

# Quad-port 28/38 GHz MIMO antenna verified with CMA for 5G mm-wave applications

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This paper introduces a novel compact dual band microstrip line-fed Multiple-Input Multiple-Output (MIMO) antenna operating at 5G mm-wave bands i.e. 28 GHz (N257/258) and 38 GHz (N262). The suggested MIMO antenna with dimensions  $20.36 \times 16.54 \times 0.4 \text{ mm}^3$  is built on an FR4 epoxy substrate with a relative permittivity of 4.3 and a dielectric loss tangent of 0.025. The proposed antenna is made up of four radiating elements (patches) with rectangular slots and stubs on the top side of the substrate and full ground on the bottom side. The first operating band is 28 GHz, which ranges from 27.3 to 28.75 GHz and is achieved by placing rectangular slots and stubs on the main patches. The second operating band is 38 GHz, spanning from 37.15 to 39.57 GHz and is obtained by etching a rectangular slot from the main patch. The isolation is improved by placing rectangular stub between the patches and arranging the MIMO antenna elements orthogonally. The performance of the developed antenna is verified by using Characteristic Mode Analysis (CMA). The designed antenna operates at 28 GHz (N257/N258) and 38 GHz (N262) bands, exhibiting stable radiation patterns, acceptable peak gain and radiation efficiency. Moreover, antenna provides very low envelope correlation coefficient, acceptable diversity gain, mean effective gain, total active reflection coefficient and channel capacity loss. The consistent patterns of the developed antenna make it suitable for 5G applications in the mm-wave band.

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**Keywords:** Multiple-Input Multiple-Output (MIMO), isolation, Characteristic Mode Analysis (CMA), 5G mm-wave

## 1. Introduction

The growing popularity of wireless communication networks has created a growing demand for much larger data rates, extremely low latency, and spectrum in wireless applications. Rapid advancements in wireless technologies have made mobile communication a part of daily life, which has led to a shortage of bandwidth and an increase in data traffic. The FCC designated the millimeter-wave spectrum of 25-70 GHz to fifth-generation (5G) technologies in order alleviate spectrum shortages in microwave bands and to meet high data rate and bandwidth needs [1]. Therefore, the development of a 5G antenna having broad performance that allows for all 2G to 5G band frequencies is highly required. A feasible way to meet 5G requirements is through the use of multiple input multiple output (MIMO) technology. MIMO technology offers the ability to improve data transfer and spectral utilization without the need for extra bandwidth or transmit power [2-3]. MIMO decreases bit errors, increases data transfer rates, eliminates fading, and improves channel capacity. Multiple antennas are used in a MIMO system at both communication endpoints. Mutual coupling, however, exists in MIMO systems because of the near spacing between antennas. As such, there is a challenge in increasing isolation or decreasing mutual coupling amongst nearby antennas [4-5].

In MIMO antenna systems, a significant amount of research has previously been done to enhance isolation and reduce mutual coupling. Many strategies have been

explored to improve isolation for 2-element MIMO antenna systems. These strategies include the following: using rectangle ground slots [6], flipped antenna structures that have substantial separation [7], by means of T-shaped and thin slits on the ground layer [8], using DGS with a T-shaped stub on the ground [9], and arranging antenna elements orthogonally [10]. Moreover, a number of techniques have been developed for enhancing isolation in 4-element MIMO configurations. These techniques include the following: incorporating a low-pass filter into the antenna design [11], installing a dual-function curved slot on the ground plane [12], creating a new wrapped patch electromagnetic band gap (EBG) cell [13], repeating conventional split-ring slots twice on a partial ground [14], combining semi-circular and circular formed gaps, and integrating a cross-shape ground altered with a long-lasting circular-shaped defect [15], defective ground with a rectangular, circular, and zigzag-shaped slotted arrangement [16], loading a basic geometric parasitic element among the MIMO antennas [17], using a partial ground plane and orthogonal patches [18], strategically placing parasitic element [19], fusion of Koch and Sierpinski methods [20], and reduction of substrate material area [21]. The earlier mentioned antennas offer good isolation, although they usually feature intricate, large-scale designs. Therefore, for mm-wave communication, a simple, miniature MIMO architecture with improved isolation is imperative.

A quadruple port MIMO antenna operating in the dual-band is reported in this study. The four patches that make up the intended antenna have full ground on the bottom surface of the substrate and rectangular slots and stubs on the top surface. By positioning the MIMO antenna elements orthogonally and inserting a rectangular stub among the patches, the isolation is enhanced. Characteristic Angle and Modal Significance are two of the CMA characteristics that are used to verify the created antenna. The following subsections provide comprehensive explanations of the desired MIMO design, including the antenna design, results discussion, and conclusions.

## 2. MIMO Antenna Design and Analysis

The intended 4-element MIMO antenna for 28 and 38 GHz bands is depicted in Fig. 1 having dimensions  $20.36 \times$

$16.54 \times 0.4 \text{ mm}^3$  and is made on a FR4 epoxy substrate with a relative permittivity of 4.3 and a dielectric loss tangent of 0.025. CST Studio Suite was used for simulation, size optimization, and the recommended antenna design. A 50-ohm microstrip line, measuring  $1.9 \times 0.96 \text{ mm}^2$ , feeds the MIMO antenna. The suggested antenna consists of four radiating elements (patches) with rectangular slots and stubs on the top side of the substrate and a full ground on the bottom side. Each patch is located at a spacing of 0.46 mm from the substrate boundary. Four rectangular patches with slots and stubs at the proper places make up the recommended MIMO design, along with a common ground. In order to attain the desired impedance matching at the designated bands of 28/38GHz, every patch with dimensions  $8.26 \times 4.47 \text{ mm}^2$  has four rectangular patches positioned vertically, each having size of  $1.37 \times 0.5 \text{ mm}^2$ .

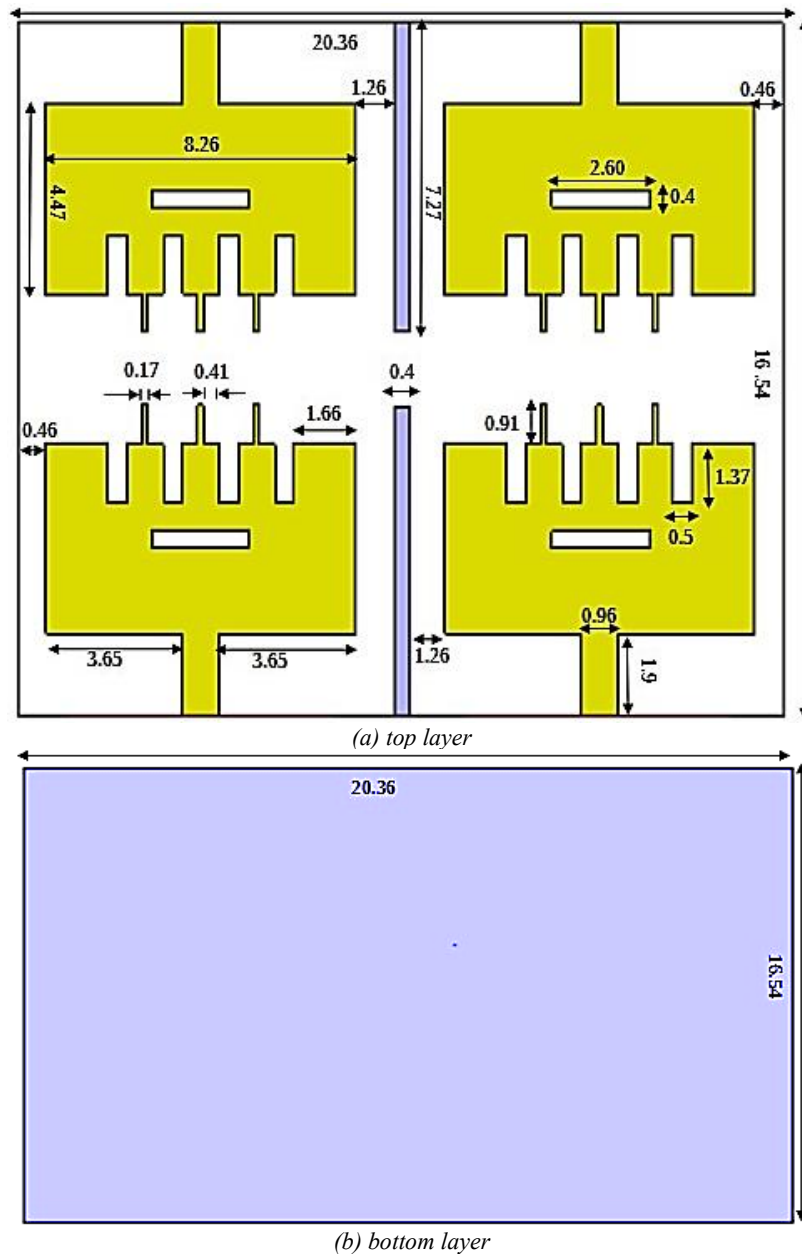


Fig. 1. The proposed 4-element mm-wave antenna (colour online)

Additionally, there are three stubs positioned vertically, each measuring  $0.17 \times 0.91 \text{ mm}^2$ , and a rectangular slot oriented horizontally, having size of  $2.6 \times 0.4 \text{ mm}^2$ . Fig. 1(b) illustrates a complete ground plane with dimensions  $20.36 \times 16.54 \text{ mm}^2$  that represents the substrate's bottom layer.

As shown in Fig. 2 (a), the first operating band is created at 28 GHz by the vertical cuts and stubs, spanning from 27.3 to 28.75 GHz, and another working band is generated at 38 GHz by the horizontal cut, spanning from 37.15 to 39.57 GHz, with good return loss values. Fig. 2(a)

shows that the antenna has appropriate impedance matching with  $S_{ii}$  ( $i=1$  to 4)  $< -10$  dB for the intended functioning bands 28 GHz and 38 GHz. As illustrated in Fig. 2 (b), the isolation  $S_{ij}$  (where  $i,j=1$  to 4) is enhanced by inserting the  $7.27 \times 0.4 \text{ mm}^2$  sized tiny rectangle stub among the MIMO structure's radiating elements. The stub is placed at a distance of 1.26 mm from the edges of the patch. The antenna clearly delivers better isolation of more than 30 dB over the operational bands of 28 and 38GHz due to the use of stub between the patches.

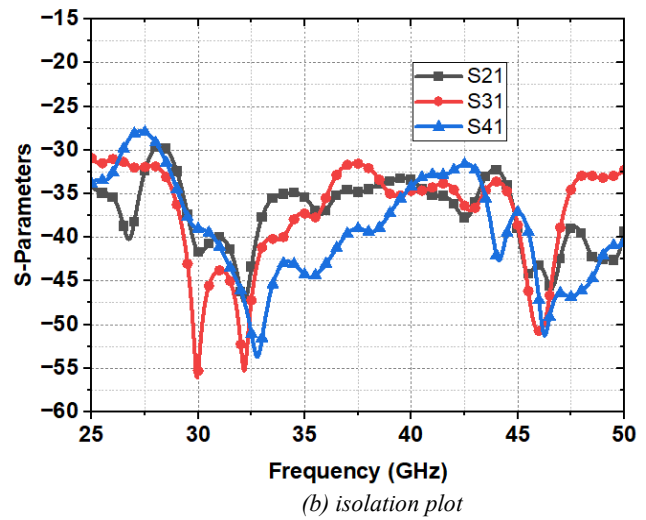
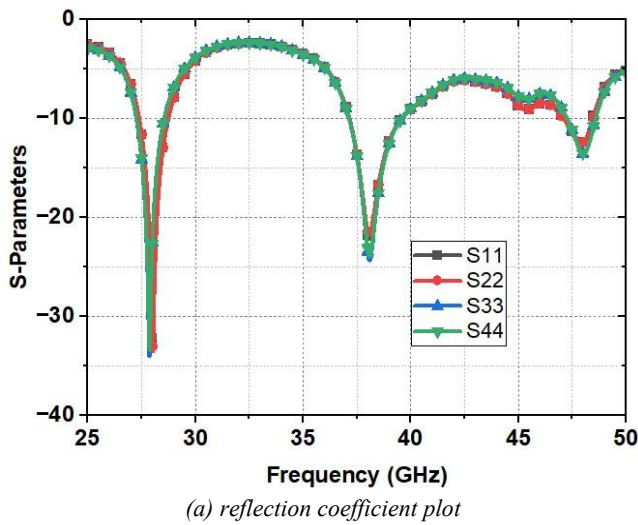


Fig. 2. Proposed mm-wave antenna's (a) impedance and (b) isolation plots (colour online)

The evolution of the proposed single element antenna is presented in Fig. 3 (a) through 3 (f) and its reflection coefficient features are given in Fig. 3(g). Initially, a rectangular element with dimensions  $8.26 \times 4.47 \text{ mm}^2$  is considered as a basic patch element as depicted in Fig. 3(a) and it operates at 30.1 GHz as shown in Fig. 3(g). Next, a stub is added to the basic patch as given in Fig. 3(b) and it radiates at 29 GHz and 49 GHz which are not desired bands of interest. Two slots are cut besides the stub of basic patch element to shift the lower and higher resonances as presented in Fig. 3(c) and it functions at 24GHz, 28.5GHz, 43.5GHz and 48 GHz. From Fig. 3(d), a couple of stubs incorporated to previous design and it resonates at 35.3 GHz and 48.5 GHz. Later, two more slots are etched from the element as shown in Fig. 3(e) but its reflection coefficient values are very less at 28.5 GHz, 33 GHz and 35GHz. Finally, the desired bands of 28 GHz and 38 GHz are

obtained by adding horizontal rectangular cut on the patch of Figure 3(f) to form the proposed single element antenna as shown in Fig. 3(g).

The stages of development of the proposed 4-port MIMO structure and its S-parameter based reflection coefficient characteristics are displayed in Fig. 4(a) through (d). The single element antenna, as shown in Fig. 4(a), is formed by inserting multiple slots and stubs on the basic rectangular antenna in order to attain resonances at the necessary frequencies of 28 GHz and 38 GHz. As shown in Fig. 4(d), the slots and stubs generate the resonances at the desired bands with  $S_{11}$  of -25 dB by selecting the appropriate sizes. Fig. 4(b) depicts the 2-element MIMO configuration with stub, which is created by positioning two antenna components side by side (element spacing of 2.92 mm) and inserting a rectangular stub among the patches.

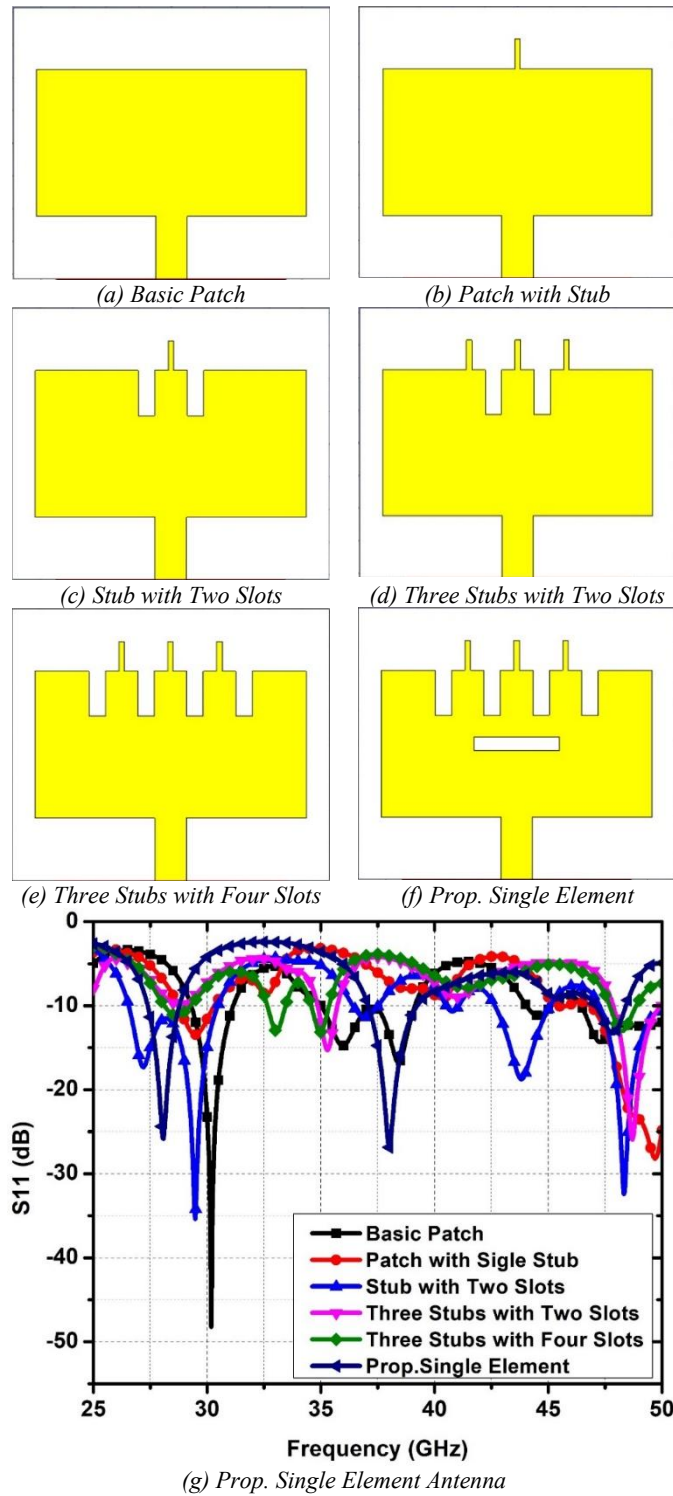


Fig. 3. The evolution of proposed single element antenna (colour online)

The stub between the patches improves the isolation between the antenna ports. Fig. 4(d) demonstrates that the 2-element MIMO arrangement provides  $S_{11}$  of -28 dB at 28 GHz and -27 dB at 38 GHz, as well as isolation of well over 33 dB across the two operating bands. Finally, the presented 4-port MIMO design is formed by adding two more elements to the 2-element antenna as shown in Fig. 4(c).

Without the need for a complicated decoupling structure, antenna diversity could be enabled by using stubs between patches and patch arrangements to further reduce mutual coupling between various antenna elements. Fig. 4(d) shows that the 4-port MIMO structure has  $S_{11}$  of -33 dB at 28 GHz and -22.5 dB at 38 GHz, along with isolation of more than 30 dB throughout the two working bands.

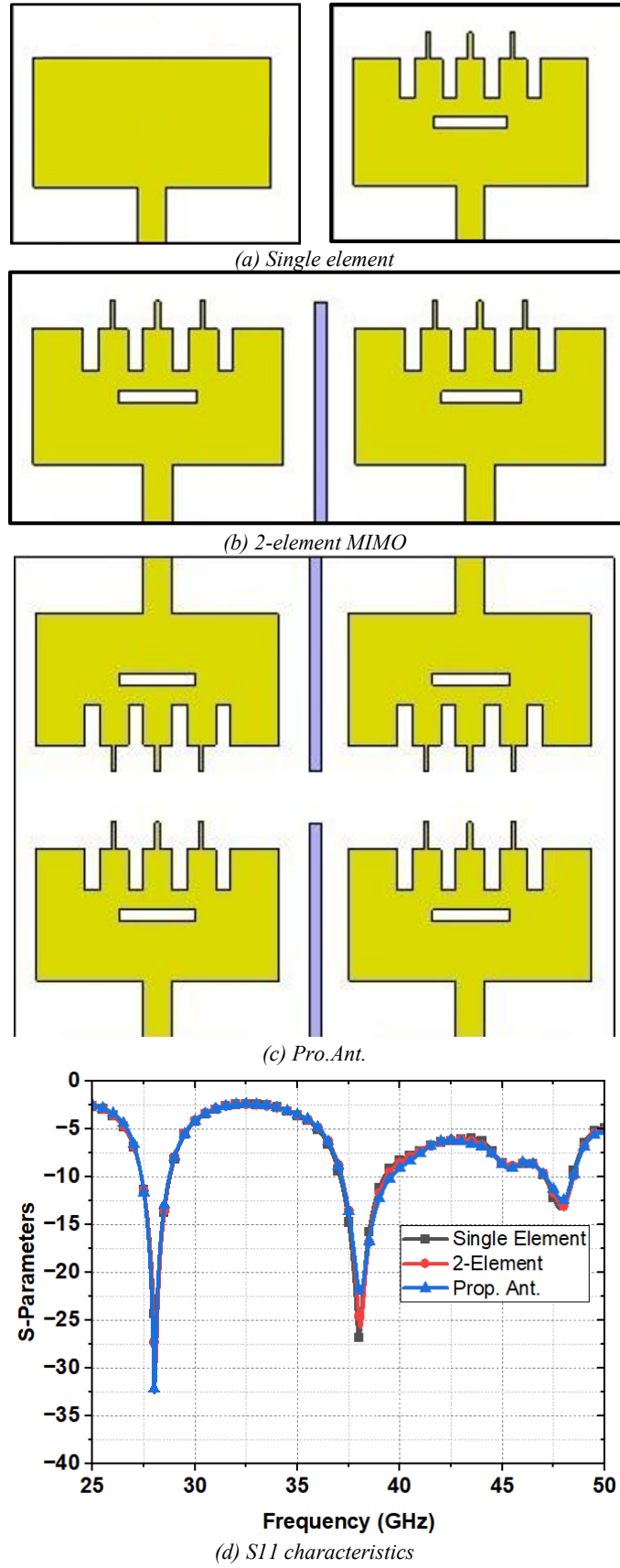


Fig. 4. The suggested MIMO antenna phases of evolution (colour online)

By varying the feed widths  $W_f$ , patch slot lengths  $P_s$ , and stub lengths individually while holding all other

variables constant, the efficiency of the suggested antenna is further evaluated in terms of reflection coefficient ( $S_{11}$ ),

as illustrated in Figs. 5(a) through 5(c) and Tables 1 through Table 3. Fig. 5 and Tables 1-3 show that the requisite bands are accomplished at 28 GHz from 27.3-28.7 GHz, which includes the N257 band, and 38 GHz from 37.1-39.5 GHz,

which caters to the N262 band, with high  $S_{11}$  for  $W_f=0.96$  mm,  $P_s=2.6$  mm, and stub length=0.91 mm, and so has been used in this study.

Table 1. Working spectrum,  $S_{11}$  and resonant frequencies for various feed widths  $W_f$

| Feed width $W_f$ (mm) | Working spectrum (GHz) |            | $S_{11}$ (dB) |       | Center Freq. (GHz) |       |
|-----------------------|------------------------|------------|---------------|-------|--------------------|-------|
| 0.7                   | 27.17-28.4             | 37-39.3    | -20.5         | -20.7 | 27.7               | 38.27 |
| 0.96 (Prop.)          | 27.3-28.7              | 37.1-39.5  | -33.0         | -22.5 | 28                 | 38    |
| 1.2                   | 27.6-28.9              | 37.2-39.27 | -25.3         | -20.7 | 28.3               | 38.04 |
| 1.8                   | 28.1-29.2              | 37.4-40.3  | -19.3         | -30   | 28.7               | 38.2  |

Table 2. Working spectrum,  $S_{11}$  and resonant frequencies for various patch slot lengths  $P_s$

| Patch slot length (mm) | Working spectrum (GHz) |           | $S_{11}$ (dB) |       | Center Freq. (GHz) |      |
|------------------------|------------------------|-----------|---------------|-------|--------------------|------|
| 2.0                    | 28.0-29.1              | 46-48.1   | -23.2         | -25.1 | 28.6               | 47.2 |
| 2.6 (Prop.)            | 27.3-28.7              | 37.1-39.5 | -33.0         | -22.5 | 28                 | 38   |
| 3.0                    | 27.1-28.2              | 36.4-39.3 | -12.5         | -23   | 27.5               | 37.7 |

Table 3. Working spectrum,  $S_{11}$  and resonant frequencies for various stub lengths

| Patch slot length (mm) | Working spectrum (GHz) |           | $S_{11}$ (dB) |       | Center Freq. (GHz) |      |
|------------------------|------------------------|-----------|---------------|-------|--------------------|------|
| 0.91 (Prop.)           | 27.3-28.7              | 37.1-39.5 | -33.0         | -22.5 | 28                 | 38   |
| 1.0                    | 26.8-28.5              | 37.6-38.5 | -33.0         | -23   | 27.5               | 37.8 |
| 1.25                   | 25.5-26.5              | 38.5-42.5 | -21.5         | -18   | 26.5               | 41.5 |
| 1.5                    | 24.5-25.2              | 37.0-41.5 | -15           | -13   | 24.5               | 38   |

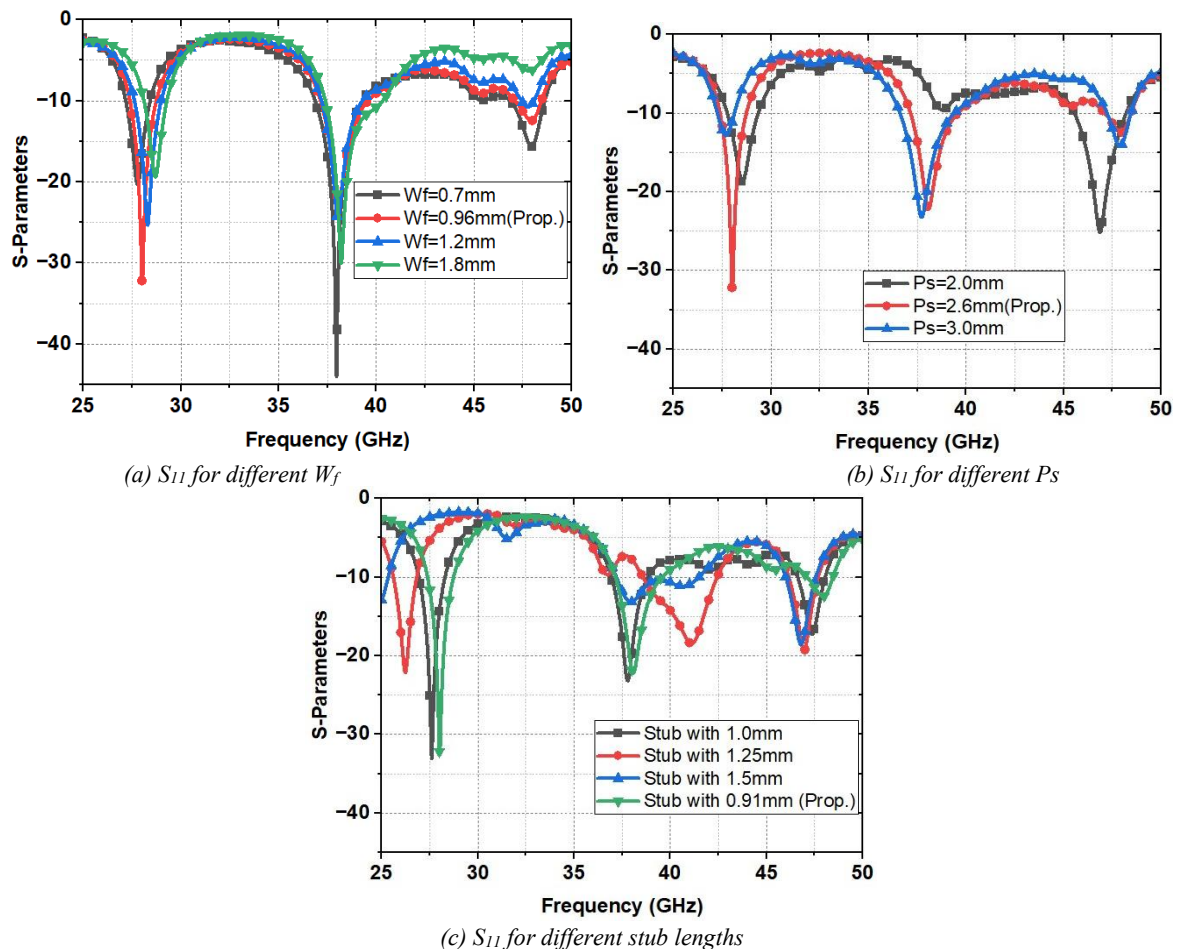


Fig. 5. Parameter evaluation of the designed MIMO antenna (colour online)

One of the most important visual features for MIMO antenna is the surface current distribution characteristic. Fig. 6 illustrates how the stub on the MIMO antenna improves isolation. It is evident that while port-1 is excited,

the stub efficiently prevents surface currents from entering port-2, and vice versa at 28 and 38 GHz. Thus, the effect of stub among the elements improves the MIMO antenna's isolation characteristics.

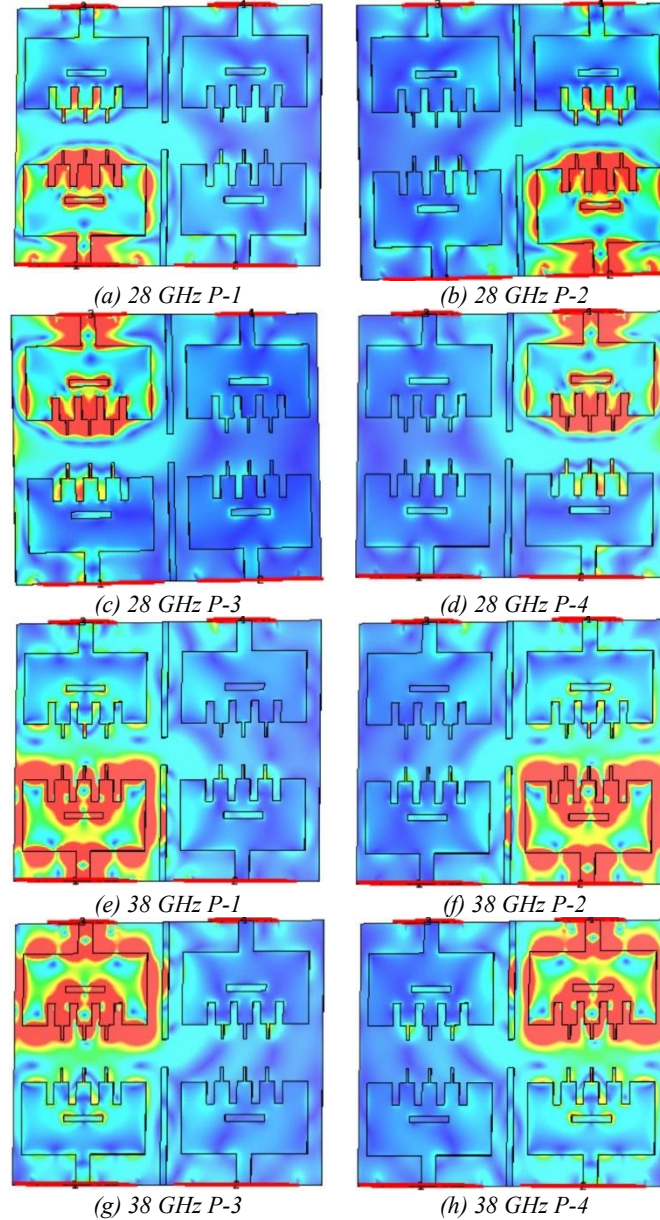


Fig. 6. The surface current distribution (colour online)

### 3. Characteristic Mode Analysis

Characteristic Mode Analysis (CMA) is the most recent technique that was first established by Garbacz [22] and then revised by Harrington [23]. The properties of the conducting body in terms of modal fields and modal currents have been determined using CMA. Through an analysis of the radiation behaviour and modal current distribution of each characteristic mode, CMA efficiently optimizes the conductive body's size and shape. Current modes that occur on a conducting body's surface and are

orthogonal to one another are known as characteristic modes. This study employs CMA to evaluate the MIMO antenna design.

The characteristic modes or characteristic currents can be determined via the eigen functions of the following specific eigenvalue equation:

$$X(J_n) = \lambda_n R(J_n) \quad (1)$$

where  $\lambda_n$  denotes eigen values,  $J_n$  represents eigen functions or eigen currents, and  $R$  and  $X$  are the real and

imaginary parts of the impedance  $Z$ . The  $\lambda_n$  values are from  $(-\infty$  to  $+\infty)$ . Values that correspond to  $\lambda_n = 0$  are considered resonant frequencies, while other values indicate the energy stored in magnetic or electrical fields. Another important metric obtained from eigenvalues is the modal significance ( $MS_n$ ). The Modal Significance (MS) is another significant metric in analyzing the antenna's radiation mechanism, and it is related to eigen values. The MS is described by the following equation as:

$$MS_n = \left| \frac{1}{1+j\lambda_n} \right| \quad (2)$$

MS has a highest value of 1 (practical value is 0.7 to 1) at its resonance frequency (when  $\lambda_n=0$ ) and subsequently decreases as eigenvalues grow. Higher MS values indicate that the modes are contributing more radiation to the antenna's overall output. Fig. 7 (a) and 7 (c) plots the  $MS_n$  as a function of frequency for single and dual bands. Modes 5 for single band (at 28 GHz) and Mode 6 and Mode 7 for dual bands (at 28 GHz and 38 GHz) are identified as resonant modes since their  $MS_n$  values are 1 and remaining modes are insignificant modes.

Alternatively, the eigenvalues can be expressed in terms of the characteristic angle  $\beta_n$  which can be computed using the formula [24]:

$$\beta_n = 180^\circ - \tan^{-1}(\lambda_n) \quad (3)$$

The characteristic angle (CA) represents the phase difference among the characteristic current  $J_n$  and the related characteristic field  $E_n$ . Also, the behavior of the mode close to the resonance can be inferred from CA. A mode is considered resonant when its  $\beta_n = 180^\circ$  degrees. The modes are capacitive or inductive, when the CA values range from 90 to 180 degrees or 180 to 270 degrees, respectively. Modes with CA near to  $90^\circ$  and  $270^\circ$  are inefficient radiators that primarily contribute to energy storage, whereas modes with CA close to  $180^\circ$  serve as efficient radiators. From Figure 7 (b) and 7(d), the  $\beta_n$  values of Modes 5 for single band (at 28 GHz) and Mode 6 and Mode 7 for dual bands (at 28 GHz and 38 GHz) are close to  $180^\circ$  and hence recognized as resonant modes. The CMA results match well with the results that have already been suggested.

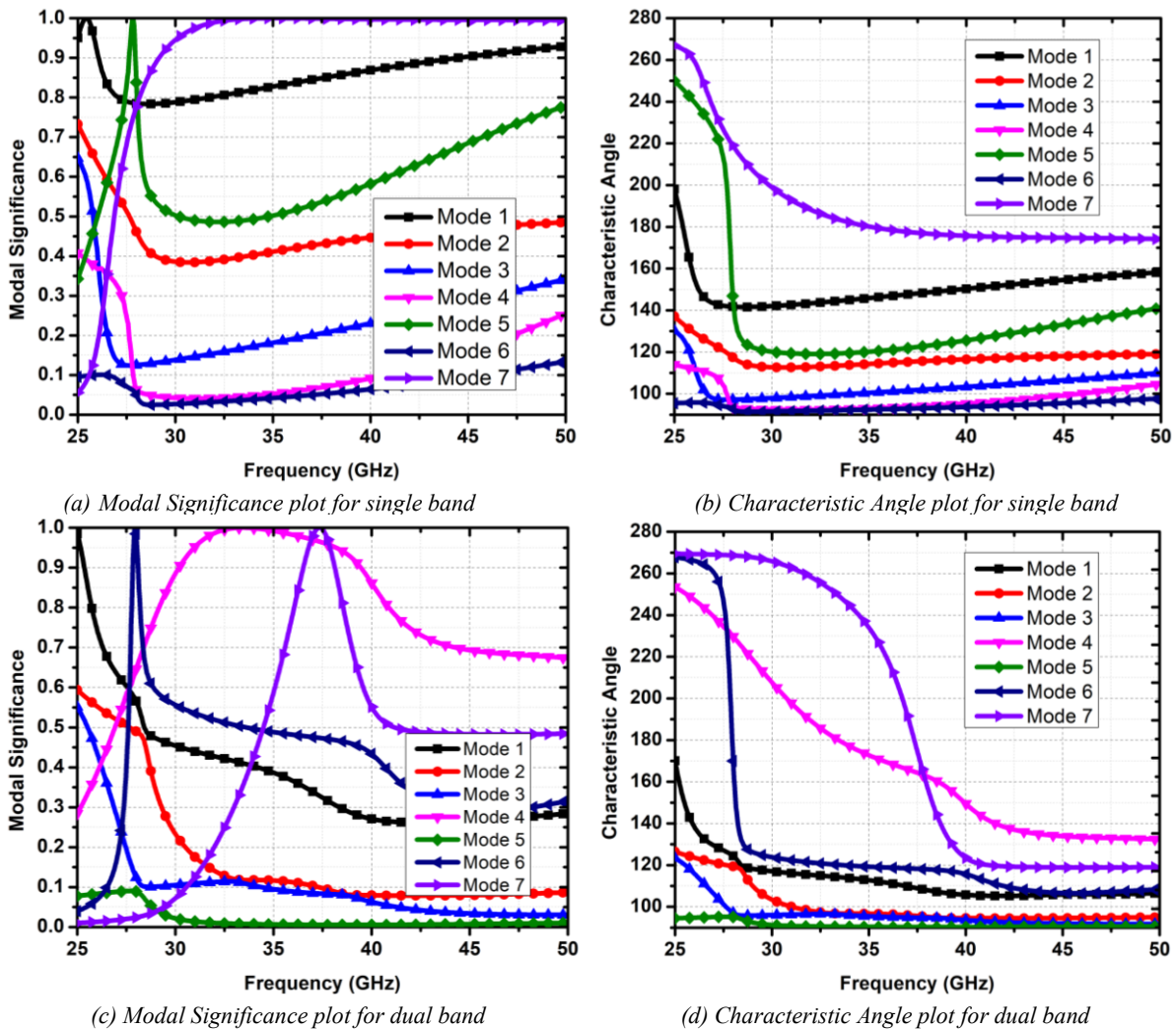
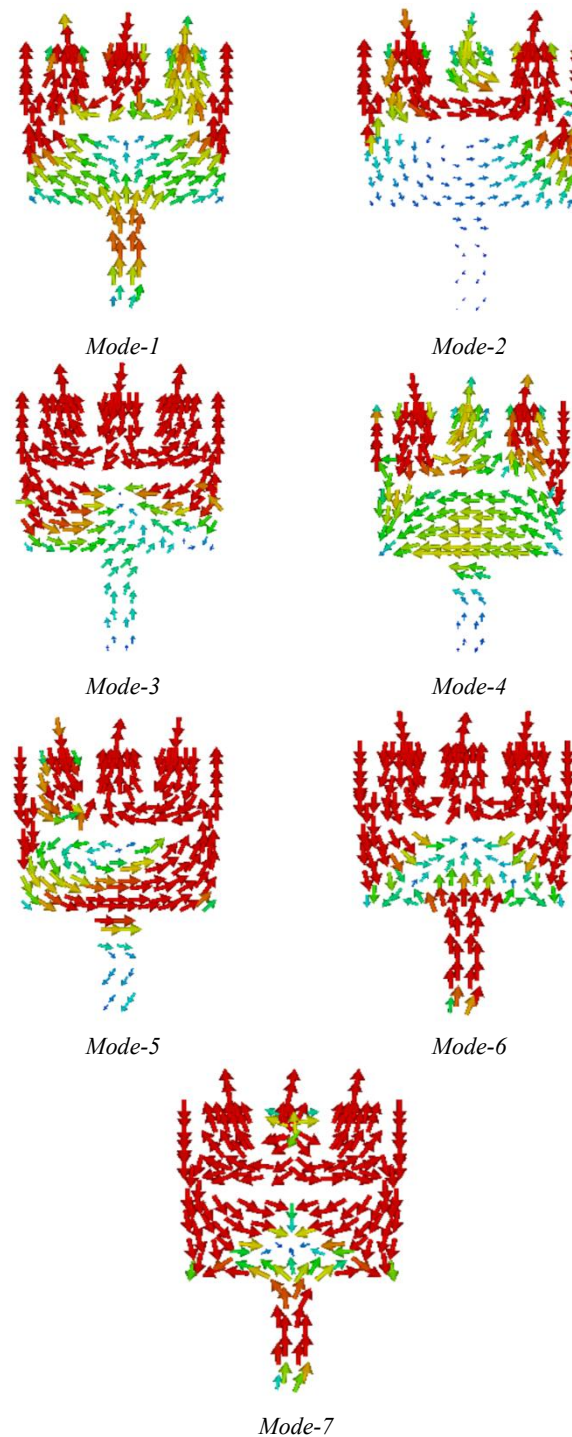


Fig. 7. Characteristic Mode Analysis of the suggested antenna (colour online)

The surface current distributions of the first seven modes at 28 GHz are shown in Fig. 8(a). Modes 1 and 2 shows, partial or weak current distributions, with asymmetric patterns and poor coupling to the feed. These modes are considered as non-resonant modes. From modes 3-5 and 7, the surface currents are either concentrated near the edges or weakly distributed, no strong resonant behaviour is observed at 28 GHz. At mode 6, the current distribution is highly symmetric with strong, opposing vectors on the patch surface and it also shows excellent coupling to the feed, confirming it as the dominant radiating mode at 28 GHz.

From modes 1-5, there are no proper alignment with the feed path and do not exhibit resonant characteristics at this frequency and are considered non-resonant as observed from Figure 8(b). Mode 6 shows lack of strong and symmetric surface current across the patch and there is a concentration of current away from the radiating edges, so mode 6 is considered as non-resonant mode. Mode 7 exhibits symmetrically distributed and strong current flow, especially concentrated in the radiating edges of the patch and along the feed path are typical characteristics of resonance, suggesting that Mode 7 contributes dominantly to radiation at 38 GHz.



(a) Modal Current Distributions at 28 GHz

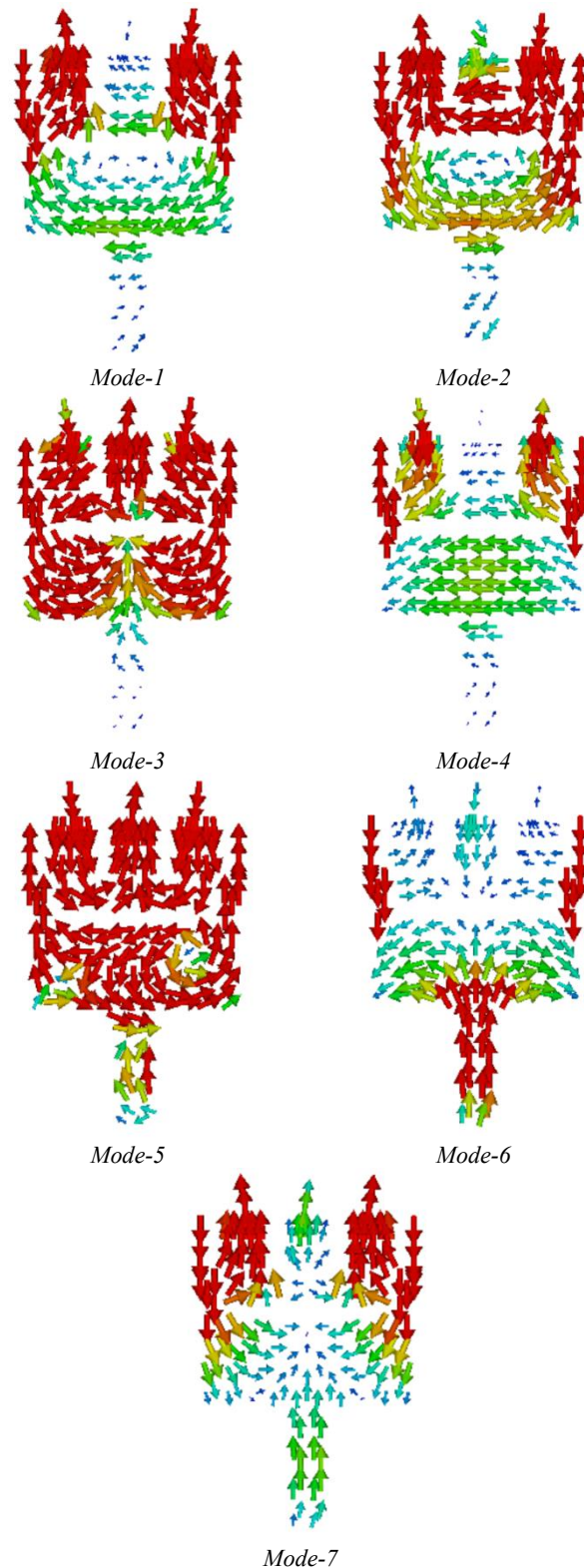


Fig. 8. Modal Current Distributions at resonant frequencies (colour online)

#### 4. Results and Discussions

In order to confirm the previously described simulation results, the proposed 4-element MIMO antenna was

created; its front and back perspectives, as well as scattering properties, are shown in Fig. 9(a) and Fig. 9(b). The antenna parameters are examined using an Agilent N5247A vector network analyser as given in Fig. 9(c). Fig. 9(d) and Fig.

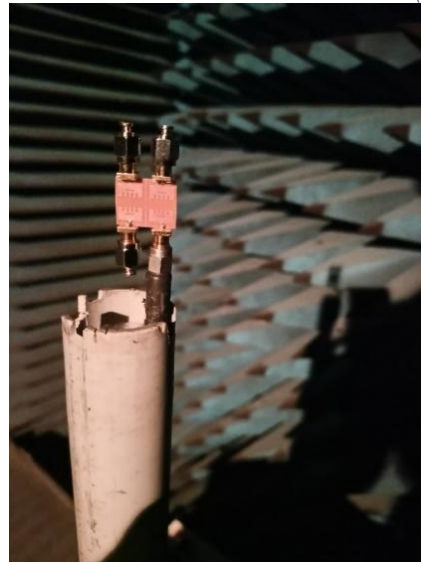
9(e) display the measured and verified reflection coefficient and isolation plots. It is discovered that the tested resonance frequency is 28 GHz and 40 GHz, while the simulated resonant frequency is 28 GHz and 38 GHz. Fig. 9(d) shows a minor deviation between the measured and simulated operating bands. The differences between the experimental and simulated results may be due to minor defects in the

instruments employed, the SMA soldering technique, the manufacturing process, or the measuring conditions. Furthermore, by employing the faulty substrate approach and orthogonally oriented radiators, the suggested antenna provides more than 20 dB higher isolation across all of its antenna ports over the work spectrum.

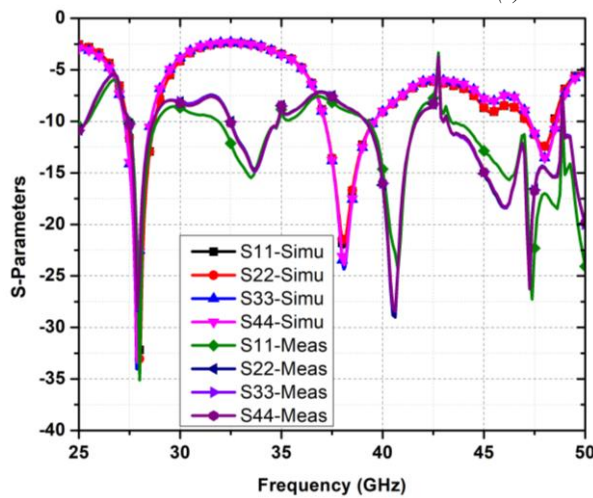


(a) Prototype- top layer

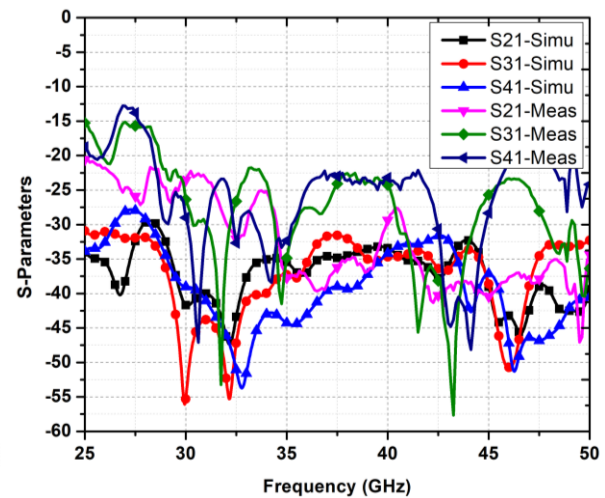
(b) Prototype- bottom layer



(c) Antenna under test



(d) reflection coefficient plot



(e) isolation plot

Fig. 9. Proposed mm-wave antenna's: (a) Prototype- top layer, (b) Prototype- bottom layer, (c) Antenna under test, (d) reflection coefficient plot and (e) isolation plot (colour online)

Radiation performance is one of the most essential qualities of an antenna's which represents the directional properties. The 2-D radiation patterns at 28 GHz and 38 GHz when port 1 is excited and the remaining ports are loaded with 50-ohms are shown in Fig. 10. At 28GHz and 38 GHz, the recommended antenna radiates almost equally in all directions. Fig. 11 depicts the simulated and tested peak gain curves of the proposed 4-Element MIMO antenna. As depicted in the figure, the antenna has maximum gains of 5.45 dBi at 28 GHz and 3 dBi at 38 GHz. At 38 GHz, the dimension of the antenna elements is

smaller relative to wavelength when compared with antenna dimension at 28 GHz. The smaller dimension may lead to reduced gain at 38 GHz when compared to 28 GHz. Additionally, Higher frequencies cause the fringing fields to become more noticeable and a greater amount of electromagnetic energy to be dissipated in the substrate instead being radiated into space, which lowers gain and radiation efficiency. Although, high dielectric constants can result in a reduced antenna size, but they also raise surface waves and losses, limiting gain.

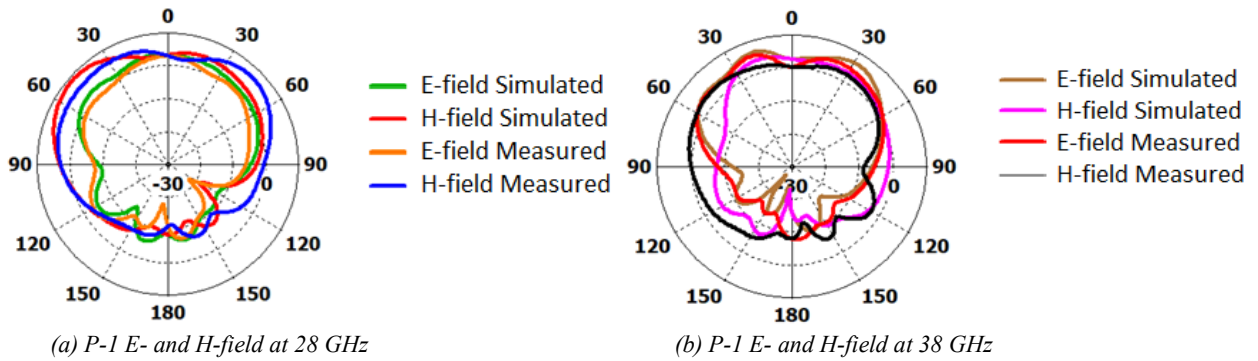


Fig. 10. 2-D Radiation patterns at (a) 28 GHz and (b) 38 GHz (colour online)

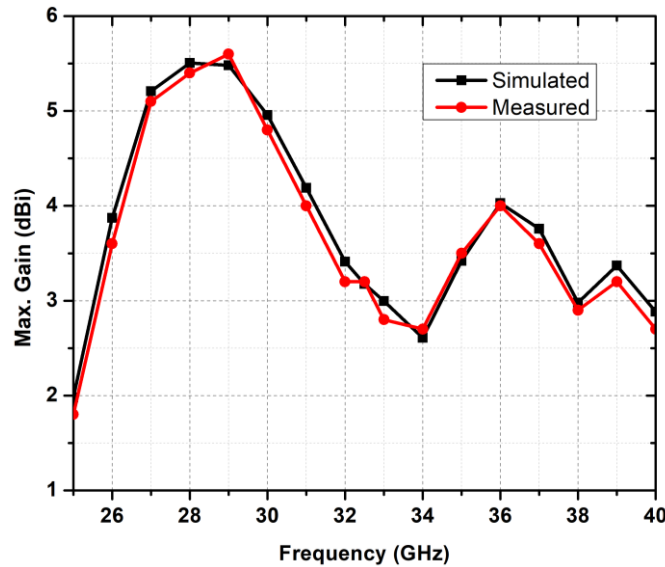


Fig. 11. The maximum gain vs frequency plot (colour online)

To evaluate the MIMO antenna's performance, the following metrics are used: envelope correlation coefficient (ECC), diversity gain (DG), mean effective gain (MEG), total active reflection coefficient (TARC) and channel capacity loss (CCL). These parameters are calculated using the formulas found in [25-27]. The parameter ECC describes the correlation between the channels. In actuality, ECC should be less than 0.5. Equation (4) is used to determine the ECC of an N-element MIMO system utilizing scattering characteristics.

$$ECC_{S-Par.} = \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|^2}{(1 - (|S_{ii}|^2 + |S_{ij}|^2))(1 - (|S_{jj}|^2 + |S_{ij}|^2))} \quad (4)$$

Fig. 12 (a) shows the computed and measured ECC curves for the planned MIMO antenna. It is found that the ECC is attained throughout the band at  $< 0.00003$ , which is considerably lower than the actual ECC criterion of 0.5.

Furthermore, the effectiveness of antenna diversity strategies is measured by the diversity gain. The DG's optimal value is 10dB, which may be calculated using Equation (5) [25-27]. Fig. 12 (b) represents the modelled

and tested DG plots which shows that the proposed antenna creates a 10dB DG across the working frequency.

$$DG = 10\sqrt{1 - |ECC_{S-Par.}|^2} \quad (5)$$

Mean effective gain (MEG), another diversity performance parameter, measures an antenna's capacity to detect electromagnetic radiation in a multi-path situation [28-29] and is computed by employing Equation (6). The calculated and tested MEG curves in Figures 12 (c) show that the proposed MIMO antenna generates a MEG of -3dB.

$$MEG_i = 0.5\eta_{i,rad} = 0.5 \left[ 1 - \sum_{j=1}^M |S_{ij}|^2 \right] \quad (6)$$

MIMO system performance can also be estimated using TARC. Self and mutual impedance fluctuations are considered by TARC [27, 29-30]. Using Equation (7), the TARC for a MIMO system is calculated. As shown in Fig. 12(d), the proposed MIMO design provides both measured and simulated TARC <-10 dB across the entire band.

$$TARC_{S-Par.} = \sqrt{\frac{|(S_{11}+S_{12}e^{j\theta})^2| + |(S_{21}+S_{22}e^{j\theta})^2|}{2}} \quad (7)$$

Designing MIMO antennas also requires evaluating CCL. This parameter is a function of the S-parameters [29-30] and can be found using the formulas in (8-10). Fig. 12(e) displays the results of the CCL simulation and measurements at the necessary frequency ranges. Across all operational frequency bands, the CCL is less than 0.03 bit/s/Hz.

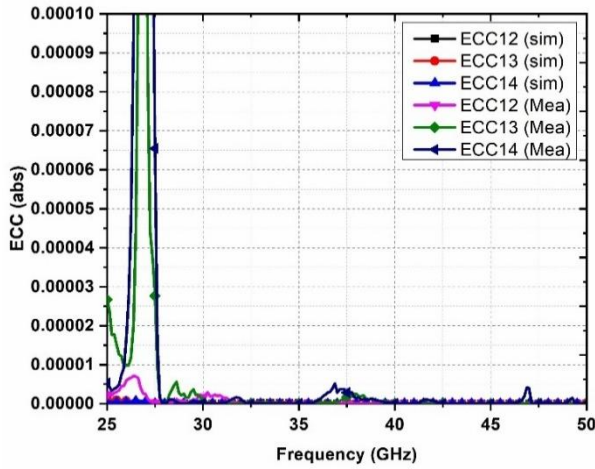
$$C_{Loss} = -\log_2 \det(\alpha^R) \quad (8)$$

where,

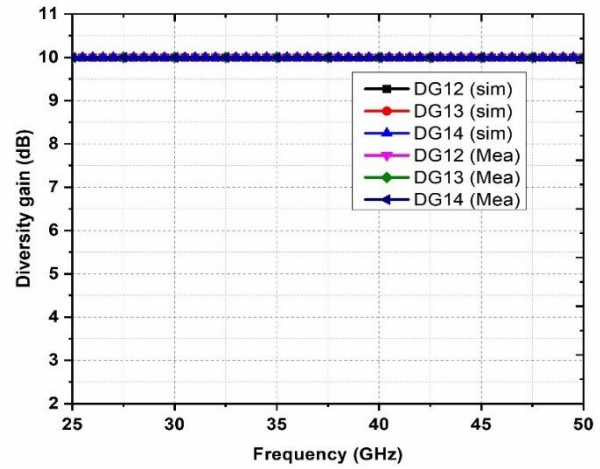
$$\alpha^R = \begin{bmatrix} \alpha_{ii} & \alpha_{ij} \\ \alpha_{ji} & \alpha_{jj} \end{bmatrix}$$

$$\alpha_{ii} = 1 - (|S_{ii}|^2 + |S_{ij}|^2); \quad \alpha_{ij} = -(S_{ii}^* S_{ij} + S_{ji}^* S_{jj}); \quad (9)$$

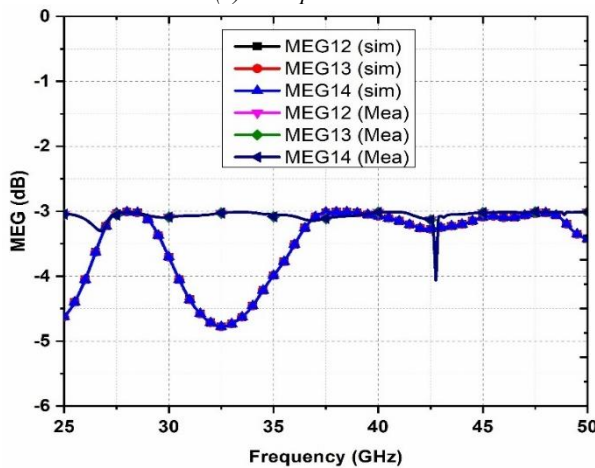
$$\alpha_{ji} = -(S_{jj}^* S_{ji} + S_{ij}^* S_{ii}); \quad \alpha_{ii} = 1 - (|S_{jj}|^2 + |S_{ji}|^2) \quad (10)$$



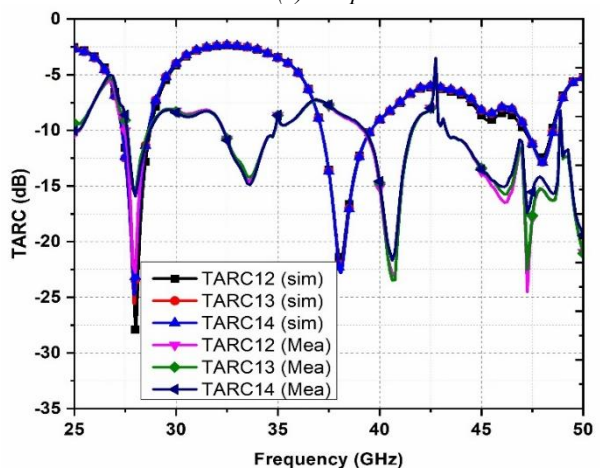
(a) ECC plot



(b) DG plot



(c) MEG plot



(d) TARC plot

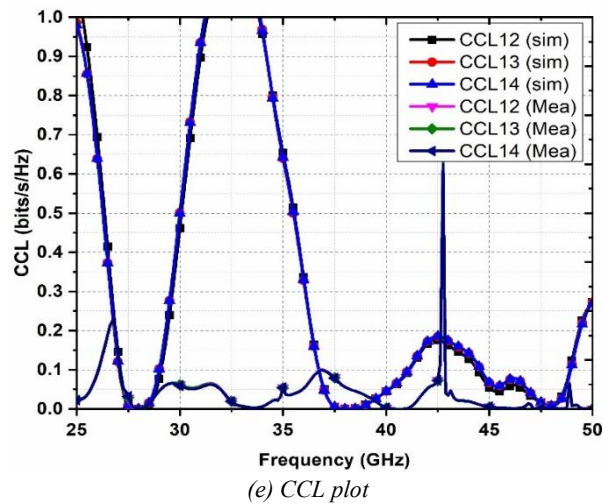


Fig. 12. The MIMO diversity characteristics of an Antenna (colour online)

The effectiveness of the proposed MIMO antenna was compared with models that had already been made published in Table 4. It is evident that the recommended antenna structure outperforms in terms of compact antenna footprint (size), high isolation, acceptable gain and very low

ECC compared to antennas that are currently in the literature. As a result, the recommended antenna design performs better than previous designs and is suitable for both current and future 5G mm-wave communications.

Table 4. Suggested and earlier MIMO antennas' performance evaluations

| Ref.              | Number of ports | Footprint/Size (in sq. m)            | Bandwidth/suitability (GHz)    | Isolation (dB) | Gain (dBi)     | Env. Corr. Coef.   | Complexity | Scalability |
|-------------------|-----------------|--------------------------------------|--------------------------------|----------------|----------------|--------------------|------------|-------------|
| [6]               | 2               | $30 \times 15$                       | 28                             | >28            | 5.42           | <0.005             | moderate   | high        |
| [7]               | 2               | $30 \times 15$                       | 25.5-30, 35-40                 | >29            | >5             | <0.0001            | high       | good        |
| [8]               | 2               | $22 \times 26$                       | 3.1-11.8                       | >20            | >3             | <0.03              | high       | low         |
| [9]               | 2               | $18 \times 21$                       | 2.8-12.2                       | >25            | 2-5            | <0.013             | very high  | limited     |
| [10]              | 2               | $27.65 \times 12$                    | 26-30, 36-41.5                 | >22            | >5.2           | <0.001             | moderate   | high        |
| [11]              | 4               | $19.25 \times 26$                    | 27.8-30, 36.5-39.6             | >25            | >5             | <0.004             | high       | moderate    |
| [12]              | 4               | $104 \times 104$                     | 2.4-5.1, 5.1-5.6, 23-30        | >16            | >5.1           | <0.01              | very high  | moderate    |
| [13]              | 4               | $75 \times 150$                      | 3.3-3.9                        | 18             | 3              | <0.001             | high       | moderate    |
| [14]              | 4               | $50 \times 12$                       | 25.1-37.5                      | >22            | >4.5           | <0.001             | moderate   | good        |
| [15]              | 4               | $43.6 \times 43.6$                   | 27.5-28.35, 37-37.6            | >20            | >3             | 0.002              | high       | moderate    |
| [16]              | 4               | $30 \times 35$                       | 25.5-29.6                      | >17            | >5             | <0.01              | moderate   | good        |
| [17]              | 4               | $28 \times 28$                       | 26.5-31.5, 36-41.7             | >25            | >4             | <0.001             | high       | moderate    |
| [18]              | 4               | $20 \times 20$                       | 27.25-29, 34.5-41              | >24            | >4             | <0.0001            | high       | moderate    |
| <b>Prop. Ant.</b> | <b>4</b>        | <b><math>16.5 \times 20.3</math></b> | <b>27.3-28.75, 37.15-39.57</b> | <b>&gt;30</b>  | <b>&gt;5.5</b> | <b>&lt;0.00003</b> | <b>low</b> | <b>good</b> |

## 5. Conclusions

The new twin band MIMO antenna that operates at the 5G mm-wave bands of 28 GHz and 38 GHz is presented in this work. The suggested antenna consists of four radiating

patches with rectangular slots and stubs on the top side of the substrate and a full ground on the bottom. The first operational band at 28 GHz, which ranges from 27.3 to 28.75 GHz, is obtained by including rectangular slots and stubs into the main radiating elements. The second

operational band at 38 GHz, extending from 37.15 to 39.57 GHz, is created by carving a rectangular slit into the primary radiating element. The isolation is increased by inserting a rectangular stub among the patches and aligning the MIMO antenna elements orthogonally. The constructed antenna has been examined using Characteristic Mode Analysis. The planned antenna functions in the 28 GHz (N257/N258) and 38 GHz (N262) bands, with isolation of >30dB, consistent radiation patterns and adequate peak gain. Furthermore, the antenna has a ECC of <0.00003, diversity gain of 10dB, MEG of -3dB, TARC of <10dB, and CCL of <0.03bits/sec/Hz in whole functional bands. The results demonstrate that the presented antenna suitable for 5G mm-wave band services. There are various difficulties associated with mutual coupling, size, complexity of design, diversity performance (ECC, DG), and obtaining exact control over the phase and amplitude of signals given to every antenna element when a 4-port microstrip antenna is scaled to a higher order MIMO system or customized for beamforming. In particular, it becomes more difficult to increase the number of antenna elements while preserving isolation and attaining the required radiation patterns.

## References

- [1] N. Al-Falahy, O. Y. Alani, *Physical Communication* **32**(2), 120 (2019).
- [2] G. J. Foschini, M. J. Gans, *Wireless Personal Communications* **6**(3), 311 (1998).
- [3] W. A. Awan, A. Zaidi, N. Hussain, S. Khalid, A. Baghdad, *International Conference on Computing, Electronic and Electrical Engineering (ICE Cube)*, 1 (2018).
- [4] S. Soltani, R. D. Murch, *IEEE Transactions on Antennas and Propagation* **63**(3), 1140 (2015).
- [5] B. Yang, Z. Yu, J. Lan, R. Zhang, J. Zhou, W. Hong, *IEEE Transactions on Microwave Theory and Techniques* **66**(7), 3403 (2018).
- [6] N. Hussain, W. A. Awan, W. Ali, S. I. Naqvi, A. Zaidi, T. T. Le, *AEU-International Journal of Electronics and Communications* **132**(3), 153612 (2021).
- [7] W. A. Ali, A. A. Ibrahim, A. E. Ahmed, *Wireless Personal Communications* **129**, 2959 (2023).
- [8] C. R. Jetti, V. R. Nandanavanam, *AEU-International Journal of Electronics and Communications* **83**, 11 (2018).
- [9] C. Jetti, V. Nandanavanam, *Progress in Electromagnetic Research C* **82**, 13 (2018).
- [10] A. R. Sabek, W. A. Ali, A. A. Ibrahim, *Journal of Infrared, Millimeter, and Terahertz Waves* **43**(3-4), 335 (2022).
- [11] D. T.T. Tu, N. T. B. Phuong, P. D. Son, V. Van Yem, *Journal of Communications* **14**(1), 1 (2019).
- [12] M. Ikram, N. Nguyen-Trong, A. Abbosh, *IEEE Transactions on Antennas and Propagation* **67**(8), 5705 (2019).
- [13] N. Ojaroudi Parchin, T. I. Al-Yasir, H. Jahanbakhsh Basherlou, R. A. Abd-Alhameed, J. M. Noras, *IET Microwaves, Antennas and Propagation* **14**(6), 457 (2020).
- [14] S. F. Jilani, A. Alomainy, *IET Microwaves, Antennas and Propagation* **12**(5), 672 (2018).
- [15] B. Aghoutane, S. Das, M. E. Ghzaoui, B. T. P. Madhav, H. El Faylali, *AEU-International Journal of Electronics and Communications* **145**, 154071 (2022).
- [16] M. Khalid, S. Iffat Naqvi, N. Hussain, M. Rahman, S. S. Mirjavadi, M. J. Khan, Y. Amin, *Electronics* **9**(1), 71 (2020).
- [17] M. Hussain, W. A. Awan, E. M. Ali, M. S. Alzaidi, M. Alsharef, D. H. Elkamchouchi, A. Alzahrani, M. Fathy Abo Sree, *Micromachines* **13**(11), 1918 (2022).
- [18] N. Sghaier, A. Belkadi, I. B. Hassine, L. Latrach, A. Gharsallah, *Journal of Infrared, Millimeter, and Terahertz Waves* **44**, 297 (2022).
- [19] M. Sharma, B. R. Perli, L. Matta, T. Addepalli, K. Sharma, F. N. Sibai, *Scientific Reports* **14**(1), 29100 (2024).
- [20] J. Babu Kamili, T. Addepalli, B. R. Perli, B. Kiran Kumar, Y. T. Mohammed, *International Journal of Electronics* **111**(12), 2085 (2024).
- [21] T. Addepalli, *Wireless Networks* **31**(2), 1463 (2025).
- [22] R. Garbacz, R. Turpin, *IEEE Transactions on Antennas and Propagation* **19**(3), 348 (1971).
- [23] R. Harrington, J. Mautz, *IEEE Transactions on Antennas and Propagation* **19**(5), 622 (1971).
- [24] M. Cabedo-Fabres, E. Antonino-Daviu, A. Valero-Nogueira, M. F. Bataller, *IEEE Antennas and Propagation Magazine* **49**(5), 52 (2007).
- [25] K. J. Babu, R. W. Aldhaheri, L. S. Sai, B. R. Perli, T. Addepalli, S. R. Pasumarthi, B. K. Kumar, V. K. R. Devana, *J. Optoelectron. Adv. M.* **24**(7-8), 355 (2022).
- [26] S. Blanch, J. Romeu, I. Corbella, *Electronics Letters* **39**(9), 705 (2003).
- [27] T. Addepalli, V. S. Nagaraju, S. Medasani, J. C. Rao, P. Badugu, C. M. Kumar, R. Uppada, B. K. Kumar, *International Journal of Communication Systems* **37**(16), e5895 (2024).
- [28] A. A. Glazunov, A. F. Molisch, F. Tufvesson, *Antennas and Propagation* **3**(2), 214 (2009).
- [29] T. Addepalli, *Wireless Personal Communications* **132**(3), 2203 (2023).
- [30] T. Addepalli, R. Manda, T. Vidyavathi, K. J. Babu, B. K. Kumar, *International Journal of Communication Systems* **36**(8), e5465 (2023).

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