



Compact elliptic ring 2×2 and 4×4 MIMO-UWB antenna at 60 GHz for 5G mobile communications applications

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Abstract

In this paper, a new design of compact Multi Input and Multi Output (MIMO) elliptic ring antenna applied to 5G-UWB wireless mobile communications is discussed. There are two designs, first design consists of two radiators both are perpendicular in single side. The second design consists of four radiators and they are perpendicular to each other in single side. Those designs are compact with small size of substrate material Roger 4003 mounted over partial ground with dimensions of $30 \times 30 \times 0.203 \text{ mm}^3$ for four antenna radiators and $15 \times 30 \times 0.203 \text{ mm}^3$ for two antenna radiators. The operating frequency of the proposed designs which support MIMO microstrip patch antennas is 60 GHz for Milli-Meter short wave range applied for 5G Ultra-Wide Band (UWB) applications. The simulated results are validated by testing the fabricated antenna model and a good consistency is observed in terms of impedance and radiation characteristics. The diversity performance is also tested and good results are obtained in terms of ECC and DG.

1 Introduction

Nowadays, new generations of mobile communications systems take a wide place in our life. It always needs to be developed; 5G technology is one of important and latest technology nowadays where it supports a huge data and information with extreme quality, high reliability, low latency that with simplicity in design, light weight

ease fabrication and low cost. In order to achieve the previous requirements, a special type of antenna is required which is micro-strip patch antenna and shall be compatible with 5G wireless mobile applications (Alassawi et al. 2021). The spectrum of operating frequencies of new mobile generations technology ranges from 3GHz up to 300GHz for millimetric wave applications (Compact wideband 2022; Choukiker et al. 2014). Specifically, 5G mobile generation needs to work on operation frequencies 28 GHz, 38 GHz and 60 GHz. According to those frequencies will work on a new antenna design that is operating on frequency of 60 GHz. There are many advantages to work on this frequency such that according to U.S Federal Communications Commission (FCC), the unlicensed band spectrum is 57-64 GHz is suitable for industrial Scientific and medical (ISM) applications (Ali and Ibrahim 2022). 5G wireless mobile applications need to work on Ultra-Wide Band (UWB) in order to contain a large amount of information and a high data rate with low latency; bandwidth of 500 MHz, 1 GHz and 2 GHz (Elsheakh and Abdallah 2017, 28 GHz broadband helical inspired end-fire antenna and Its MIMO configuration for 5G pattern diversity applications. 2022). There are many researchers are considering that type of antenna design as in 28 GHz broadband helical inspired end-fire antenna and Its MIMO configuration for 5G pattern diversity applications. 2022; Ali

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et al. 2021; Imran, et al. 2018; Taher et al. 2022), but they want to reach to small and compact size in this model. In addition to that, the main purpose is increasing number of radiator elements in small size which works on a major problem which is mutual coupling and this coupling should be less than -15 dB between radiators. The mutual coupling is occurring due to the electromagnetic field between radiators elements which need to minimize that interference field as much as possible and it can be solved by using metallic isolators to stop that effect (Ali et al. 2021). There are many important parameters are need to be measured in that type of antenna as return loss, mutual coupling, gain, radiation pattern and for MIMO diversity performance, the envelope correlation coefficient (ECC) and the diversity gain (DG) need to be developed and reach to optimum values because they are major parameters of MIMO antennas (Imran, et al. 2018; Ibrahim and Ali 2021a; Kiem et al. 2013).

In this paper will discuss the new design of circular-elliptic antenna ring which aims to have minimum dimensions, light weight, low cost of fabrication and achieve to reach for an excellent result of 2×2 and 4×4 patch antenna MIMO-UWB elliptic antenna. This paper is divided into five sections. First section will illustrate the conducted work on the design of suggested antenna, the antenna is elliptic circular ring antenna. Also, will present all dimensions and material that are being used to get the best results on that new design. Second section will explain MIMO configuration of the design where increase number of radiators (2 elements) on small size of substrate ($15 \times 30 \text{ mm}^2$) and present the effect of orthogonal position of antenna elements for getting optimum results. Third and fourth sections present MIMO antenna where increase number of radiators (4 elements) to able to work on MIMO-UWB and these two parts will show the effect of different positions of 4 orthogonal radiators as central position and side position on the antenna performance. Finally in the fifth section, the proposed antenna model will be fabricated and its results will be compared with the simulated results to confirm the suitability of the antenna for 5G mobile applications.

2 Elliptical-circular antenna design

This section will demonstrate a new antenna design where its radiator consists of two rings (circular and elliptical), which is compatible to work on 5G wireless mobile applications operating frequency at 60 GHz (Ibrahim and Ali 2021b; Mneesy et al. 2020). The dimensions of the proposed antenna is demonstrated in

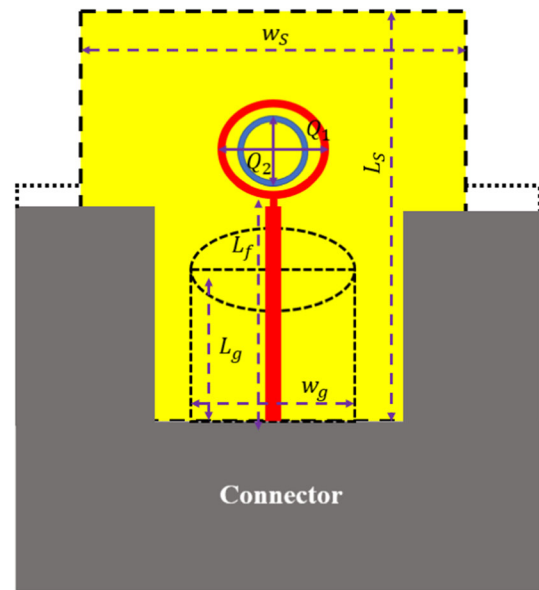


Fig. 1 Single element antenna with design parameters

Fig. 1, where using one antenna radiator to illustrate all antenna demission. The proposed antenna is printed on Roger 4003 substrate with relative permittivity 3.55 and dielectric tangent loss 0.0027 of dimensions $9 \times 10 \times 0.203 \text{ mm}^3$ for one radiator where all results are shown in previous work (Allassawi et al. 2021). The dimensions of design parameters of the proposed antenna re listed in Table 1.

In the upper side of the antenna, it consists of two-parts line feed and two rings (circular and elliptical); and the lower side using partial ground which is two united parts ellipse and rectangle of dimensions $w_g = 3.5 \text{ mm}$ and $L_g = 4 \text{ mm}$ as shown in Fig. 1. The equations used to calculate feed line dimensions (Imran et al. 2018; Taher et al. 2022) are

$$\lambda_g : \text{guid wavelenth } \lambda_g = \frac{\lambda_r}{\sqrt{\epsilon_{eff}}} \quad (1)$$

$$\lambda_r = C/F; \epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{h}{w} \right] \quad (2)$$

$$L_f : \text{Line feeding } L_f = 2.07 \lambda_g \quad (3)$$

two elliptical rings Q_1 (outer ring) and Q_2 (the inner ring) of radius of 1.17 mm with ratio 1.17 and of radius 0.9 mm with ratio 0.95, respectively.

Table 1 Dimensions of single antenna parameters in mm

L_s	w_s	L_g	w_g	L_f	Q_1	Q_2
10	9	4	3.5	5.2	1.17	0.9

where $Q_1 = 0.48\lambda_g, Q_2 = 0.4\lambda_g$ (4)

3 2 × 2 Elliptical-circular perpendicular antenna design antenna elements

This part will discuss the new antenna design 2 × 2 elliptical circular antenna as in Fig. 2. The two antenna radiators are located at 2.7 mm from the edges of substrate and both radiators are in upper side of the antenna. As shown in Fig. 2, the elements of antenna are orthogonal where the dimension of substrate is 15 × 30 × 0.203 mm³ with Roger 4003 material and supported by partial ground 4 × 3.5 mm², and the antenna radiators have the same dimensions as in previous part.

Figure 3 is presenting the return loss S11 and S22 of both antenna’s radiators reaches up to -28 dB with bandwidth of 5 GHz from 58 to 63 GHz which is compatible for UWB applications and support 5G huge data around operating frequency 60 GHz. Figure 4 is presenting the effect of mutual coupling effect between antenna radiators which almost there is no interference between elements where it reaches -44 dB at 60 GHz which is optimum result of antenna radiator elements. When working on MIMO antenna, it needs to calculate the Envelope Correlation Coefficients (ECC) and Diversity Gain (DG) of antenna (Ibrahim and Ali 2021a; Kiem et al. 2013).

where,

$$ECC = \rho_e = |\rho_{ij}| = \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|^2}{(1 - (|S_{ii}|^2 + |S_{jj}|^2))(1 - (|S_{ij}|^2 + |S_{ji}|^2))}$$

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

ECC is the envelope correlation coefficients between antenna elements, the standard relation should be less

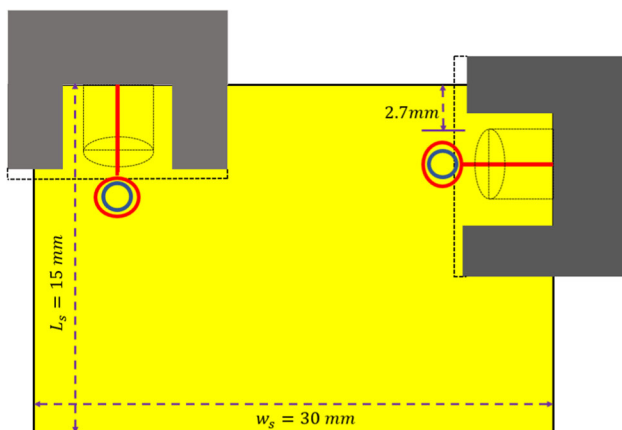


Fig. 2 Two-element MIMO-UWB antenna

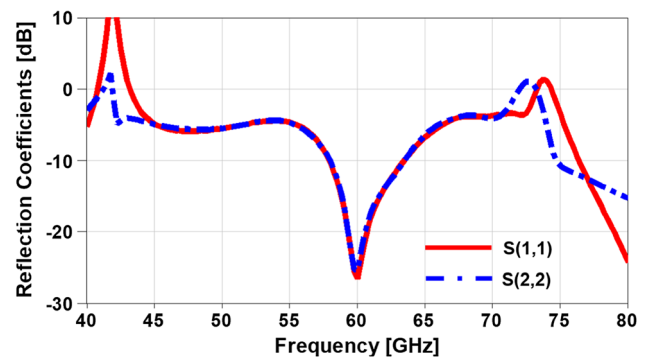


Fig. 3 S(1,1) and S(2,2) of elliptical-circular MIMO antenna

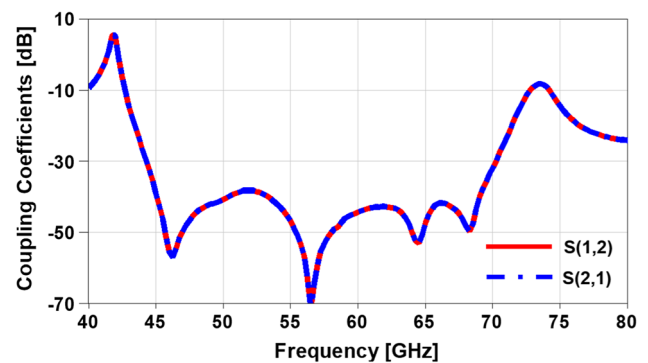


Fig. 4 S(1,2) and S(2,1) two elliptical-circular MIMO-UWB antenna

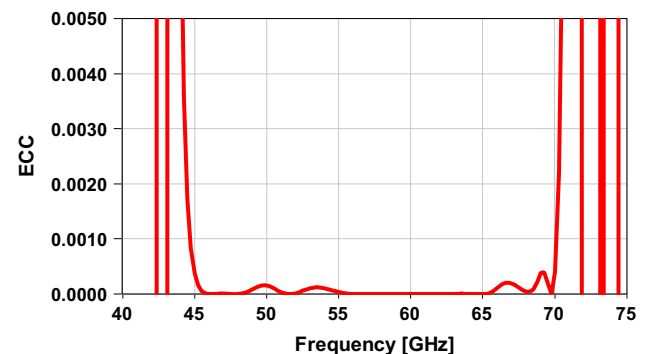


Fig. 5 Envelope correlation coefficient of two orthogonal antenna elements

than 0.5 (Mneesy et al. 2020; Kumar et al. 2020) as in Fig. 5 ECC at 60 GHz is approximately zero that make the antenna design is perfect and suitable for 5G wireless applications. The diversity gain (DG) is a second parameter that can be used to investigate the performance of the MIMO system. The diversity gain is related to ECC as in equation of DG (Compact wideband patch antenna and its MIMO configuration for 28 GHz applications. 2022; Elsheakh and Abdallah 2017) and Fig. 6 illustrating the performance of DG parameter. Third parameter is antenna gain reaches up to 9.6 dB as it appears in Fig. 7 and the radiation pattern of the

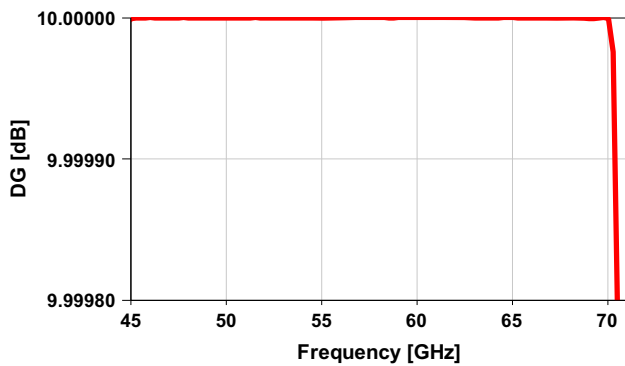


Fig. 6 Diversity gain of two orthogonal antenna elements

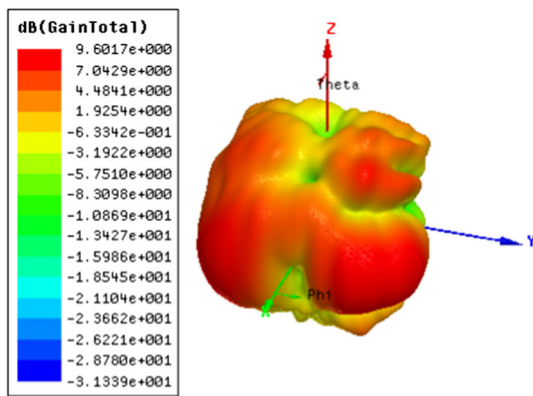


Fig. 7 3-D gain of two-element MIMO antenna

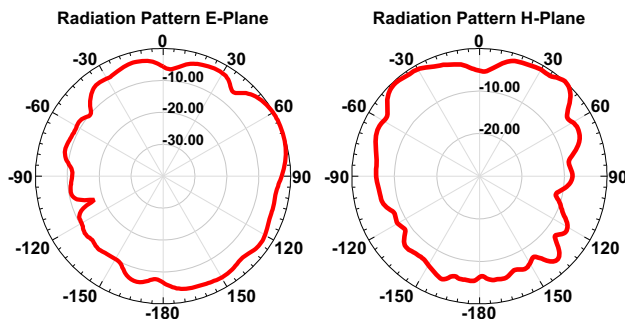


Fig. 8 Radiation pattern of E and H planes of two orthogonal antenna elements

design is omni-direction as showing in Fig. 8 that means a good radiation of the antenna.

4 4 × 4 Elliptical-circular central antenna design antenna elements

This section introduces another model of the design where increasing the numbers of antenna elements to be four antenna elements identically located at the central edges of substrate as shown in Fig. 9; the substrate dimensions are

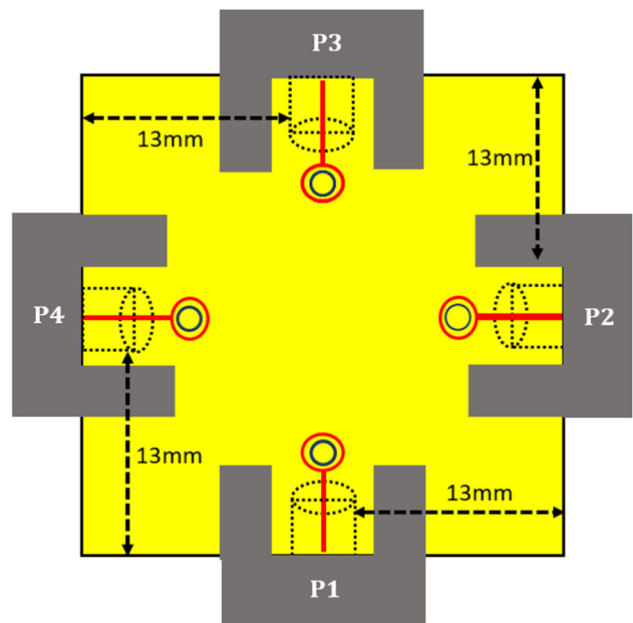


Fig. 9 Four-element elliptical-circular MIMO-UWB antenna

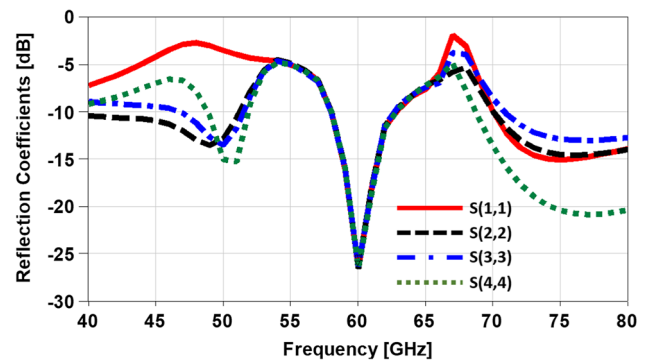


Fig. 10 Return loss of elliptical-circular 4 × 4 MIMO-UWB antenna

30 × 30 × 0.203 mm³ and each element is distant from X–Y axis 13 mm by using Roger 4003 material with the relative permittivity 3.55 and dielectric tangent loss 0.0027.

Figure 10 represents the effect of reflection coefficients (S11, S22, S33, S44) and it can be noticed that all radiators approximately have the same response where all reach to -27 dB at operating frequency 60 GHz. The effect of mutual coupling appears in Fig. 11 where S(1,3) is giving better result where the two elements are distant around 14 mm but S(1,2) and S(1,4) are not giving a good performance since the distance between element (P1) and elements (P2 and P4) is around 7 mm. Thus, the S(1,3) should have better performance because of long distance between elements. Finally, ECC and DG of this model are also reaching to the optimum results at operating frequency 60 GHz where ECC of all radiator elements tend to zero and DG is 10 dB as in Fig. 12. The radiation pattern in

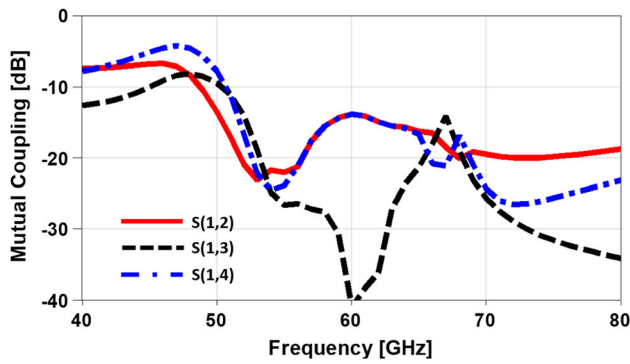
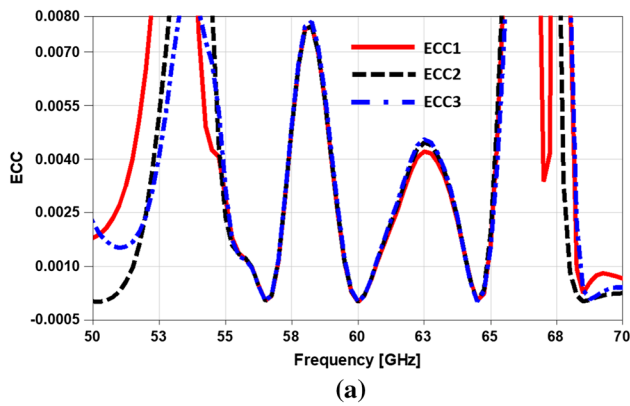
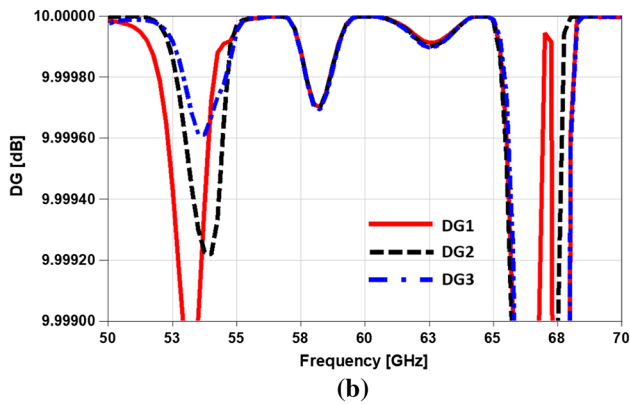


Fig. 11 Mutual coupling of elliptical-circular 4×4 MIMO-UWB antenna



(a)



(b)

Fig. 12 Diversity parameters of 4×4 elliptical-circular MIMO antenna (a) ECC (b) DG

E-plane and H-plane are omni-direction as in Fig. 13. The 3-D gain of this model is 8.65 dB as it is clear in Fig. 14 which is very good and compatible with 5G applications but needs to improve that design to minimize mutual coupling.

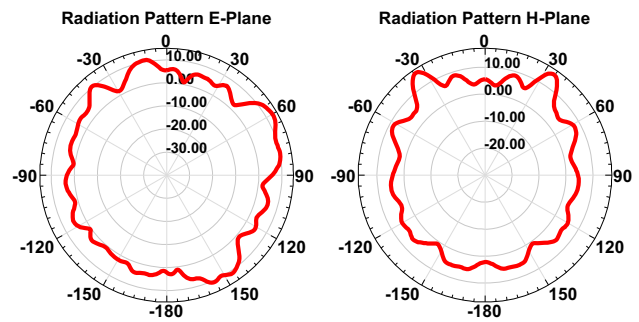


Fig. 13 Radiation pattern of E and H planes of 4×4 elliptical-circular MIMO antenna

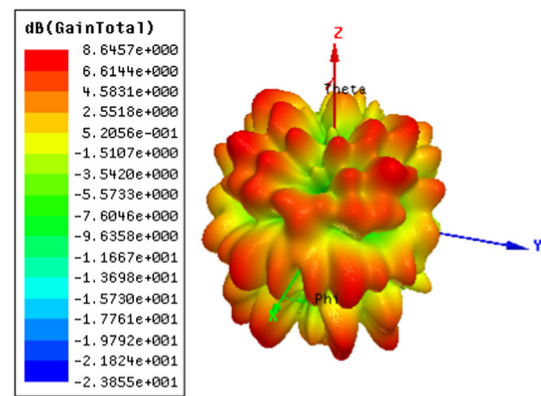


Fig. 14 3-D gain of four-element MIMO antenna

5 4×4 Elliptical-circular orthogonal antenna design antenna elements

In this section, the four elements MIMO antenna configuration will be modified for decreasing the distance between radiators as in Fig. 15. There are two models of antenna designs in that part, first design is without isolators and another model with metallic rectangular isolators. So, the results will be compared between two designs.

For both models, the four antenna radiators are identically located at 2.7 mm from sides of substrate as shown in Fig. 15 where Fig. 15a without isolators and Fig. 15b with isolators and each isolator is away from confront connector by 6 mm. The substrate size is $30 \times 30 \times 0.203 \text{ mm}^3$ using Roger 4003 material with the relative permittivity 3.55 and dielectric tangent loss 0.0027. Figure 16 shows the performance of S-parameters where Fig. 16a is showing the performance of (S11, S22, S33 and S44) in model without isolators where it reaches up to -30 dB at 60 GHz. Another model when adding rectangular isolators, the S-Parameters (S11, S22, S33 and S44) have approximately the same response without isolation as shown in Fig. 16b and it is worth

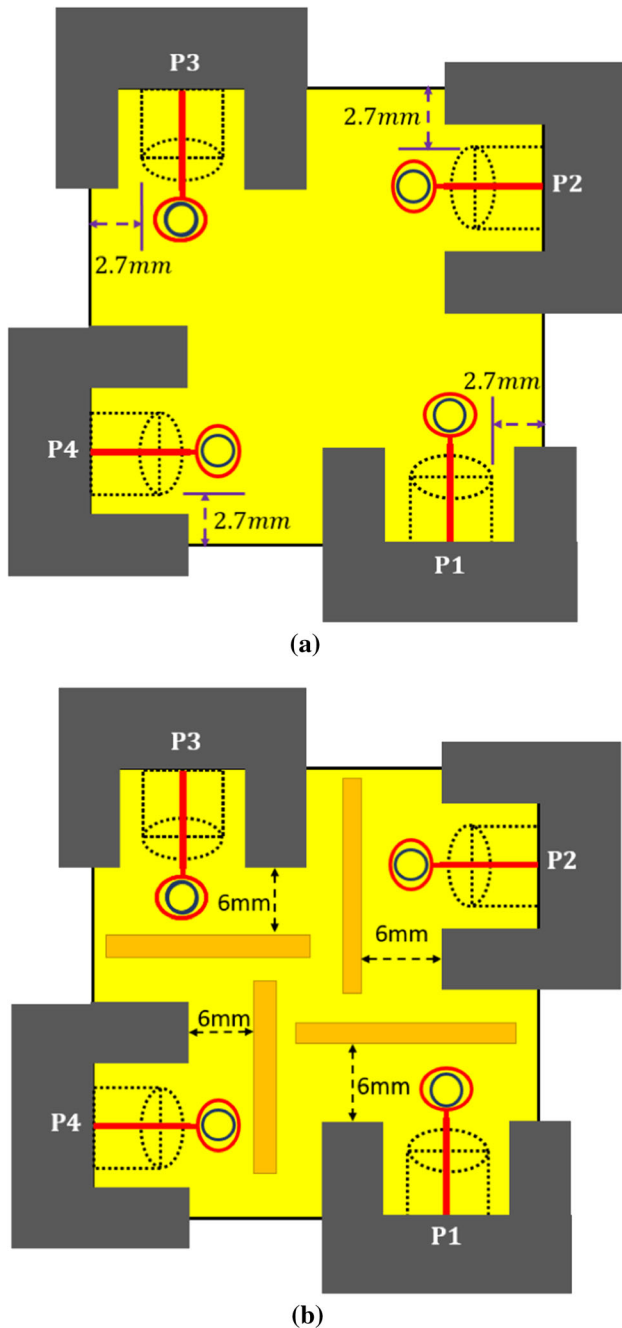


Fig. 15 Elliptical-circular orthogonal 4×4 MIMO antenna (a) without isolation (b) with isolation

noting that the return losses are reaching up to -25 dB and the bandwidth is 5 GHz for both models.

As it clear in Fig. 17 the mutual coupling is improved where all patch antenna radiators are gathering in -28 dB at 60 GHz in model with isolators as in Fig. 17b. Figure 17a is the design without isolators so the mutual coupling effects appearing in $S(1,2)$ and $S(1,4)$ is better where it reaches up to -38 dB that because of the two patch antenna elements are orthogonal, while $S(1,3)$ is reaching

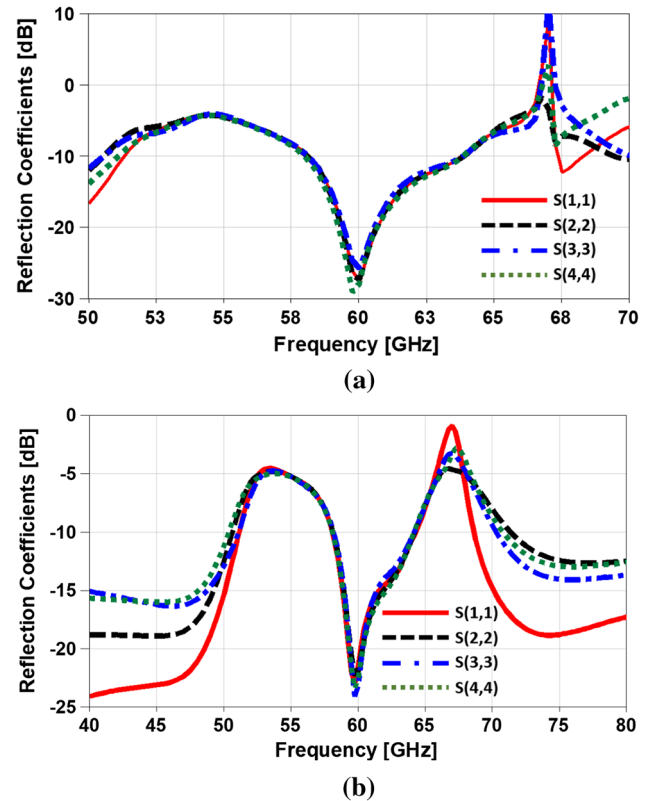


Fig. 16 Return loss of four-radiator MIMO antenna (a) without isolation (b) with isolation

up to -15 dB that because two elements are 180 phase shifts. As a result, we were forced to put isolators between elements to reach an optimum result of mutual coupling.

The effect of ECC is appearing in Fig. 18 of both models ((a) and (b)) where it is reaching approximately zero which is the requested target. DG is giving optimum results in two models ((a) and (b)) as illustrated in Fig. 19. The radiation pattern (E and H planes) of the two designs ((a) and (b)) as shown in Fig. 20 are omnidirectional which means the perfect radiation in all directions. The total antenna gain is very compatible to 5G wireless mobile applications where the total antenna gain in model without isolators reaches up to 10 dB and 9 dB in second model with isolators as in Fig. 21. Finally, the effect of current distribution of two designs ((a) and (b)) is uniform as in Fig. 22 where there is no interference between antenna elements when one radiator is excited and the 3 other radiators are terminated with 50Ω loads. A performance comparison between one, two, and four elements antenna is investigated in Table 2 and it is clear that the performance of 4 elements antenna is quite efficient for UWB MIMO 5G applications.

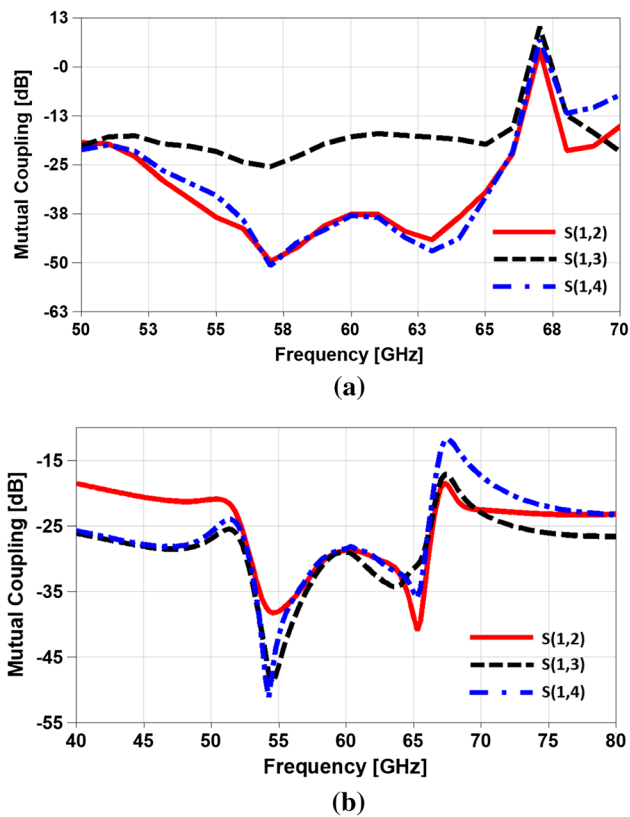


Fig. 17 Mutual coupling of four MIMO antenna elements (a) without isolation (b) with isolation

6 Experimental 4 × 4 elliptical-circular orthogonal antenna design antenna elements

According to results shows in previous designs of MIMO elliptical-circular antenna in this paper, that the best obtained result as it clear was in the 4th design which consists of four antenna radiators with isolators in upper side and in lower side the partial ground as shown in Fig. 15b. Figure 23 shows the photograph of fabricated antenna model and the antenna is printed on Rogers 4003 substrate with a thickness of 0.203 mm. A vector network analyzer R& S ZVA 67 is being used to measure the proposed antenna performance through four end launcher connectors 1.85 mm. This part will discuss the comparison between experimental and simulated results of 4 × 4 MIMO elliptical-circular antenna.

As it is clear in Fig. 24, the experimental work gives results better than simulated S-parameters where four antenna elements radiators reach up to − 38 dB, which is perfect for that type of MIMO antenna in practical work, but in simulated reach to − 25 dB around the

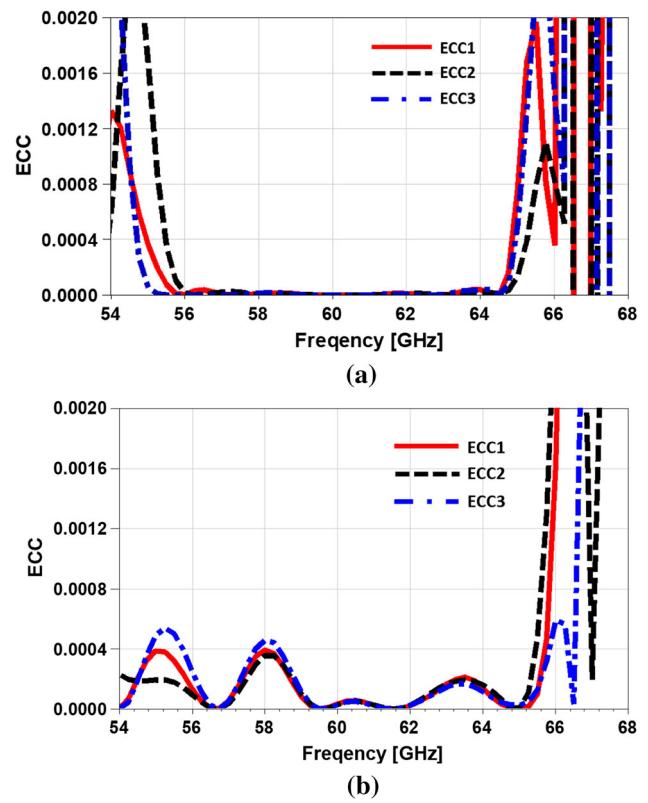


Fig. 18 ECC of MIMO antenna (a) without isolation (b) with isolation

operating frequency 60 GHz, in practical work the bandwidth is minimizing around operating frequency 60 GHz where in simulated gives 5 GHz and in experimental work gives 2 GHz as bandwidth from 59 to 61 GHz. Although of that the effect of that antenna is compatible with 5G mobile application and also can work on UWB range. Figure 25 is illustrating the effect of mutual coupling between antenna elements radiators [S12, S13, S14] as shown in this figure the mutual coupling at operating frequency 60 GHz in experimental work reach to − 30 dB which is better than from the simulated that means there is approximately no interference between antenna radiators. According to those results, the antenna performance is improved and reach to optimum results with lowest latency and minimum cost of fabrication (Jiang et al. 2019; Kamboh et al. 2021; Rengasamy et al. 2021). From all of that, the purpose of that elliptical-circular MIMO antenna design in this paper is superior, compatible and perfect in 5G wireless mobile applications. A performance comparison between the proposed model with the recently published work is demonstrated in Table 3 and it can be noticed

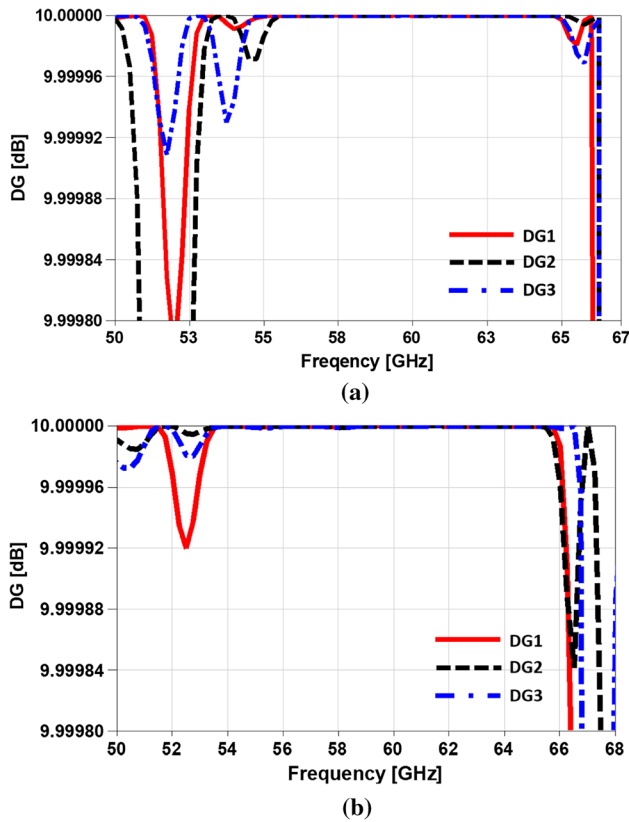


Fig. 19 DG of MIMO antenna (a) without isolation (b) with isolation

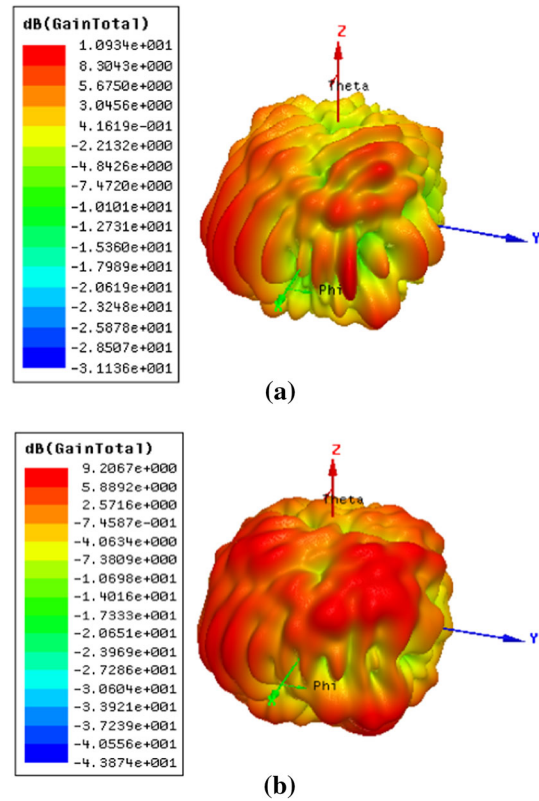


Fig. 21 3-D gain in (dB) of four-element MIMO antenna (a) without isolation (b) with isolation

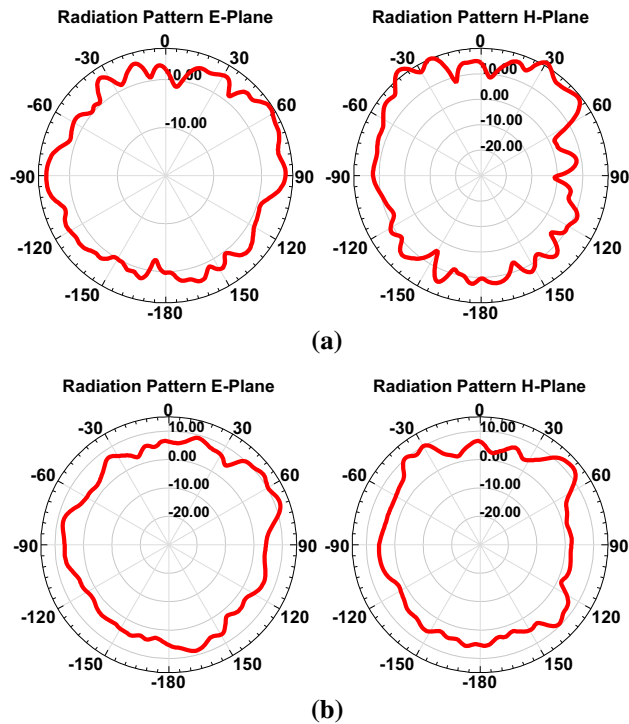


Fig. 20 Radiation pattern of four-element MIMO antenna (a) without isolation (b) with isolation

that the proposed MIMO antenna outperforms other 4×4 MIMO antennas in terms of size, isolation, and gain.

7 Conclusion

Through what was previously mentioned in this paper, more than one model of the same design were presented by increasing the number of elements to obtain the best results required. All models are perfect and suitable to work on 5G wireless mobile applications. The performance of all antenna models using 2×2 and 4×4 antenna radiators elements are excellent where the return loss of models around -26 dB and -28 dB, the total antenna gain reach 9.6 dB, 10.9 dB and 9.2 dB and the radiation pattern is omni-direction in all designs. Furthermore, the diversity performance parameters such as ECC and DG were reached to the perfect values as required for MIMO-UWB antenna but our destination problem is the effect of mutual coupling between antenna radiators, so added rectangular metallic isolators between radiators in both sides of patch antenna, improve the results to reach -28 dB for all radiators at 60 GHz. The proposed design is fabricated and we have obtained excellent results as reflection coefficients

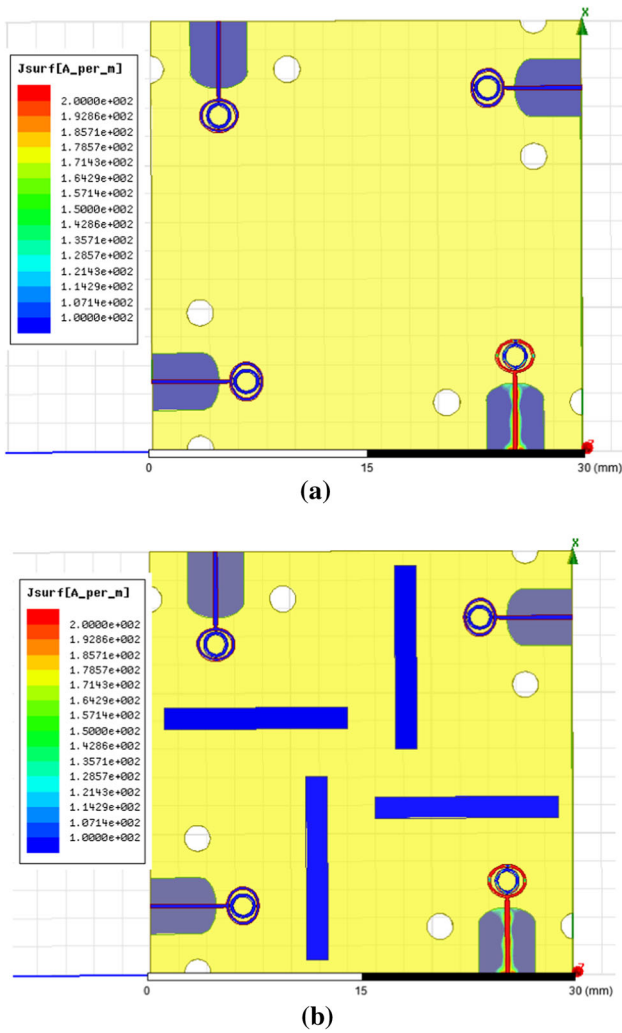


Fig. 22 Current distribution of four-element MIMO antenna (a) without isolation (b) with isolation

reach -37 dB and effect of mutual induction has improved to reach below -28 dB between elements. From this, it is clear that the best results were obtained from the fourth model, and its manufactured version also achieved excellent results supported by achieving its goal, which is combatable for 5G wireless mobile application working at 60 GHz.

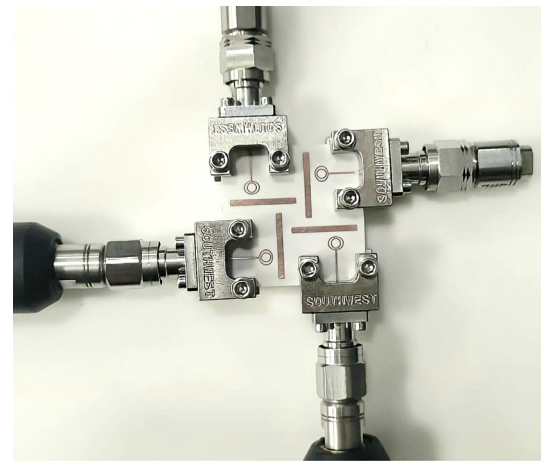


Fig. 23 Photograph of 4×4 elliptical-circular orthogonal MIMO Antenna

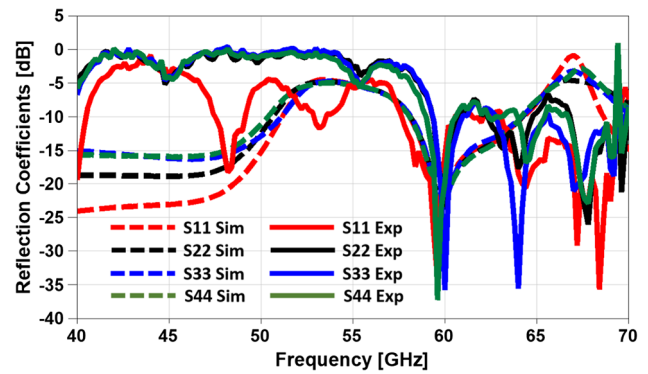


Fig. 24 S-parameters of antenna measured and simulated

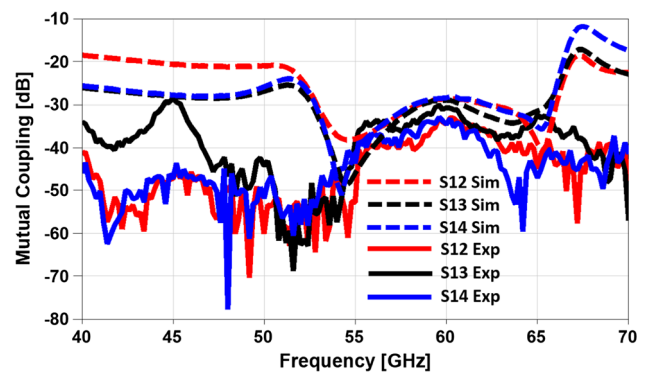


Fig. 25 Mutual coupling of antenna measured and simulated

Table 2 Comparison between one radiator, two radiators and four radiators

	One radiator	Two radiators orthogonal	Four radiators without isolation	Four radiators with isolation
Return loss	-23 dB	-28 dB	-28 dB	-26 dB
Insertion loss	-43 dB	-13 dB	-15 dB	All radiator
		-43 dB	-38 dB	-28 dB
Gain	5 dB	9.6 dB	10.9 dB	9.2 dB

Table 3 Comparison between suggested model with the state of the art

Ref	# of elements	Substrate	Size (mm ²)	Frequency (GHz)	Gain (dB)	Isolation (dB)	Bandwidth (GHz)
Ali and Ibrahim (2022)	4	FR4 Epoxy (4.4)	40 × 40	4–11	6	> 25	3
Taher et al. (2022)	1	FR4 Epoxy (4.4)	10 × 28	3.1–10.7	5	> 22	6
Ibrahim and Ali (2021b)	4	Roger 4003 (3.55)	47 × 47	28	10	> 25	5.5
Sabek et al. (2022)	2	Roger 4003 (3.55)	27.65 × 12	28/38	5.2/5.3	> 30/22	1.9/5.5
Aghoutane et al. (2022)	2	RT5880 (2.33)	31.891 × 37.528	28/38	18/14.5	> 22	2.6/3.3
This work	4	Roger 4003 (3.55)	30 × 30	60	9.2	> 28	5

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