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A compact four port MIMO antenna for millimeterwave applications

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ABSTRACT

A novel compact microstrip MIMO antenna with high isolation and low envelope correction coefficient has been proposed and presented in this paper. The proposed antenna is compact in size with 3.22x4.86 mm^2, operating over the frequency band of 60GHz. The MIMO antennas have been designed andsimulated using electromagnetic design and verification platformIE3DTM. Two ports MIMO antenna with the size of 3.22x1.93 mm^2 resonates at 58.1 GHz covering a band of 57-59.3 GHz, with the bandwidth of 2.3 GHz, gain of 5.2 dBi, and directivity of 8.67 dBi. It also provides aninput reflection coefficient of -18.41 dB with isolation of -19.98 dB. Proposed four port MIMO antenna resonates at 58 GHz covering a range of 56.9 GHz to 59.2 GHz, with a bandwidth of 2.3 GHz, gain of 5.44 dBi, and the directivity of 9.75dBi. It provides goodisolationranging from -19 dB to -30 dB with input reflection coefficient of -18.09 dB. The envelope correlation coefficient (ECC) of the proposed four-port MIMO antenna is below 0.06 in far-field radiation characteristics. The proposed MIMO antenna has been analyzed for its diversity performance in terms of ECC, mean effective gain, and diversity gain.

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1. INTRODUCTION

With the rapid demand for the increase in data rate and channel capacity, the sub-3 GHz frequency spectrum is over utilized and its becoming crowded with lot of applications working in the same band of frequencies. On the other hand, the frequency spectrum of 3-300 GHz range remains underutilized. There is lot of research reported to utilize this band for 5G communications. The 3-300 GHz spectrum band is called as the millimeter-wave bands with wavelengths ranging from 1 to 100 mm [1], [2]. In order to achieve the high data rate and channel capacity for various applications; one can utilize this millimeter wave band of frequencies. Factor such as signal fading, atmospheric absorptions, attenuation is very dominant at mm wave band of frequencies as the wavelength is comparable to the size of the components. All these factors can degrade the systems performance and this need to be resolved. Using one antenna in the system can make these factors more significant [3]. Hence there is a need of multiple inputs multiple output (MIMO) antenna for the millimeter wave communication. MIMO systems can improve the performanceby utilizing multiple antenna elements and have been received a growing amount of interests as it improves the channel capacity [4]. By increasing the number of antenna elements in the system can improve the channel capacity and bandwidth, without radiating any extra power [5]. The most challenging task while designing the MIMO antenna systems is the space occupied by the antenna system. As the number of antenna elements increases the space will be limitation especially for portable devices. It is difficult to place a largenumber of radiating elements within a limited space [6], [7]. Also, when many antennas are placed together in close proximity; isolation between the ports and envelope correlation coefficient (ECC) among the radiating elements becomes quite challenging, which deteriorates the overallperformance of the MIMO system.To study and analyze MIMO structure, certain parameters needs to carefully examine such as isolation, ECC, diversity gain, and mean effective gain (MEG). Mutual coupling is one of theimportant factors because higher mutual coupling means lowerantenna efficiency. The correlation coefficient between the twoantennas is another important parameter since it is associatedwith the loss of spectral efficiency and degradation of performance of a MIMO system [8]. The 60 GHz band of frequency from the Millimeter-wave band has unlicensed spectrum of 7-9 GHz [9] which can be used for short-range wireless communication [10]. Several industrial standards have been developed, such as wireless HD technology, ECMA-387, IEEE 802.15.3c, and IEEE 802.11ad [1], [11]. The use of the 57-64 GHz band is also being promoted as it provides multigigabit data rates for short-range connectivity and wireless local area networks. The 60-GHz antenna must provide high gain, highly directive for short range and with compact size [12].

In this study, a novel compact four port MIMO antenna with overall size of 3.22x4.86 mm^2 operating in the millimeter wave band between 56and 60 GHz has been designed. The antenna configuration consists of four identical rectangular patch antennas with the fed network. The antenna has been designed by means of an electromagnetic design and verification platform IE3D™ [13]. The four portMIMO antenna performance has been analyzed in terms of S-parameters, bandwidth, isolation loss (mutual coupling), radiation patterns; gain, directivity, ECC with diversity gain (DG) and MEG.

In order to achieve a good isolation between the ports, the MIMO antenna elements are located at a distance of $\lambda/2$ to each other; a good isolation between all four ports has been achieved without using any other extra geometry in between the ports. Antenna elements are being placed orthogonal to each other. MIMO antenna has showngood results in terms of its low correlation, high diversity gain and good bandwidthetc. The proposed paper is organized as follows: The antenna design and description is discussed in sections 2. Antenna performance outcomes and MIMO performance metrics and are mentioned in sections 3 and 4, respectively.

2. PROPOSED ANTENNA: DESIGN AND DESCRIPTION

A single patch of microstrip patch antenna has been designed on 0.2 mm height of low cost FR-4 substrate with dielectric constant of εr=4.4 at millimeter wave frequency of 60 GHz. This simple patch antenna has been fed using 50 Ω transmission line. To match the impedance of both the patch antenna and the 50 Ω transmission line, a quarter wave transformer has been designed. The dimensions of the single patch antenna has been calculated using the equations [14] with length L=1.11 mm and width W=1.52 mm. The fed line of 50 Ω has been designed at 60 GHz to energize the patch antenna. The dimensions of the 50 Ω line is length L_{50}=0.68 mm and W_{50}=0.37 mm. The dimensions of the quarter wave transformer islength Lq=0.75 mm andwidth Wq=0.045 mm. The dimension of the single patch with the feed network is 1.11x1.93 mm^2 as shown in Figure 1. The dimensions of the individual components areshown in Table 1.

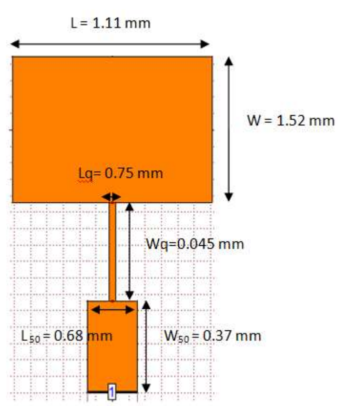

Figure 1. Single port microstrip patch antenna

Table 1. Dimensions of the components

Parameter	Length (mm)	Width (mm)
Rectangular patch antenna	L=1.11	W=1.52
Quarter wave transformer	Lq=0.75	Wq=0.045
50 Ω line	L_{50}=0.68	W_{50}=0.37

To investigate the best MIMO antenna design which provides the best possible results for millimeter wave applications, two designs of MIMO antenna having two and four ports is presented. The two port antenna is designed by adding one more single patch antenna to the existing one. The distance between the two patch antennas is maintained at greater or equal to λ/2, to minimize the effect of mutual coupling. The dimension of the two port antenna is 3.22 x 1.93 mm^2. Two port antenna systems is shown in Figure 2. Four port antenna system has been designed with 4 patch antennas separated with the distance greater or equal to λ/2. The dimension of the four port antenna is 3.22 x 4.86 mm^2. The four port antenna system is shown in Figure 3.

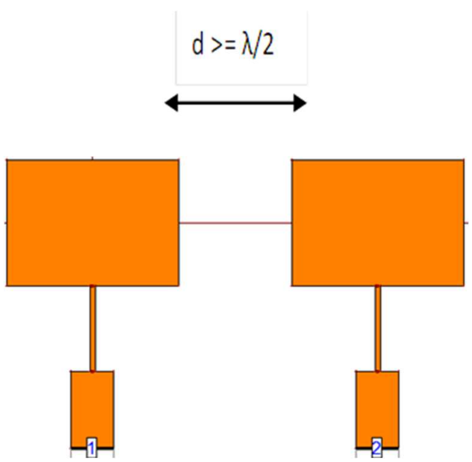

Figure 2. Two port MIMO patch antenna

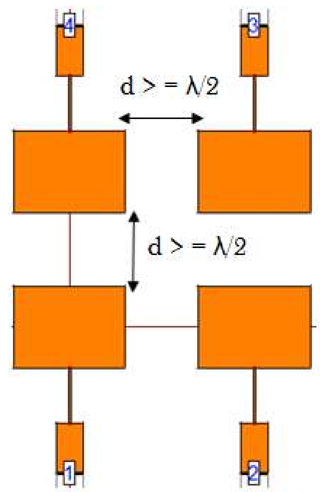

Figure 3. Four ports MIMO patch antenna

3. RESULTS AND DISCUSSION

3.1. Antenna performance parameters

In this section, the microstrip patch antennas, presented in the previous sections, have been analyzed and simulated using IE3D™ simulator based on moments of methods. It is observed that the single port micro strip patch antenna resonates at 58.1 GHz covering a band of frequencies from 57.1-59.2 GHz, providing the bandwidth of 2.4 GHz.

The S11 for the single port antenna wasat -19.84 dBas depicted in the Figure4. The two ports MIMO antenna resonates at 58.1 GHz with the cover range of57-59.3 GHz, having bandwidth of 2.3 GHz. The reflection coefficientwas found to be at -18.41 dB, it also provides a good isolation of -19.98 db as can be noticed Figure 5. The four port MIMO antenna resonates at 58 GHz with input reflection coefficient of -18.09 dB, providing a bandwidth of 2.3 GHz over a frequency range of 56.9-59.2 GHz. S parameter graph can be seen from Figure 6. The more the number of ports there will be a mutual coupling existing between the ports, which degrade the antenna system. The four port MIMO antenna gives a very good isolation between all four ports making the system desirable for millimeter wave communication. It provides a good isolation of -19 dB to -30 dB as can be seen from Figure 7.

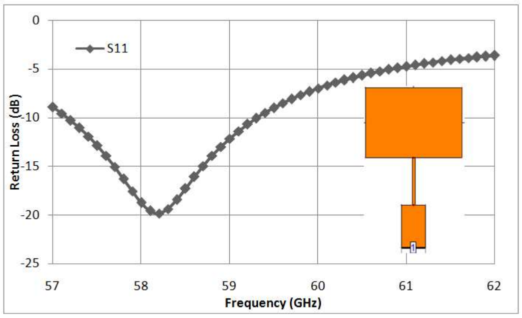

Figure 4. |S11| of the single port microstrip patch antenna

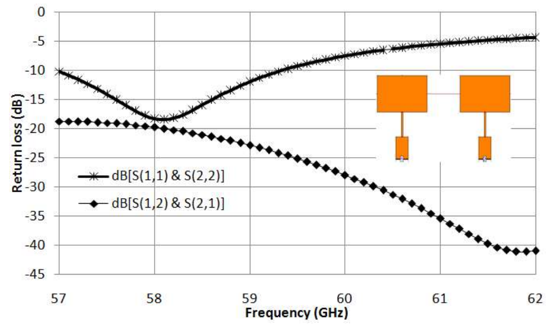

Figure 5. S parameter of the two port microstrip patch antenna

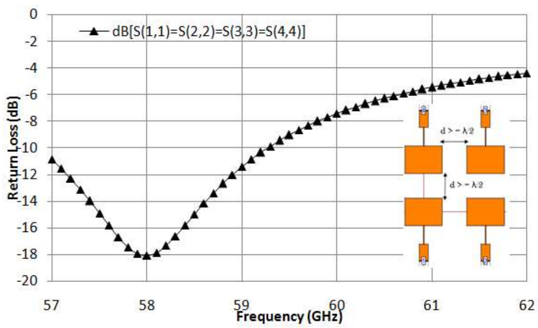

Figure 6. S parameter of the four portmicrostrip patch antenna

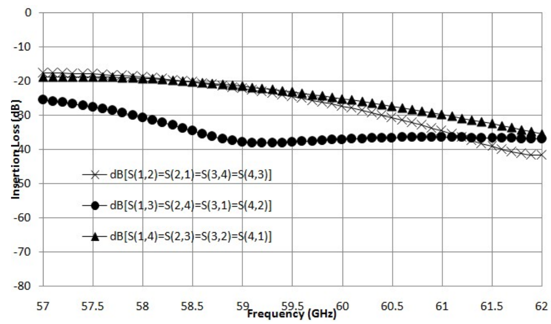

Figure 7. S parameter (isolation loss) of the four port microstrip patch antenna

The peak gain and directivity plot of the single port, two ports and four ports MIMO antenna is presented in Figure 8 to Figure 10. It is observed that, for the single port antenna, the gain is 3.10 dBiwith the directivity of 6.99 dBi. For the two ports MIMO antenna it is noticed that the gain is 5.2 dBi and directivity is 8.67 dBi. For the four port MIMO antenna, it gives a gain of 5.44 dBi and directivity of 9.75 dBi. Voltage standing wave ratio (VSWR) for all the three designs is <2 as can be noticed from Figure 11, Figure 12 and Figure 13. Table 2 shows the comparative results of all three antennas and it is investigated that four ports MIMO antenna performs better in terms of gain and directivity which is the requirement for millimeter wave applications.

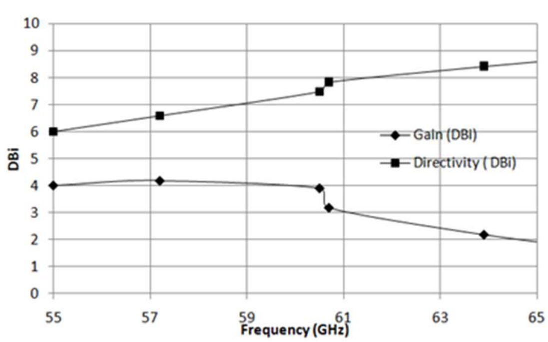

Figure 8. Gain and directivity of the single portmicrostrip patch antenna

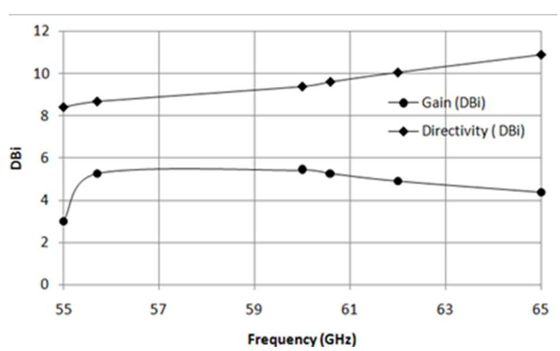

Figure 9. Gain and directivity of the two port microstrip patch antenna

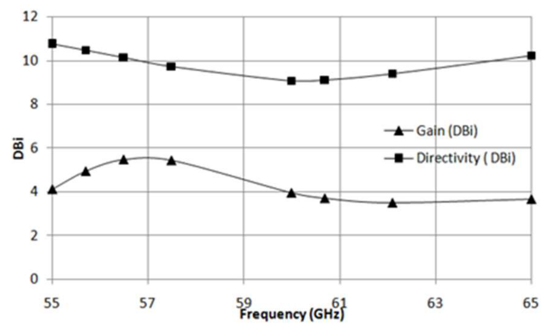

Figure 10. Gain and directivity of the four port microstrip patch antenna

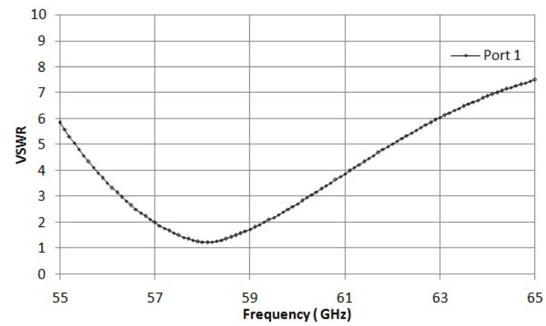

Figure 11. VSWR of thesingle port microstrip patch antenna

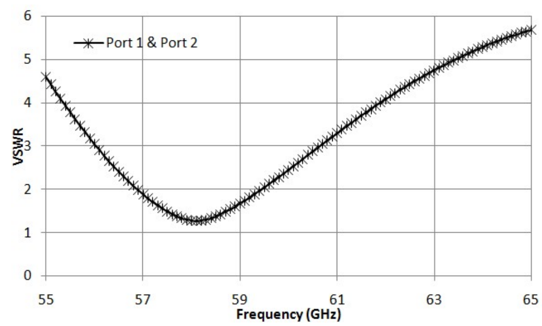

Figure 12. VSWR of the two ports microstrip patch antenna

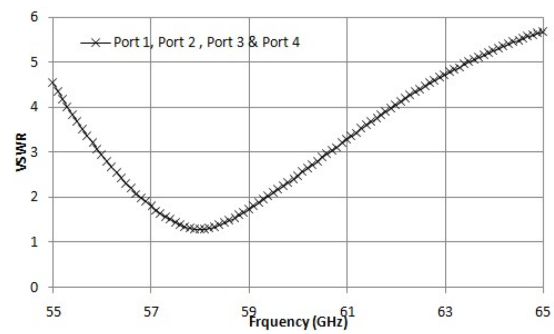

Figure 13. VSWR of the four ports microstrip patch antenna

Table 2. Comparitiveanalysis of the antenna's

Parameters	Single port	2 Ports	4 Ports
Resonant frequency (GHz)	58.1	58.1	58
Bandwidth (GHz)	2.4	2.3	2.3
Input reflection coefficient (dB)	-19.84	-18.41	-18.09
Gain (dBi)	3.10	5.2	5.44
Directivity (dBi)	6.99	8.67	9.75
Antenna efficiency (%)	40.90	45.71	37.10
Radiation efficiency (%)	42.44	47.76	37.47

3.2. MIMO performance parameters

To analyze the performance of the four ports MIMO antenna, the key performance parameters such as ECC, DG and MEG has been evaluated.

a. Envelope correction correlation

ECC is one of the key performance parameters of the MIMO antenna. It is a measure of the correlation between antenna elements in the MIMO structure. It is evaluated from the far field radiation properties [15], [16] using (1) and as well as from S-parameters [8], [17], [18] using (2). The second method is only efficient for the antenna with higher antenna efficiency [19].

$$ECC = \frac{|\ \iint [F_1(\theta,\varphi) * F_2(\theta,\varphi) d\Omega]\ |^2}{\iint |F_1(\theta,\varphi)|^2 d\Omega \iint |F_2(\theta,\varphi)|^2 d\Omega} \quad (1)$$

Where F_i is the far field radiation pattern of the antenna systemwhen port i is excited, and *denotes the Hermitian product.

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

Where i and j number of ports. In this case, there are 4 ports, i and j will vary from one to four.

The ECC values are simulated by IE3D™ simulation software against frequency. Figure 14 and Figure 15 depict the simulated values of ECC for the four port MIMO antenna from both methods. For the ideal case, ECC has to be 0, andin a practicalenvironment, the acceptable limit of ECC is less than 0.5 [20]-[22]. ECC value for the overall antenna is below the required limit which ensures the good performance of the MIMO antenna.

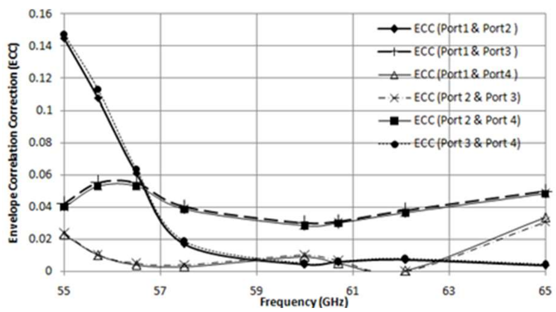

Figure 14. ECC values from far field radiation patterns

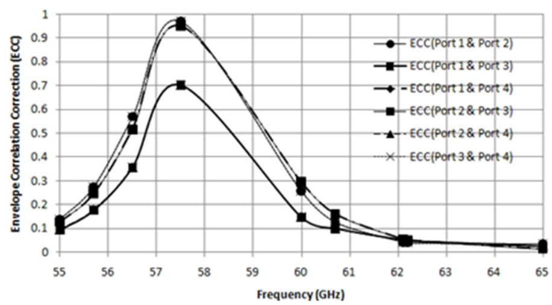

Figure 15. ECC values from S parameters

b. Diveristy gain

The DG of the MIMO antenna has to be high [23] for good, reliable system and it is calculated by using (3). From Figure 16, it is observed that DGis above 9.8 dB over the operating range ensuring a good performance of the MIMO antenna.

$$DG = 10\sqrt{1 - |\rho_{ij}|^2} \quad (3)$$

Where ρ_{ij} is the envelope correlation of the antenna

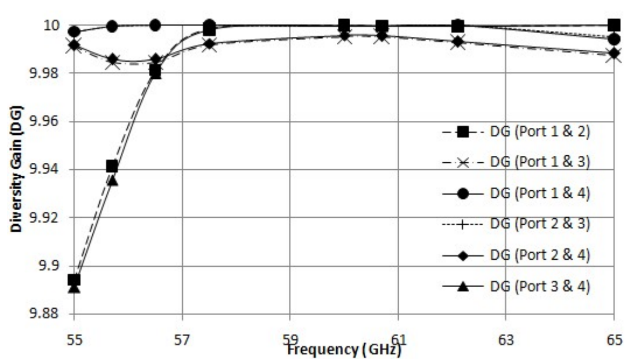

Figure 16. Diversity gain

c. Mean effective gain

MEG is the measure of power received by thediversity antenna relative to the power received by an isotropic antenna in the fading environment [1], [24]. It is calculated using (4) and graph of the same is shown in Figure 17.

$$MEG_i = 0.5\,\{1 - \textstyle\sum_{j=1}^{k} |S_{ij}|^2\} \quad (4)$$

Where k is the number of antennas, i is the antenna under consideration. In this case, for the four port antenna, k=4.

Therefore we have,

$$MEG_1 = 0.5\,\{\,1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2 - \,|S_{14}|^2\}$$
$$MEG_2 = 0.5\,\{\,1 - |S_{21}|^2 - |S_{22}|^2 - |S_{23}|^2 - \,|S_{24}|^2\}$$
$$MEG_3 = 0.5\,\{\,1 - |S_{31}|^2 - |S_{32}|^2 - |S_{33}|^2 - \,|S_{34}|^2\}$$
$$MEG_4 = 0.5\,\{\,1 - |S_{41}|^2 - |S_{42}|^2 - |S_{43}|^2 - \,|S_{44}|^2\}$$

For good diversity performance, the MEG analysis for the proposed four port element antenna the ratio of MEG1/MEG2 and MEG3/MEG4 should be < 3 dB [24], [25]. It is validated from the Figure 20 as MEG values are less than 1 dB. Table 3 shows the MIMO performance metrics for the proposed four port antenna, which shows that the antenna is having a good diversity characteristics and is well suited for the millimeter wave applications.

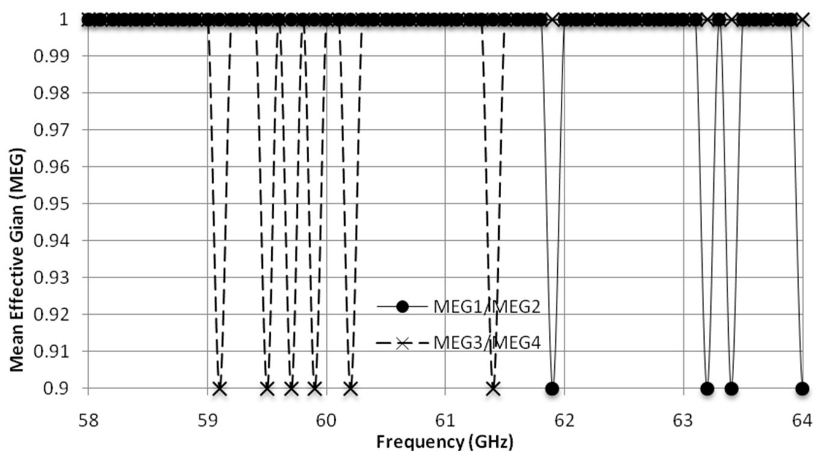

Figure 17. MEG1/MEG2 and MEG3/MEG4

Table 3. MIMO performance parameters for 4 ports MIMO antenna

Parameters	Results
Resonant frequency	58 GHz
ECC	<0.06 (using far field radiation method)
	< 0.9 (using S parameter method)
DG	> 9.8 dB
MEG	< 1 dB

4. CONCLUSION

In this study, a novel compact microstrip MIMO antenna has been designed and analyzed. The four ports MIMO antenna works perfectly for millimeter wave applications with the gain of 5.44 dBi and directivity of 9.75 dBi. It also gives a wide bandwidth of 2.3 GHz at 60 GHz band which is suited IEEE 802.11ad wireless networking standard. The MIMO performance metrics also has been analyzed and it is found that four ports MIMO antenna gives a good performance at the resonant frequency. The ECC is about 0.06 using far field radiation pattern and 0.9 using s parameter method of calculation. Diversity gain of four port MIMO antennas is greater than 9.8 dB with MEG of less than 1 dB.

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