)$$

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \quad (6)$$

where,

λ_g is guided wavelength

$\lambda_o = \frac{c_0}{f_r}$ is free space wavelength,

f_r is center frequency of notch band

c_0 is velocity of light

ε_r = dielectric constant

Figure 1(ii) presents the geometrical specifications and design of iteration-2. S11 characteristics of iteration-1 and 2 are illustrated in figure 1(iii) along with measured characteristics of iteration-2. It is fabricated on FR-4 substrate of dielectric-constant 4.4 and dimensions 37×40×1.6mm3. The proposed single element antenna, iteration-2 achieved a wide bandwidth of 16GHz from 2.2GHz to 18.2GHz with dual notches at 3.6GHz (WiMAX) and 8.3GHz (military/radar). The measured results are very close to simulated results, thereby validating the designed single element. Figure 1(iii) gives the geometrical specifications of proposed single element antenna.

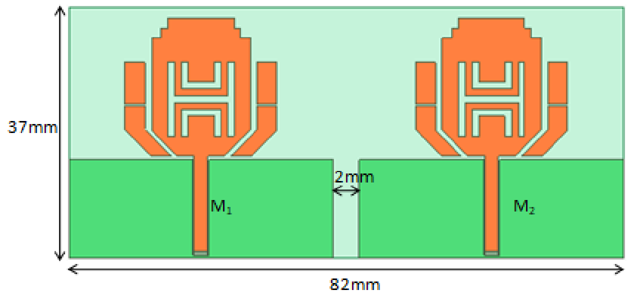
III. MIMO ANTENNA

A 2-element collinear MIMO antenna with 2mm spacing among elements M_1 and M_2 is given in figure 2(i). It is fabricated on FR-4 substrate of dimensions $37 \times 82 \times 1.6mm^3$. The simulated and experimented Scattering parameters are illustrated in Figure 2(ii). As the elements are identical, for simplicity only port1 (M_1) S-parameters S_{11} and S_{12} are analyzed. From S_{11} characteristics of the antenna, it operates from 3.3GHz to 17.6GHz with a notch at 8.3GHz. S_{12} characteristics give coupling between the 2-elements. It is less than −20dB in the entire operating band and isolation is very high at 7.6GHz. The lower operating band is filtered in this MIMO structure.

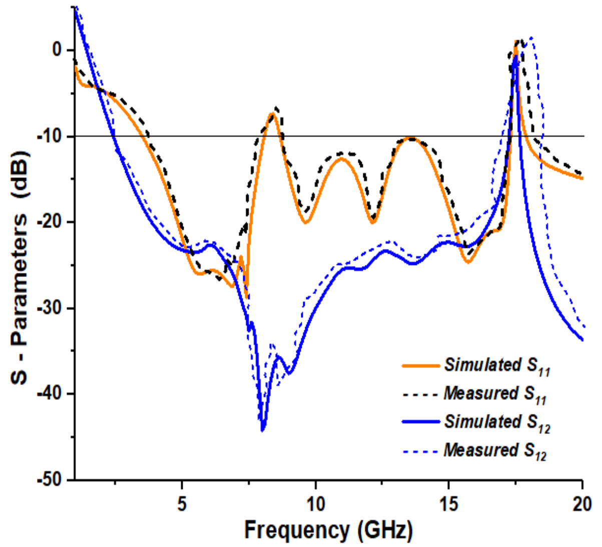
Figure 3(i) presents a 2-element MIMO antenna with the elements M_1 and M_2 placed in opposite direction (180°).

The illustrated antenna dimensions are $37 \times 80 \times 1.6mm^3$, fabricated on FR-4 substrate. S-parameter (port1) characteristics are illustrated in Figure 3(ii). It operates from 2.1GHz to 18.2GHz with notches at 3.6GHz and 8.3GHz. Isolation between the elementsM_1 and M_2 is above 20dB.

To further reduce the coupling between MIMO elements, the elements M_1 and M_2 are placed orthogonal to each other as represented in figure 4(i). The antenna dimension is $40 \times 80 \times 1.6mm^3$ and is fabricated on FR-4 substrate. S-parameters of the MIMO antenna for port1 (M_1) excitation are illustrated in figure 4(ii). It operates from 2.1GHz to 16.5GHz with dual notch at 3.8GHz and 8.4GHz and mutual coupling is less than −30dB from 4GHz through



(i) Simulated geometry of 2-element collinear MIMOantenna.



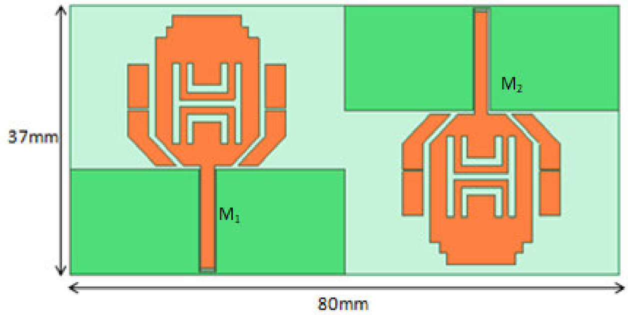
(ii) S-parameter characteristics of 2-element collinear MIMO antenna.

FIGURE 2. Two element collinear MIMO antenna.

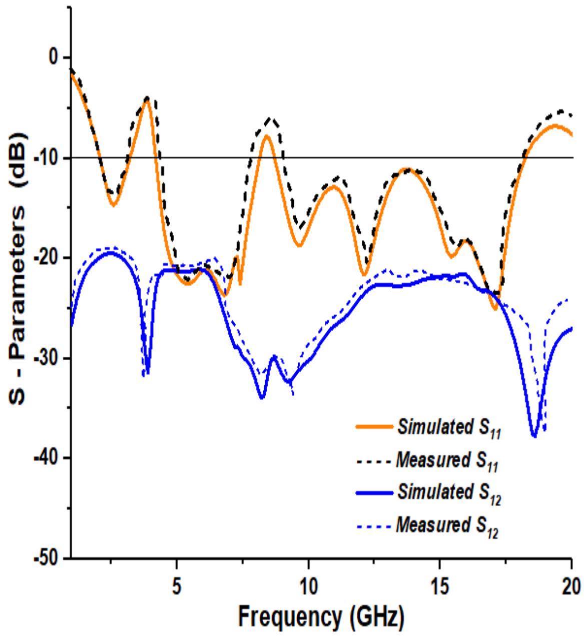
operating band. Therefore, isolation is increased by placing the elements orthogonal to each other.

A four-element orthogonal MIMO is proposed as presented in figure 5(i) for bandwidth enhancement and better isolation. The MIMO model used splitted ground plane to reduce the coupling among elements in the MIMO array. This has a drawback that the ground reference is not located in the MIMO antenna array and depends on the ground system of the device where the antennas are connected to. Hence, this reduces the reliability of the antenna because its behavior can change between two different devices. To overcome this, the splitted ground planes of 4 elements in MIMO antenna are joined together through 0.2mm width connection lines to have common ground plane for the proposed MIMO antenna array. The final proposed 4-element MIMO antenna array with connected ground plane is illustrated in figure 5(ii). It is

$$ECC = \frac{\left| \int_0^{2\pi} \int_0^{\pi} \left(XPR\, E_{\theta 1} E_{\theta 2}^{*} P_\theta + E_{\varphi 1} E_{\varphi 2}^{*} P_\varphi \right) d\Omega \right|^2}{\int_0^{2\pi} \int_0^{\pi} \left(XPR\, E_{\theta 1} E_{\theta 1}^{*} P_\theta + E_{\varphi 1} E_{\varphi 1}^{*} P_\varphi \right) d\Omega \text{ X} \int_0^{2\pi} \int_0^{\pi} \left(XPR\, E_{\theta 2} E_{\theta 2}^{*} P_\theta + E_{\varphi 2} E_{\varphi 2}^{*} P_\varphi \right) d\Omega} \quad (7)$$



(i) Simulated geometry of 2-element MIMO antenna.



(ii) S-parameter characteristics of 2-element MIMO antenna.

FIGURE 3. Two-element MIMO antenna.

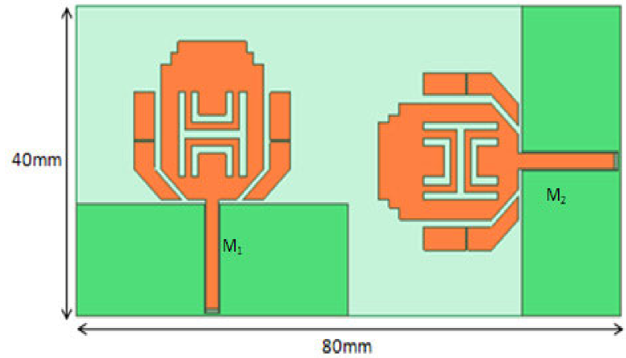
prototyped on FR-4 substrate with dielectric constant 4.4 and dimensions $80 \times 80 \times 1.6mm^3$.

Fabricated prototype is given in figure 5(iii). The simulated and measured Scattering parameters S_{11}, S_{12}, S_{13} and S_{14} of proposed antenna for port1 are illustrated in Figure 5(iv). The proposed antenna achieved a wide impedance bandwidth ($S_{11} < -10$dB) of 17.9GHz from 2.1GHz to 20GHz with dual notched characteristics at 3.6GHz and 8.3GHz. The isolation between the elements (M_1, M_2) and (M_1, M_4) is less compared to (M_1, M_3) and M_2 and M_4 are adjacent to M_1. The average isolation of proposed antenna is greater than -26dB over the entire operating range. The measured and simulated Scattering parameter characteristics in all cases are in good agreement and therefore, the proposed 4-element orthogonal MIMO antenna can be validated for UWB applications.

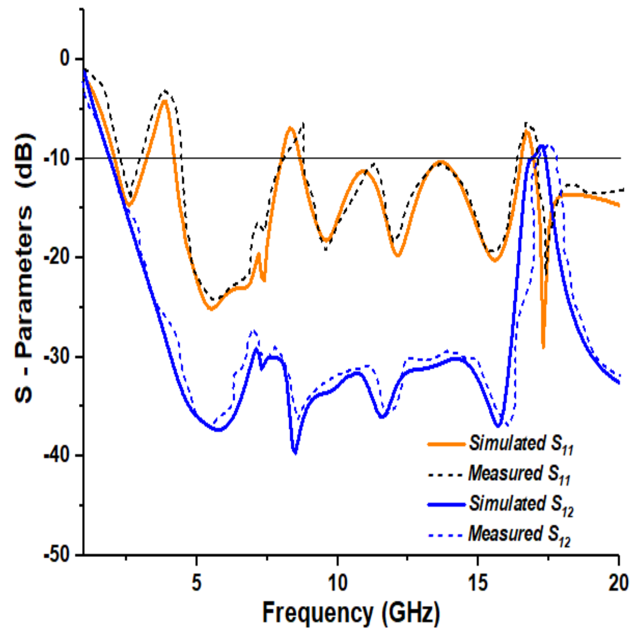
IV. RESULTS AND DISCUSSIONS

A. SURFACE CURRENT DISTRIBUTION

The surface current distributions of proposed 4-element MIMO antenna are investigated at the notch frequencies



(i) Simulated geometry of 2-element orthogonal MIMO antenna.



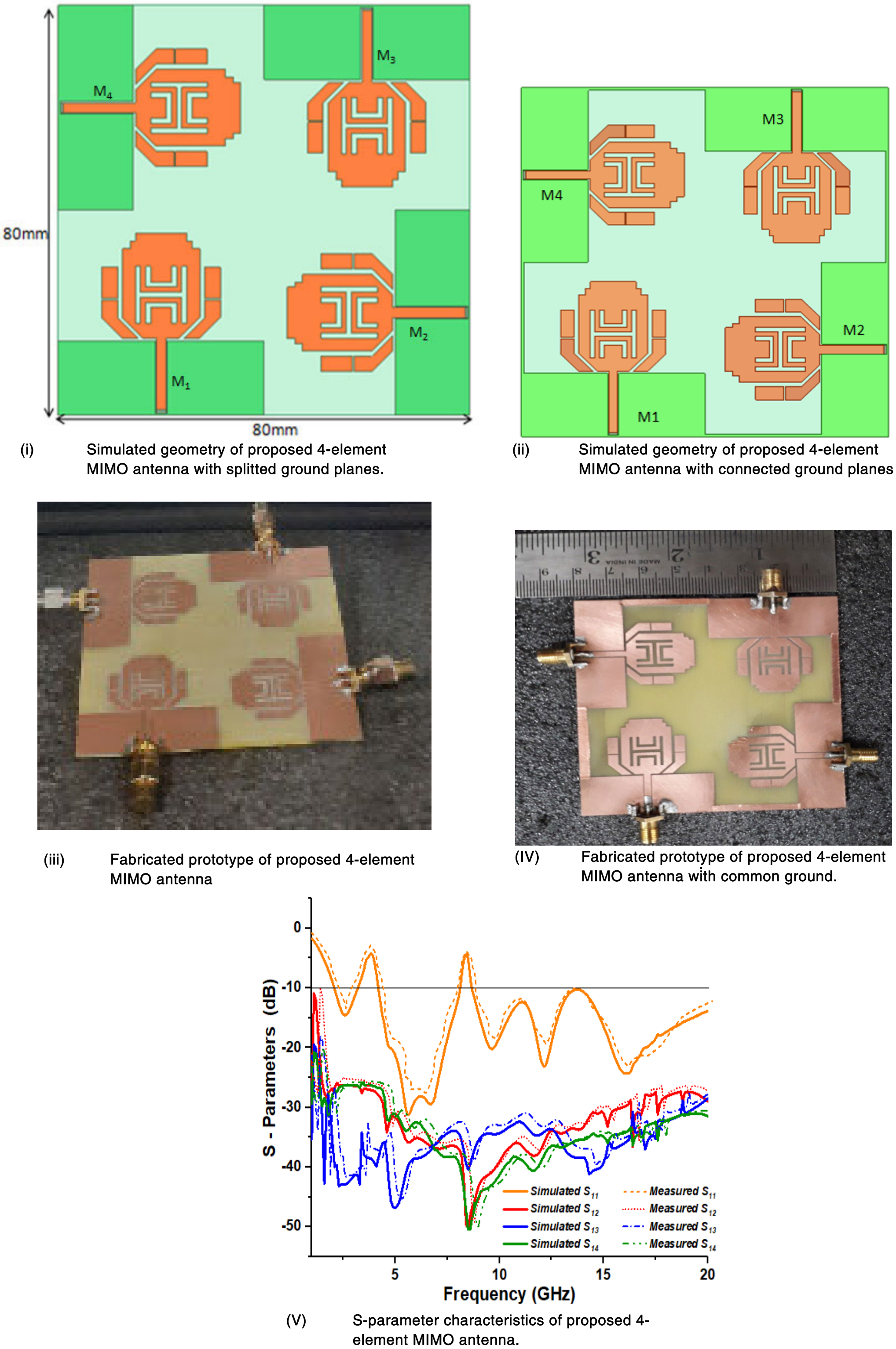
(ii) S-parameter characteristics of 2-element orthogonal MIMO antenna.

FIGURE 4. Two-element orthogonal MIMO antenna.

3.6GHz and 8.3GHz and also at 5.8GHz and 10GHz in the operating band. As presented in Figure 6, the net resultant radiation at notch frequencies is very less as the generated opposite currents nullify each other. Figure 7 illustrates the surface current distribution at 10GHz and 5.8GHz with individual ports excitation. It is evident from these figures that coupling among the elements M_1, M_2, M_3 and M_4 is very less and hence the proposed 4-element MIMO antenna has superior diversity characteristics.

B. RADIATION PATTERNS

Figure 8 and 9 present the simulation and experimental results of two dimensionalradiation-patterns in polar coordinates of the proposed MIMO antenna in xy, yz and zx planes at 10GHz and 5.8GHz frequencies respectively. The proposed antenna radiates along the antenna plane i.e. is xy plane. Therefore, Gain-Phi is co-polarization and Gain-Theta is cross-polarization. At 10 GHz in xy plane



(i) Simulated geometry of proposed 4-element MIMO antenna with splitted ground planes.

(ii) Simulated geometry of proposed 4-element MIMO antenna with connected ground planes

(iii) Fabricated prototype of proposed 4-element MIMO antenna

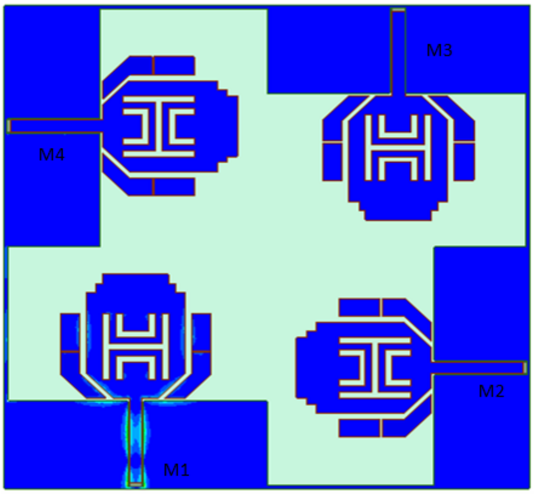
(IV) Fabricated prototype of proposed 4-element MIMO antenna with common ground.

(V) S-parameter characteristics of proposed 4-element MIMO antenna.

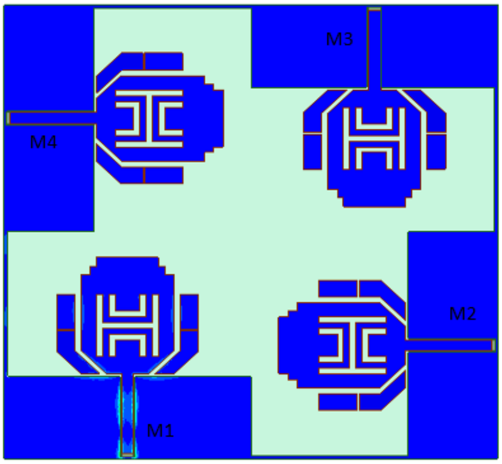
FIGURE 5. **Proposed 4-element orthogonal MIMO antenna.**

there are two main beams in end-fire direction radiating maximum at 45° and 135°. The steadiness of simulated and experimental results validates the correctness of design. The radiation-patterns are more directional in nature and the variationamong co-polarization and cross-polarization is in minimum acceptable range.

Simulated and measured gain characteristics of the proposed MIMO antenna with port1 (M_1) excitation are

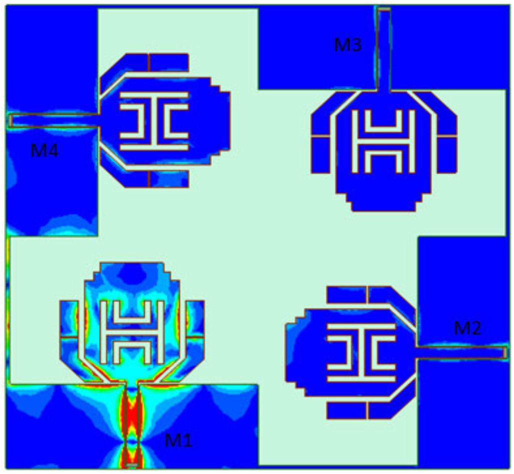


(i). Surface current distribution of proposed MIMO antenna at 3.6GHz

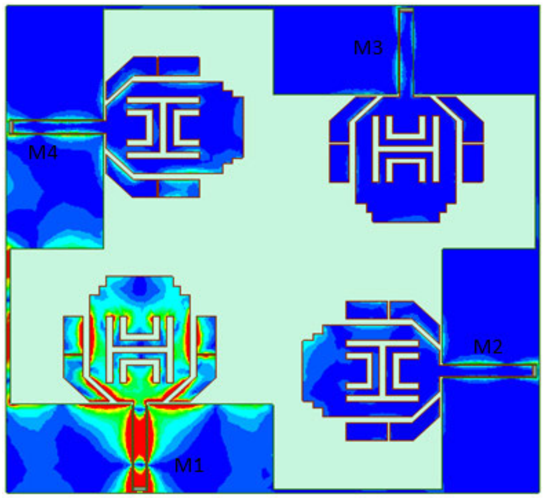


(ii). Surface current distribution of proposed MIMO antenna at 8.3GHz

FIGURE 6. (i). Surface current distribution of proposed MIMO antenna at 3.6GHz. (ii). Surface current distribution of proposed MIMO antenna at 8.3 GHz.



(a) Port1 excited
(i). Surface current distribution of proposed MIMO antenna at 10GHz



(a) Port1 excited
(ii). Surface current distribution of proposed MIMO antenna at 5.8GHz

FIGURE 7. (i). Surface current distribution of proposed MIMO antenna at 10GHz. (ii). Surface current distribution of proposed MIMO antenna at 5.8GHz.

illustrated in Figure.10. Gain is less at lower frequencies and increases with increase in the frequency. However, it can be observed that gain decreases sharply at notch frequencies. A peak gain of 5.8dB is achieved in UWB range. Hence, the projected 4-element MIMO antenna with dual notch exhibits good notched band characteristics. Figure.11 gives simulated and measured radiation efficiency characteristics for port1 (M_1) excitation. The typical efficiency of proposed MIMO antenna is above 80% except at notch frequencies. Efficiency of proposed antenna falls below 70% at notch frequencies.

C. MIMO PERFORMANCE PARAMETERS

1) ENVELOP CORRELATION COEFFICIENT (ECC)

Diversity among the elements of proposed 4-element MIMO antenna is represented in-terms of correlation coefficient in Figure 12. ECC of MIMO antenna with port1 and port2 can be measured from radiation patterns as given in equation (7), as show at the bottom of the 3rd page. For any MIMO antenna ECC should be below 0.5 to exhibit fine diversity. From figure 12, it can be observed that both simulated and experimental ECC values are less than 0.02 in the entire UWB range excluding at notches. At notch frequencies, ECC is not more than 0.05. Therefore, the projected MIMO antenna exhibits fine diversity with low ECC values.

2) DIVERSITY GAIN

Diversity gain is a performance metric of MIMO antenna, defined with the equation (8):

$$DG = 10\sqrt{1 - ECC^2} \tag{8}$$

Figure.13 illustrates the simulated and experimental diversity gain of proposed MIMO antenna among the elements

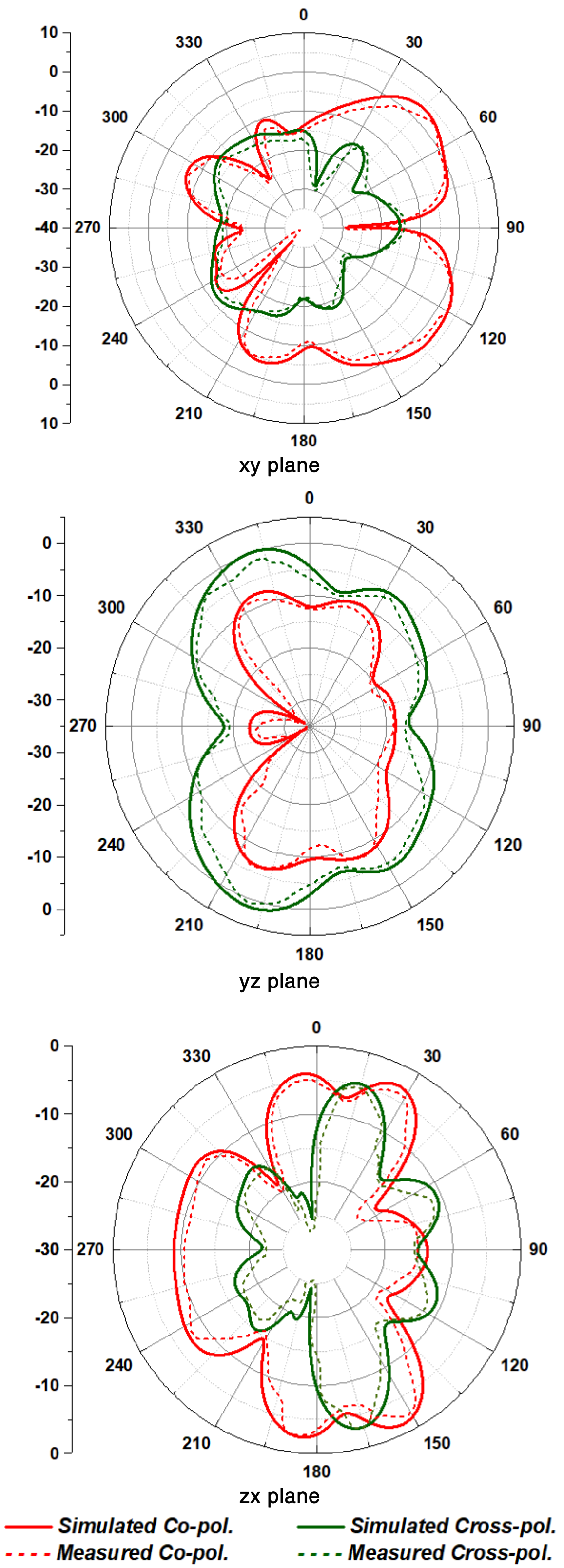


FIGURE 8. Radiation patterns of proposed MIMO antenna at 10 GHz.

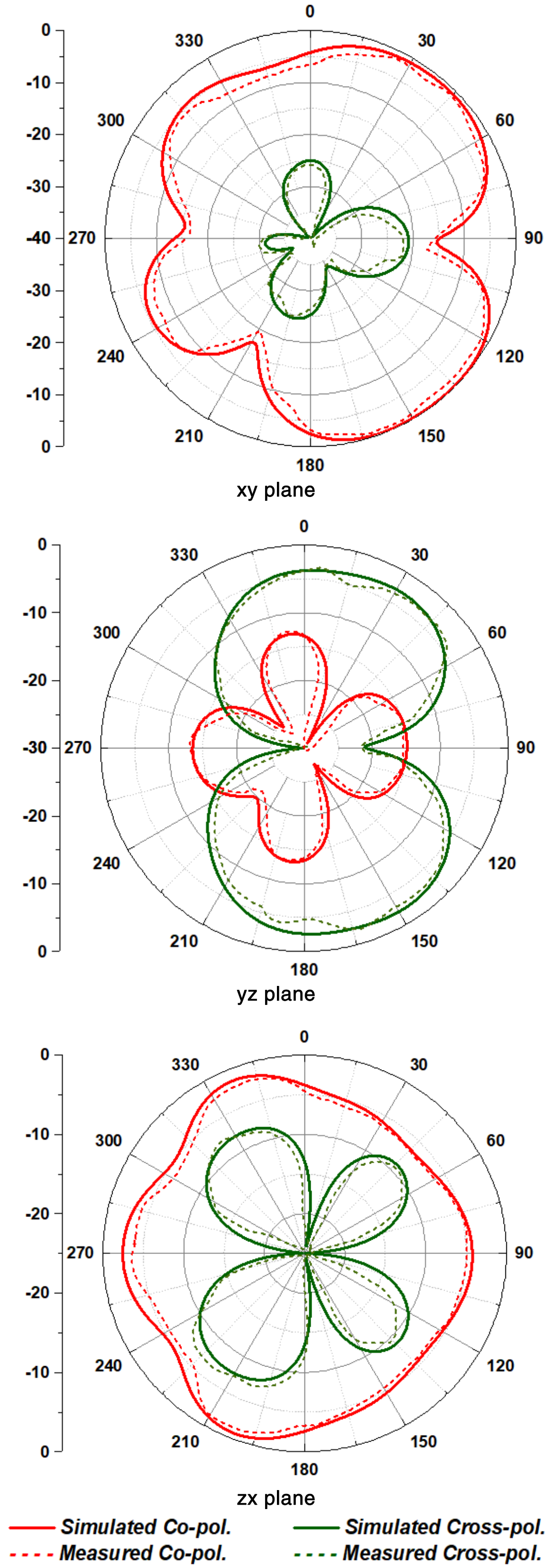


FIGURE 9. Radiation patterns of proposed MIMO antenna at 5.8 GHz.

(M_1,M_2), (M_1,M_3) and (M_1,M_4). For all the elements, DG is greater than 9.99 and fluctuations are more at notch frequencies. The proposed MIMO antenna exhibits good DG characteristics.

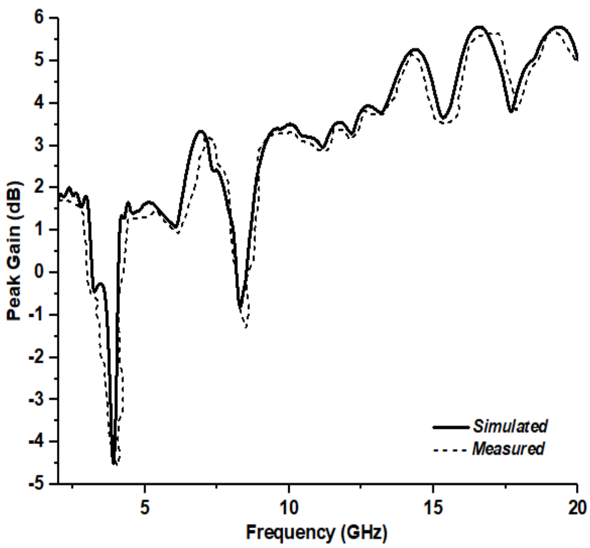


FIGURE 10. Peak gain characteristics of the proposed MIMO antenna.

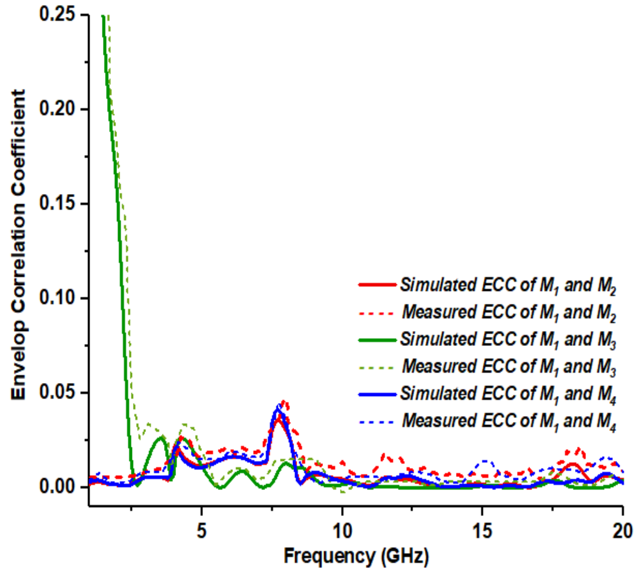


FIGURE 12. Envelop correlation coefficient of the proposed MIMO antenna.

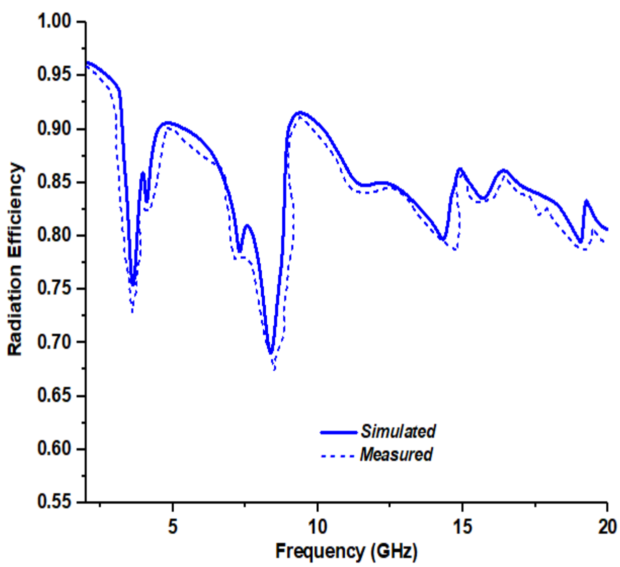


FIGURE 11. Radiation efficiency characteristics of the proposed MIMO antenna.

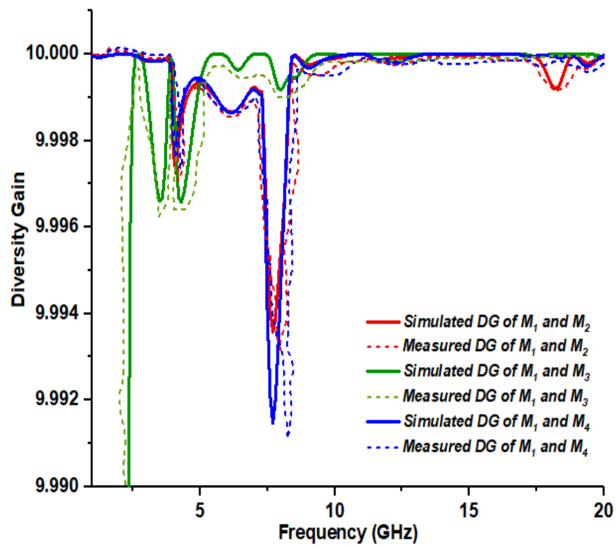


FIGURE 13. Diversity gain of the proposed MIMO antenna.

3) TOTAL ACTIVE REFLECTION COEFFICIENT (TARC)

TARC curves give the effective operating bandwidth of MIMO antenna system. For a two port network, the expression to calculate TARC from the obtained S-parameters is given as in equation (9),

$$\Gamma_a^t = \sqrt{\frac{\left(\left(\left|S_{11} + S_{12}e^{j\theta}\right|^2\right) + \left(\left|S_{21} + S_{22}e^{j\theta}\right|^2\right)\right)}{2}} \tag{9}$$

where, θ is the input feeding phase.

4) CHANNEL CAPACITY LOSS (CLL)

Channel capacity of MIMO system can be characterized by CCL parameter. To have good diversity performance for MIMO antenna, CCL value is desired to be smaller than 0.4bps/Hz. Figure 14 illustrates TARC characteristics and CCL of the proposed 4-element MIMO antenna. It is observed from figure 14 that CCL is less than 0.4bps/Hz in the entire operating band except at notches and TARC value is also less than −10dB in the operating band except at notches.

5) GROUP DELAY

Group delay is a time domain characteristics of MIMO antenna. Figure 15 presents the variations in group delay of four elements M_1, M_2, M_3 and M_4 over ultra wide-band

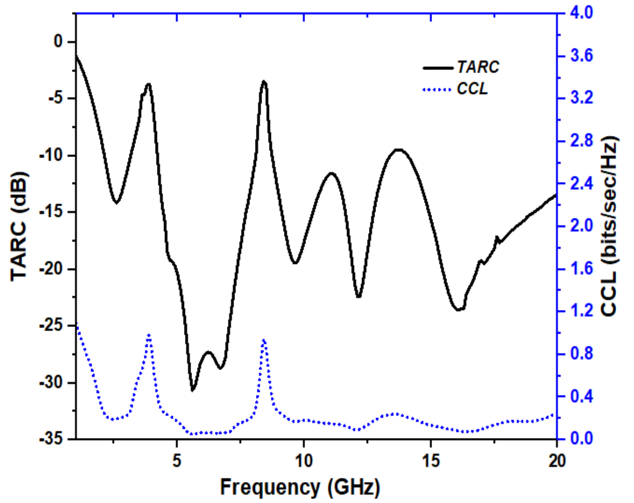


FIGURE 14. TARC characteristics and CCL of the proposed MIMO antenna.

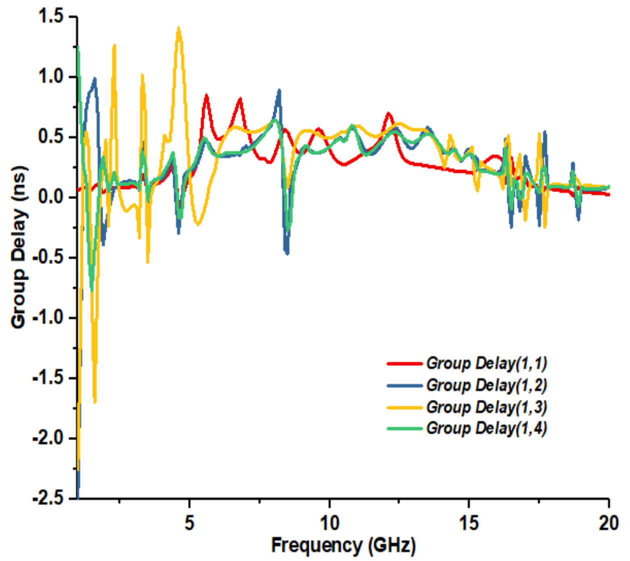


FIGURE 15. Group delay of the proposed MIMO antenna.

range. Group delay (1, 1) gives delay from port1 to port 1, Group delay (1, 2) denotes the delay from port1 to port 2 and similarly Group delay (1, 3), Group delay (1, 4). As the element in the proposed MIMO antenna are identical and symmetrical, Group delay (1, 2) and Group delay (1, 4) are almost similar as observed in Figure 14. The variations in Group delay (1, 3) are high at lower frequencies. The overall group delay values are less than 1.5 ns for proposed MIMO antenna.

6) COMPARISON

Antenna performance parameters of the proposed UWB MIMO antenna are compared with recent existing antenna models in Table 1.

V. CONCLUSION

A novel and compact 4-element MIMO antenna is proposed here for UWB applications. Dual notched band is achieved by incorporating H and U-slots in monopole antenna with gap sleeves. The projected MIMO antenna is fabricated on FR-4 substrate of dimensions 80 × 80 × 1.6mm^3. Simulated and experimental results are investigated at different center frequencies and notch frequencies. Antenna performance parameters like S_{11} characteristics, surface current distribution, far-field radiation characteristics, ECC, DG, group delay are discussed. The proposed MIMO antenna achieved an impedance bandwidth (S11 < -10dB) from 2.1GHz - 20GHz with notches from 3.3GHz - 4.1GHz and 8.2GHz - 8.6GHz frequency bands. These achieved notches can filter the interference of WiMAX (3.3GHz - 3.7GHz), and military/radar applications band (8.2GHz - 8.6GHz). Mutual coupling among the elements is also below -25dB.A peak gain of 5.8dB is observed in the operating band and antenna radiation efficiency is greater than 80% except at notches. The proposed MIMO antenna has superior isolation, low ECC (<0.02) and fine diversity properties. The investigated results of the proposed antenna validate that it obtains wider impedance bandwidth with dual notches, directional radiation patterns and stable gain. Hence, proposed 4-element MIMO antenna is recommended as a good aspirant for UWB applications with notches at WiMAX and military/radar applications.

TABLE 1. Antenna parameters comparison.

Author /Reference	Operating Band (GHz)	Ports	Notch Band Frequency (GHz)	Gain (dB)	ECC	Isolation (dB)
J.F.Li [5]	3.0 - 11.0	2	3.3-3.7, 5.15 – 5.85	NA	<0.012	>20
S. M. Khan [11]	2.7 - 12	4	4.8 – 6.2	5.5	<0.025	>17
D. Yadav [13]	3.1-10.6	2	4.7 – 5.4	5.2	<0.03	>20
R.Chandel [15]	2.93-20	2	5.1-5.8, 6.7-7.1	6.5	<0.01	>22
Z. Li [16]	2.9-11.6	2	5.3-5.8, 7.85-8.55	4.2	<0.02	>16
Z. Tang [19]	2.3-13.7	4	3.25 - 3.75,5.08 - 5.90,7.06 - 7.95	3.2	<0.02	>22
W Wu [21]	3.0-16.2	4	5.1- 5.6, 7.3 -9.1	8.4	<0.3	>17.4
M. S. Khan [23]	2.7 - 12	4	5.1 – 5.9	5.5	NA	>17
Proposed	2.1- 20	4	3.3 - 4.1, 8.2 - 8.6	5.8	<0.02	>25

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