Circular Equivalent Planar Array- A new approach

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Abstract—In this paper, a new configuration of four elements circular equivalent planar array has been proposed to achieve high gain and directivity with lower sidelobe level. After being designed and simulated, the proposed antenna array has achieved high directivity of 15.3 dBi with 85 % radiation efficiency. Besides, the array has a maximum realized gain of 14.51 dB and low sidelobe level of – 16 dB. The proposed antenna array has been evaluated by comparing its performances with four elements of MIMO and planar antenna arrays. It is observed that the proposed array shows greater performances in terms of all parameters compared to the other two arrays. Also, the proposed array has maximum isolation of below – 35 dB between two nearby elements. In turn, the high directivity of the proposed antenna array resonating at 5.8 GHz with very minimum return loss which makes it suitable for Radar application.

Contribution—High gain and directivity have been achieved by proposing a new Circular Equivalent Planar Array with lower sidelobe level and minimum mutual coupling effect.

Keywords— planar array, circular array, MIMO array, patch antenna, inset-fed, radar

I. INTRODUCTION

The antenna is an important element in RADAR application where, an antenna with high directivity, gain and efficiency is a necessity. There are many areas like Air traffic control, Ground traffic control, Military, Space and Remote sensing, where radar plays an important role. For a single element antenna, it is difficult to produce high gain and directivity, therefore, the antenna array is generally used for radar application. Most of the researchers have used planar array because of its design simplicity with low cost, lightweight and easy fabrication process. [1]–[3]. However, planar antenna array struggles with high side-lobe level in the radiation pattern that creates unwanted interference. Circular Equivalent Planar Array (CEPA) can be a good option to overcome the limitations by reducing the sidelobe level.

Nowadays, circular array becoming more popular as it gives better performances in terms of directivity, gain and efficiency [4], [5]. Usually, in a planar array, the directivity of the array increases with the increase in antenna elements and inter-element spacing, however, the sidelobe level getting large. Inversely, for a circular array, it is found from the MATLAB analysis that, the directivity or array factor of a circular array increases with the increase of the number of elements & circular radius. In turn, it produces low sidelobe level with better performances. Therefore, circular array works more efficiently compared to the conventional planar array (PA).

A performance analysis between circular array and the linear array has been carried out in [5]. In the work, two different arrays (circular and linear) of 8 elements have been designed, where linear array has achieved a minimum return loss as low as – 15 dB and antenna gain of around 12 dBi, on the other hand, circular array has achieved a minimum return loss as low as – 37 dB and antenna gain of around 14 dBi. Therefore, an increase in the antenna gain of 2 dBi and a decrease in the minimum return loss of – 22 dB have achieved with the circular array. A circular phased array with uniform array configuration has been proposed in [4], where the main beam is steered towards a specific direction. However, it has high sidelobe level. To reduce sidelobe level different approaches have been proposed by the researchers. Likewise, an interesting approach has been applied in [6], [7]. In [6], a central element in the array arrangement has used to achieve the high directive pattern, which leads to a decrease in the sidelobe level, however, by placing a huge number of elements that leads an increase in the array dimensions. Besides, an increasing number in the elements creates complexity in the design and reduces array performances. Likewise, the antenna array with 4 elements has achieved peak gain and directivity of 10.7 dB and 10.8 dB respectively. In [7], the characteristic analysis of circular antenna array has been carried out but the paper does not report any antenna array design except the Matlab analysis only. The same approach has been considered in [8], where, authors have proposed a concentric circular array for 5.8 GHz with an increased gain and low sidelobe level. The 9 elements array has achieved 15.7 dBi gain with – 17.6 dB sidelobe level. For an array antenna, another key parameter is the mutual coupling effect that needs to be under a certain level. Some researchers are also working on it to reduce mutual coupling effects [9], [10]. This parameter is important to analysis for MIMO antennas.

The number of proposed antenna arrays with the circular arrangement is limited as most of the cases, researchers have proposed four elements MIMO array or planar phased array. Like, several numbers of planner phased array has proposed for 5.8 GHz [1], [11], [12]. A quad element phased array of 2×2 arrangement has been proposed in [1]. The antenna resonates at 5.8 GHz with a minimum return loss of -14 dB. The antenna has a dimension of 1244 mm3 in the area. However, the proposed array has achieved a peak gain of 6.2 dB. Another antenna array of 2×4 elements have been proposed in [11] for 5G application at 5.8 GHz. The antenna array has a dimension of 22167 mm^3 in the area with minimum return loss – 28.6 dB at the resonant frequency. However, the antenna has achieved a peak gain of 6.77 dB with a very large dimension. To increase antenna gain and directivity with small antenna size, a different antenna array of 2 elements have been proposed with a compact size of 10×15 mm^2. The antenna has been designed 1.6 mm thick FR4 substrate. Besides, it has achieved wide – 10 dB bandwidth of 1196 MHz with a peak gain of 7.19 dBi. To increase antenna array performances, some different approaches have been also considered in [13]–[15]. In [13], four elements of dual feeding MIMO array have been proposed to achieve a monopulse radiation pattern. With the dual feeding technique, the array has achieved a maximum gain of 8.4 dBi and 7.4 dBi at port 1 and port 2 respectively. Furthermore, the array performances have been increased by proposing a magic-T repeater array in [14]. The antenna array has achieved a higher gain of 12 dBi with an antenna size of 11,040 mm^3 in the area. A quad elements metamaterial planar array has been proposed in [15] for dual-band applications, where, a shorted pin microstrip patch array loaded with Split Ring Resonator (SRR) has been introduced. It is found that in an unloaded condition, the array resonates at 5.8 GHz with a peak gain of 9.8 dBi, while in a loaded condition, there is an increase of 1.6 dBi in the antenna gain. However, the resonant frequency has shifted from 5.8 GHz to 5 GHz with an additional resonant frequency of 2.45 GHz.

It is found from the literature that several researchers have proposed planar antenna array to achieve desire performances, however, either sometimes it is come out with good performances but with larger dimensions or vice-versa. However, it faces problems with high sidelobe level that have been tried to minimize by the antenna array with a different circular arrangement of single elements. In some cases, it has been possible to reduce sidelobe level but has a lack in the antenna gain and directivity. Therefore, a different approach can be implemented to improve antenna performances compared to the proposed circular arrangement. Likewise, rectangular single elements can be placed in such a way where all antenna elements eventually make a circular arrangement. Therefore, designing of a circular array is currently under investigation that leads to the importance of working in this field. In turn, designing antenna arrays is an interesting field of research.

In this paper, a single patch antenna has been designed with optimum directivity and efficiency. The designed single patch is used to design a 2x2 planar array (PA), multiple-input and multiple-output (MIMO) array and a circular equivalent planar array (CEPA) and the results are presented. The performance of the proposed CEPA is found better than the PA. In this paper, section II deals with the design and synthesis of antenna arrays, section III illustrates the simulation results with corresponding figures and a comparison table. Finally, the paper concludes in section IV.

II. DESIGN OF ARRAY

Initially, a single patch antenna has been designed with higher directivity and efficiency, which later used to design PA, MIMO and CEPA. Rectangular patch antenna (RPA) has been considered as a single element for all three arrays. The reason behind the selection of the RPA is the design simplicity, low cost, lightweight with higher performance stability [1], [2]. Additionally, it is easier to optimize the design to get the desired requirements (namely, impedance matching, efficiency, polarization, resonant frequency). The return loss kept as low as possible near the resonant frequency with having greater impedance matching, where mutual coupling also less than -20 dB for array configurations. All three antenna arrays have been designed and simulated in CST MWS 2019.

To design an RPA, three parameters like resonant frequency, dielectric permittivity and dielectric height must be known, where, dielectric height and dielectric permittivity are not an open choice and it depends on the material that will be used to design the antenna. The RPA, PA, MIMO and CEPA all have been designed and realized on Rogers 5880 substrate with 2.2 dielectric constants (ε_r), 0.25 mm dielectric height (h), 0.035 mm trace thickness (t) and 0.0009 dielectric loss ($tan\ \delta$). The dimensions of the RPA like patch width (W_p) and patch length (L_p) have been calculated with the following formulae [16].

$$W_p = \frac{C}{2\, f_r \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-\frac{1}{2}} \tag{2}$$

$$L_{eff} = \frac{c}{2\, f_r \sqrt{\varepsilon_{eff}}} \tag{3}$$

$$\Delta L = 0.412h\, \frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W_p}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W_p}{h} + 0.8\right)} \tag{4}$$

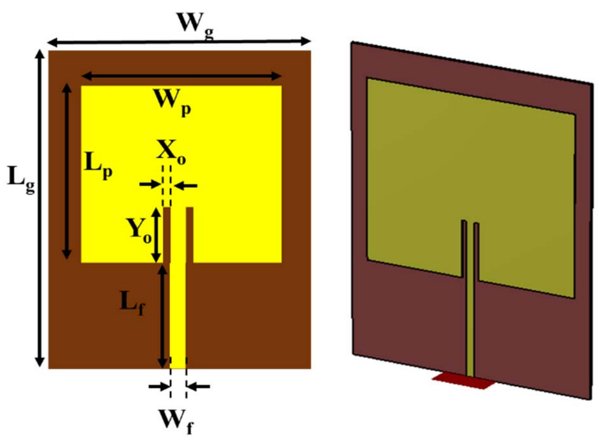
$$L_p = L_{eff} - 2\Delta L \tag{5}$$

Feedline width (W_f) and inset length (y_o) are calculated with the following formulas [2], while inset width ($y_o = {W_f}/{2}$) and L_f is a quarter-wave microstrip line.

$$W_f = \frac{7.48 \times h}{e^{\left(Zo\frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25 \times t \tag{6}$$

$$y_o = \frac{Lp}{\pi}\cos^{-1}\left(\sqrt{\frac{Z_o}{R_{in}}}\right) \tag{7}$$

Here, c is the Speed of light, Z_o is the input Impedance and R_{in} is the input Resistance. After calculating all the parameters with consideration of those values of c,Z_o,R_{in} , the RPA, PA, MIMO and CEPA have been designed and simulated in CST MWS 2019. The calculated dimensions have been optimized to achieve as minimal as possible return loss with acceptable VSWR (1 to 2) at the desired resonant frequency. The antenna geometry and the optimized values of the parameters are shown in Figure 1 and Table 1 respectively.



(a) (b)

Figure 1. Single RPA, (a) antenna geometry and (b) 3D view in CST

Table. 1 Physical dimension of the Single element

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
W_p	20	L_p	17.5
W_f	0.775	W_g	23
X_o	0.387	Y_o	5.5
L_f	9.45	L_g	30

The PA, MIMO and CEPA array antennas have been designed by using the same single RPA element that shown in Figure 2. The spacing between two nearby elements is considered as 0.6 λ that is equivalent to 31 mm. A matching network has been designed with 50Ω and 70Ω microstrip lines for PA and CEPA. The PA and MIMO antenna array geometry can be seen from Figure 2(a).

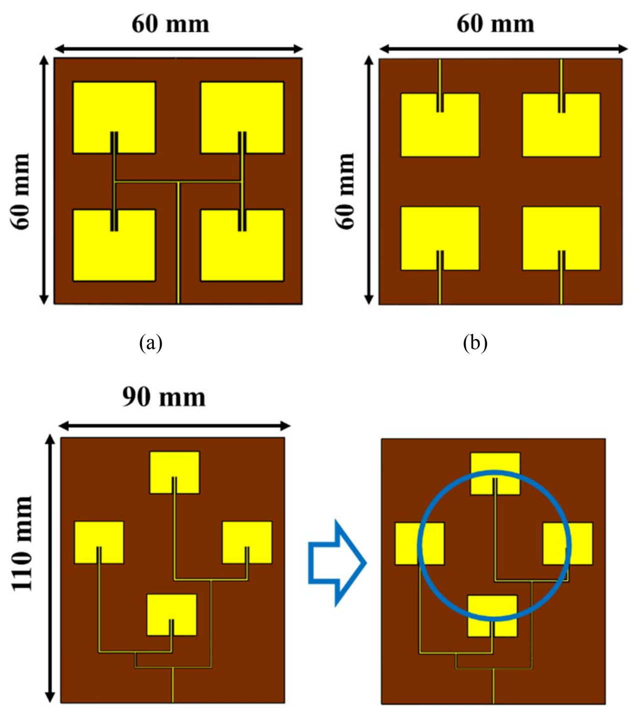


Figure 2. Antenna arrays geometry, (a) PA, (b) MIMO and (c) CEPA

The proposed CEPA antenna can be seen in Figure 2(b). This CEPA array has considered an equivalent of above PA and MIMO arrays that have also been developed with the same single RPA and all antennas are placed symmetrically. The distance between two elements is 0.6 λ as like the spacing of PA and MIMO antenna arrays, therefore, this is in the radius from the center for CEPA.

III. Results and Discussion

The simulation of the designed single RPA, PA and CEPA antenna arrays have been performed in CST MWS 2019. The simulated return loss and VSWR have been illustrated in Figure 3 and Figure 4 respectively.

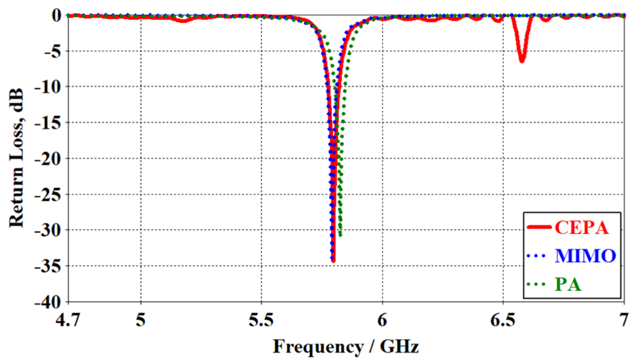


Figure 3. The return loss of CEPA, PA and single RPA

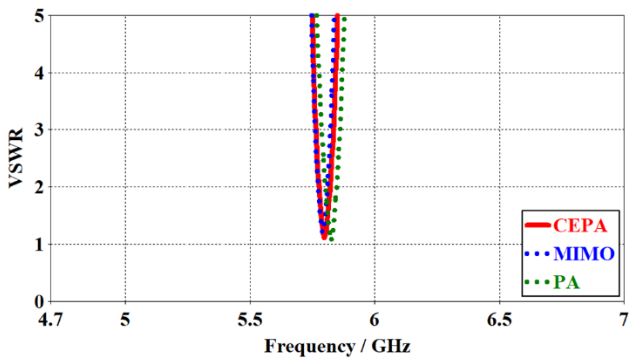
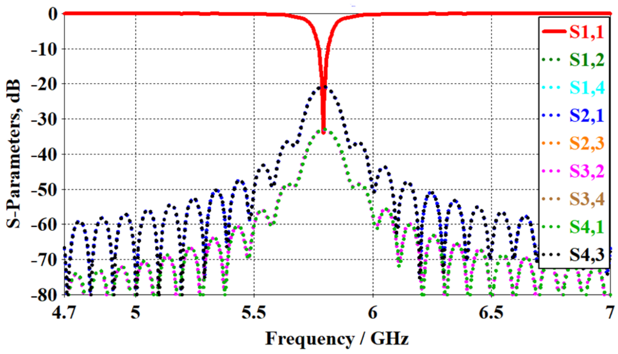
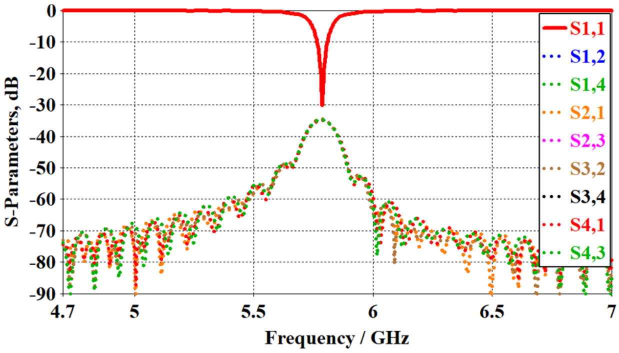


Figure 4. VSWR of CEPA, PA and single RPA

It can be seen from Figure 3 that, all three antenna arrays have resonated at around 5.8 GHz except for the PA which has shifted a little bit towards the higher frequency of 5.82 GHz. The minimum return loss of PA and MIMO is as minimum as – 32 dB and – 34 dB while, the minimum return loss of CEPA is as low as – 35 dB. Figure 4 comprises the VSWR of PA, MIMO and CEPA antenna arrays. It is seen from the figure that for all three antenna arrays, the VSWR value is close to 1 that insures a greater matching between the feedline and patch. The S_{11} and VSWR results justify the design stability that leads to achieving good radiation efficiency of the antenna. It is found from the performance analysis that the distance of 0.6 λ (31 mm) between two nearby elements gives good mutual coupling effect as shown in Figure 5. The S-parameters of Figure 5(a) shows that the maximum isolation between two nearby elements for PA antenna array is below – 20 dB while the maximum isolation between two nearby elements for CEPA antenna array is below – 35 dB as seen in Figure 5(b). Therefore, it is noticed that there is a decrease of 15 dB have achieved by the CEPA antenna array arrangement.



(a)



(b)

Figure 5. Mutual coupling effect between two nearby elements, (a) PA arrangement and (b) CEPA arrangement.

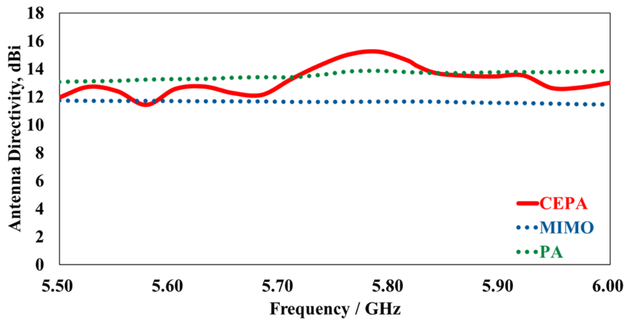


Figure 6. Directivity of CEPA, PA and single RPA

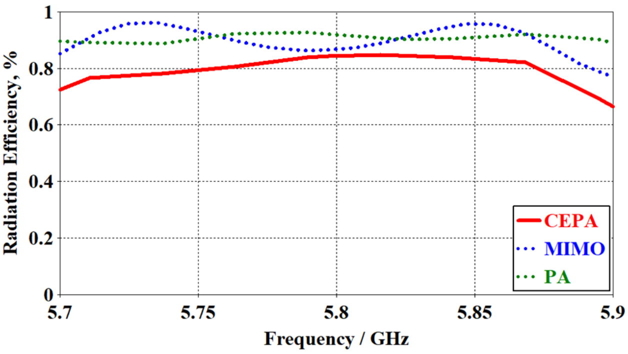
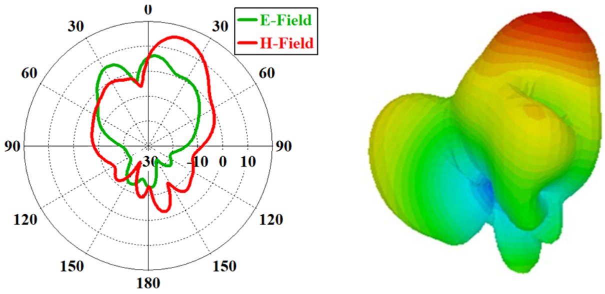
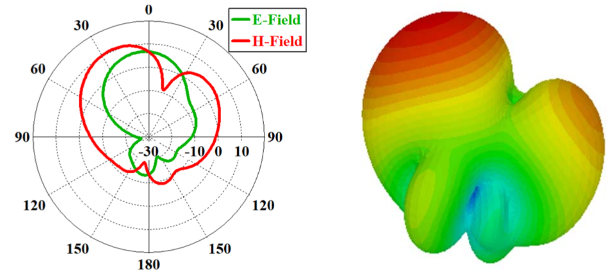


Figure 7. The radiation efficiency of CEPA, PA and single RPA

The directivity and radiation efficiency of all three antenna arrays have been presented in Figure 6 and Figure 7 respectively. It is seen from Figure 6 that the CEPA has the highest directivity of 15.3 dBi compare to the other two arrays. The directivity of PA and MIMO are of 13.8 dBi and 11.7 dBi respectively. The peak radiation efficiency of the MIMO and CEPA are very closed by 86 % and 85 % respectively, while the PA has achieved a peak efficiency of 92 % as seen in Figure 7. There is a decrease of 7 % in the radiation efficiency for the CEPA compare to PA, which is because of the large matching network.



(a)



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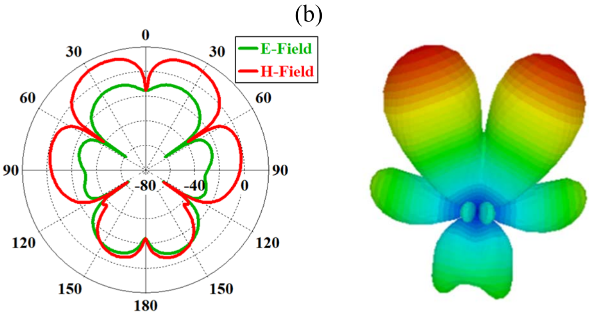

(c)

Figure 8. Polar and 3D radiation pattern of the antennas at 5.8 GHz, (a) CEPA, (b) MIMO and (c) PA

In figure 8, the polar and 3D radiation pattern of all three antenna arrays have been illustrated. It can be seen from the polar and 3D radiation pattern that in all cases the antennas have achieved directional radiation pattern. In PA radiation pattern, the main lobe has split into two lobes, while the other two arrays have one single main lobe. The proposed CEPA has achieved the lowest side lobe level compare to the others with high directivity. The sidelobe level of CEPA is – 16 dB, while, the sidelobe level of MIMO and PA are – 6 dB and – 15 dB respectively. The maximum realized gain of the antenna has been shown in Figure 9.

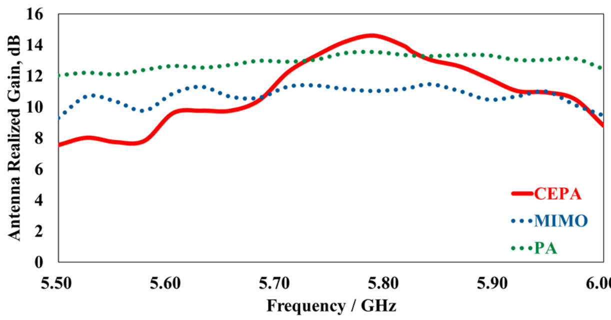

Figure 9. Realized Gain of CEPA, PA and single RPA

It can be noticed from Figure 9 that because of the high efficiency, all three antenna arrays have achieved high realized gain. The CEPA, MIMO and PA have achieved a maximum realized gain of 14.51 dB, 11 dB and 13.3 dB respectively. Meanwhile, there is an increase of 3.51 dB and 1.21 dB realized gain for the CEPA compares to the MIMO and PA respectively. It can be noticed that even though with less efficiency compared to the PA, CEPA has achieved high realized gain. A comparison in the performances between the CEPA, MIMO and PA has been reported in Table 2.

Table 2. Comparison between PA and CEPA

Parameters	**CEPA**	**MIMO**	**PA**
Dimension, mm^2	90×110	60×60	60×60
Return loss, dB	– 35	– 34	– 32
VSWR	1.1	1.2	1.06
Directivity, dBi	15.3	11.7	13.8
Realized Gain, dB	14.51	11	13.3
Efficiency, %	85	86	92
Side lobe level, dB	– 16	– 6	– 15

It is seen from the comparison table that the CEPA has achieved better performance compared to the MIMO and PA in all parameters except in the efficiency. The 7 % decrease in efficiency than PA has occurred because of the large matching network of the feedline. Besides, the VSWR value for CEPA has also increased a bit because of the feeding network that also creates an effect on efficiency. However, the overall performance of the CEPA is better than the MIMO and PA antenna arrays with high directivity, high realized gain and low sidelobe level. The prototype of the PA and CEPA have been developed to validate the array performances. Figure 10 shows the developed prototypes and its return loss responses.

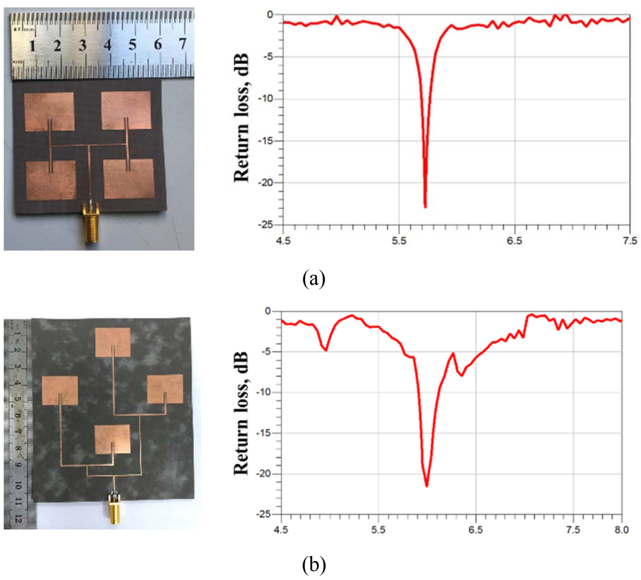

Figure 10. The measured return loss of the developed prototypes at 5.8 GHz (a) PA and (b) CEPA

It is seen from Figure 10. that the resonant frequency has shifted a little due to the fabrication process and also the antenna has obtained few bends in the shape due to the thin substrate. It is expected that with precise fabrication and precausion in handeling, the developed prototype of the proposed design should achieve more accuracy in the measurement result. However, the minimum return loss has achieved as low as less than – 20 dB at the resonant frequency for both the developed prototypes. The proposed CEPA has been evaluated with recent existing works that have been presented in Table 3. It can be observed from the table that the proposed antenna array has achieved highest directivity and realized gain compare to the other recent works. Besides, the proposed antenna array has obtained small dimension compare to some other works while it deals with more space because of the array arrangement.

Table 3. Evaluation of the proposed CEPA with existing works

Works	**Freq, GHz**	**Type of Antenna (no. of elements)**	**Dimension, mm^3**	**Reaized Gain, dB**	**Directivity, dBi**
[1]	5.8	PA (4)	1244	6.2	–
[6]	4-8	CEPA (4)	–	10.7	10.8
[8]	5.8	CEPA (4)	–	11.8	13.3
[10]	5.8	MIMO (4)	4,093	5.34	–
[11]	5.8	PA (8)	22167	6.77	–
[12]	5.8	PA (2)	240	7.19	–
[13]	5.8	MIMO (4)	12,480	8.4	–
[14]	5.8	MIMO (4)	11,040	12	–
[15]	5	PA (4)	6,039	9.8	–
This work	**5.8**	**CEPA (4)**	**2475**	**14.51**	**15.3**

IV. Conclusion

A four elements circular equivalent planar array configuration has been proposed in this paper. To evaluate the performance of CEPA, two more different four elements arrays (MIMO and PA) have been designed and a comparative analysis has been carried out between all three antenna arrays. The proposed CEPA shows better performances compare to the MIMO and PA in terms of all parameters. The CEPA has a high directivity and realized gain of 15.3 dBi and 14.51 dB respectively with 85 % radiation efficiency. Besides, it has a low sidelobe level of – 16 dB and maximum isolation is less than – 35 dB. The developed prototype of the proposed CEPA has achieved minimum return loss as low as less than – 20 dB. Moreover, the high gain and directivity of the proposed CEPA make it suitable for 5.8 GHz Radar application.

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