Design of Coplanar Proximity Coupled Feed Hexagonal Shaped Circular Polarized Microstrip Patch Antenna

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Abstract

This paper presents a broadband-multiband circularly polarized hexagonal patch antenna. The structure is fed by a unique coplanar hexagonal gap coupled proximity coupled feed with parasitic elements. The antenna is designed using a 14.2×14.2 mm^2 FR4 substrate. By introducing hexagonal slot and I slot in the patch, the structure behaves as a multiband antenna with resonating frequencies at 2.76, 5.66 and 11.52 GHz. with 0.2837, 0.4525 and 0.3356 GHz respective bandwidths. By inserting I-shaped slots and rectangular slots in patch and also, I-shaped slots in the ground, the circular polarization is achieved in the L band and C band. The proposed structure was fabricated and tested. The simulated results of the magnitude of S_{11}, radiation patterns and realized gains show good agreement with tested results.

Keywords: Multiband, Gap coupled, Coplanar proximity coupled feed, Dual circular polarization, Hexagonal patch, Parasitic elements

Introduction

As the demand of microstrip antennas is increased so has their advancement. A microstrip patch antenna has a metallic layer on top of a dielectric wafer called patch. This patch layer can have a conventional shape like square, rectangular, circular, triangular, elliptical, etc. or any unconventional shape like hexagon, ring, star, etc. [1,2]. Now days the use of unconventional shapes is preferred over conventional shapes because of their various advantages. One such advantage of these shapes is the ease of generating circular polarization. The circular polarization is an important requirement for modern wireless applications as it removes many channel losses like multipath fading, ionospheric rotation or hindrance of line-of-sight link. The CP antenna is also immune to weather conditions and polarization mismatch problems [3,4].

One of this unconventional shape is a hexagonal patch antenna which has smaller size compared to the square and circular microstrip antennas for a given frequency. It's symmetric shape aides in generating circular polarization. Its modal distribution and current distributions of TM_{11} and TM_{21} modes are similar to the modal distribution and current distributions of a circular patch antenna. Hence it is designed by equating it to the design formulas of a circular patch antenna [5,6]. However, though hexagonal patch antenna has advantages over conventional design, it still has the disadvantage of low bandwidth.

One of the methods to enhance bandwidth and gain of the antenna is by the application of a suitable feeding mechanism. Conventionally there are 2 types of feeding techniques. They are contact and non-contacting feeding methods. The former supplies power to patch through direct path and the latter supplies power to patch through magnetic coupling. The strip line feed and coaxial feed are contact feed methods. Aperture and proximity feed are non-contact methods. A comparative study of these 4 techniques shows that the proximity gap coupled feed yields the largest bandwidth compared to other coupling methods. This method uses electromagnetic coupling between the feed line and the radiating patches, printed on separate substrates. The big disadvantage of this method is overall increase in the thickness of the antenna and its properly aligned fabrication [7]. An example of conventional application of proximity feed method is of Jie *et al*. [8] who proposed a proximity-coupled circularly polarized

slotted-circular microstrip antenna for RF energy harvesting applications. The antenna consists of a circular-patch antenna with proximity-coupled feed. Two asymmetric-circular slots were cut diagonally into the antenna to generate circular polarization. The antenna generated a narrow bandwidth (2.36 - 2.40 GHz). The overall antenna volume of this antenna is 60×60×3.2 mm^3. Hence, this method increases the volume of the antenna unnecessarily.

In the recently reported works it is suggested to apply the feed line in the same plane along with the patch antenna. One such example is of Dadel *et al.* [9] who proposed a 5-element log periodic array using inset fed triangular microstrip patches. Gap was introduced in the feed line to the elements one at a time. Best results were observed when the second element was fed using gap coupling between the frequency ranges of 6.8 and 12 GHz with 10 and 43 % linearly polarized bandwidth. Another example is of Abraham *et al.* [10] who proposed a dual-band array structure by using 2 parasitic patches gap coupled to the single layered proximity coupled feed. This technique converted a 2-D structure into a single layered structure with 2.58 and 3.05 GHz as resonating frequencies but the bandwidth was less than 9 % in each band. Next, Chen *et al.* [11] proposed a circular series-fed microstrip patch array of 7 elements for the X band. The patch elements are excited by a dual port circular microstrip line through coplanar proximity coupling. The structure behaves as a single band, narrow band circularly polarized patch antenna with 10 GHz as its resonating frequency. Chaudhuri *et al.* [12] proposed a single layered 2 port microstrip line series fed DCP antenna structure for the C band. The structure consists of twelve patch elements arranged in a circular shape with phase shifters after each element. though the structure behaved as narrowband, most of the bandwidth was circularly polarized with good inter port isolation. Bui *et al.* [13] proposed a single layered dual band multi element patch structure for satellite communication. It consists of 2 linear circular patch arrays of different radius that are gap coupled to a 2 port microstrip line feed. The structure radiates as a dual band circularly polarized antenna array structure with 11 and 10 % bandwidth in each band. Darimireddy and Park [14], presented a hybrid antenna for Long-Term-Evolution (LTE-2600 MHz) applications. The proposed antenna consists of a hexagonal-shaped patch loaded with a hexagonal-split-ring slot and a parasitic rectangular dielectric resonator block. The structure was fed using a conventional proximity coupled feed. The structure behaved as narrowband antenna with 7 % bandwidth, most of the bandwidth was circularly polarized. The overall dimension of the antenna is 60×60×3.15 mm^3 which is larger in comparison to the previous papers.

Although the above reported antennas had achieved circular polarization and, in some cases, single layered structures were also developed. Most of the work was done on array antennas which have large dimensions. The bandwidths generated were either too narrow or ultras wide which limited the use of these antennas to some particular applications. The designing of compact, low-profile, broadband circular polarized antennas having wide AR beamwidth for modern wireless applications, is still a challenge. In this paper a single layered multi band broad band circularly polarized patch antenna with coplanar proximity feeding is presented. It consists of multiple slots in the patch and ground to achieve broadband at 2.76, 5.66 and 11.52 GHz with circular polarization. The proposed antenna has a dimension of 14.2×14.2×1.6 mm^3.

Materials and methods

Antenna design
Design of hexagonal patch antenna with coplanar proximity feed
The design of the proposed antenna structure was initiated with the consideration of dual port coplanar proximity coupled fed hexagonal patch antenna using FR4 substrate (substrate thickness 'h' = 1.6 mm, ϵ_r = 4.4, tan δ = 0.02). The proposed antenna structure is located on the x-y plane, and its normal direction is parallel to the z-axis. The hexagonal patch was designed using Eq. (1) along with I slots and hexagonal slots in the patch. The equation used to design the antenna is as follows;

$$S = \frac{c}{3.1033 fr\sqrt{\epsilon r}} \tag{1}$$

where, S is the length of one side of the hexagonal patch, c is the velocity of light, ϵ_r is the dielectric constant of the material and f_r is the desired resonant frequency of the patch [5]. The equation used to calculate feed length is as follows;

$$W_l = \frac{\lambda}{4} - \frac{\lambda}{4\sqrt{\epsilon r}} \tag{2}$$

where, W_l is the length of the rectangular feed, ϵ_r is the dielectric constant of the material and λ is the wavelength of the desired resonant frequency of the patch. The equation used to calculate feed width is as follows;

$$Z_c = \frac{60}{\sqrt{\epsilon r}} \ln \left[\frac{8h}{W_t} + \frac{W_t}{h} \right] \tag{3}$$

where, W_t is the width of the rectangular feed, ϵ_r is the dielectric constant of the material, h is the height of dielectric material, Z_c is the impedance value takes as 50.

The value of f_r is taken as 5.8 GHz for calculations. The final value of S after some optimizations is 4.6 mm. This patch antenna is fed with a 2-port hexagonal gap coupled feed whose outer dimension of one side is 5.2 mm. This feed is connected to 2 rectangular microstrip lines whose length W_l is calculated to be 2.85 mm. The final value of W_t after some modifications is 1.2 mm. The application of gap coupled feed converts the structure into a single layered structure and also increases the coupling strength between the patch and the feed. Hence, the gap between the feed and the structure is kept small and constant. The gap between the patch and feed is of 0.3 mm. The antenna now behaves as a multiband antenna with 2 very close narrow bands in the C band with poor return loss values. To merge these 2 bands together 2 hexagonal parasitic elements of different length with a gap of 0.2 mm are added to the structure as shown in **Figure 1(a)**. These elements merge the 2 bands together which increases its bandwidth in the C band.
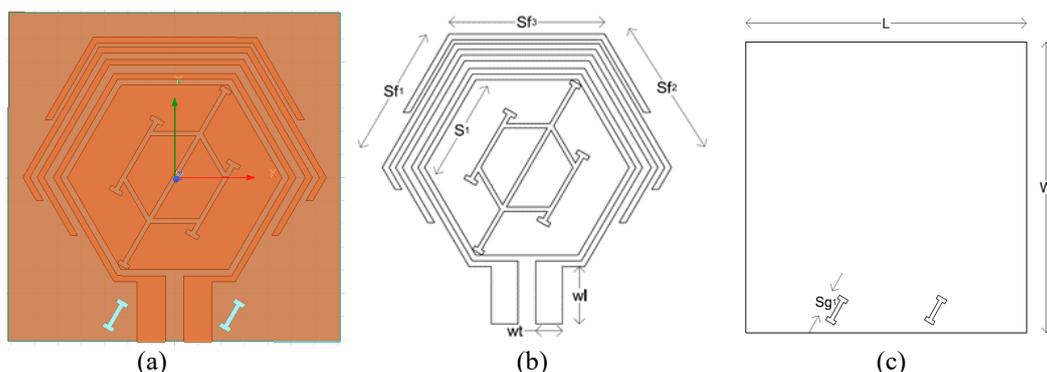

| (a) | (b) | (c) |

Figure 1 (a) Simulated design of hexagonal patch antenna with coplanar proximity feed. (b) Design of hexagonal patch antenna with coplanar proximity feed with dimensions in mm. (c) Design of ground with dimensions in mm.

The I slot introduced at 60 ° at the center of the structures increases its bandwidth but the resonant frequency shifts forward in the 7 GHz range. The introduction of hexagonal slot shifts the frequency back in the desired frequency range. The 2 slots in ground improve the overall return loss value of the structure. The final dimensions of the structure are given in **Table 1**.

Table 1 The final dimensions of the structure.

Dimension	Value in mm	Dimension	Value in mm
L	14.2	S_{f1}	5.2
W	14.2	S_{f2}	5.9
S_1	4.6	S_{f3}	6.5
W_t	1.2	S_{g1}	0.5
W_l	2.85		

The band width of each band was calculated by using the following formula;

$$\text{Percentage bandwidth} = \frac{f_u - f_l}{f_c} \times 100 \qquad (4)$$

were, f_u is upper cut off frequency, f_l is lower cut off frequency and f_c is central resonating frequency [15-19]. If the bandwidth is found to be more than 11 % the antenna has been classified as a broadband antenna.

Hence, the simulated result indicates a multiband broadband patch antenna structure with 2.77 GHz (with bandwidth of 2.42 - 3.22 GHz or 28.8 %), 5.86 GHz (with bandwidth of 5.03 -7.62 GHz or 44.19 %) and 9.47 GHz (with bandwidth of 8.56 - 12.12 GHz or 37.59 %) as central frequencies as shown in **Figure 2**.
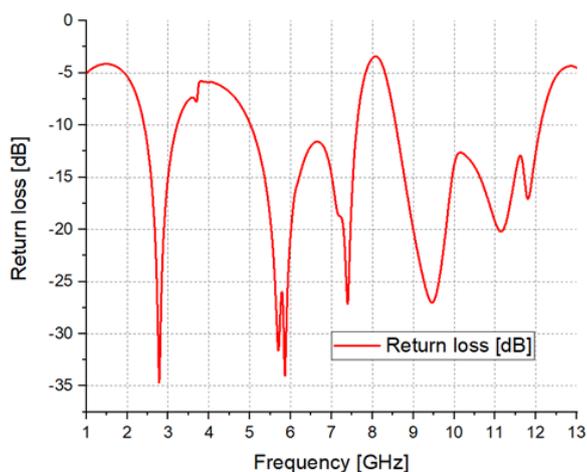

Figure 2 The return loss graph as a function of frequency hexagonal patch antenna with coplanar proximity feed.

Design of circularly polarized hexagonal patch antenna with coplanar proximity feed

The next step is to realize circular polarization for the frequency hexagonal patch antenna with coplanar proximity feed. So, 2 I slot are introduced at the sides of the central slot at 60 °. An I slot is also introduced into the ground at center at an angle of 120°. These slots improve circular polarization at the 5 GHz band. Introduction of 2 I slot at sides at an angle of 60° and 2 rectangular slots on top generates circular polarization in the 2 GHz band. The introduction of these slots distorts the return loss parameter of the antenna. To improve the return loss of the antenna, 2 additional I slots are introduced in the ground. To improve the gain 2 slots are introduced on the top of the patch structure. The final antenna structure is shown in **Figures 3(a)** and **3(b)**. The final dimensions of the structure are shown in **Table 2**.
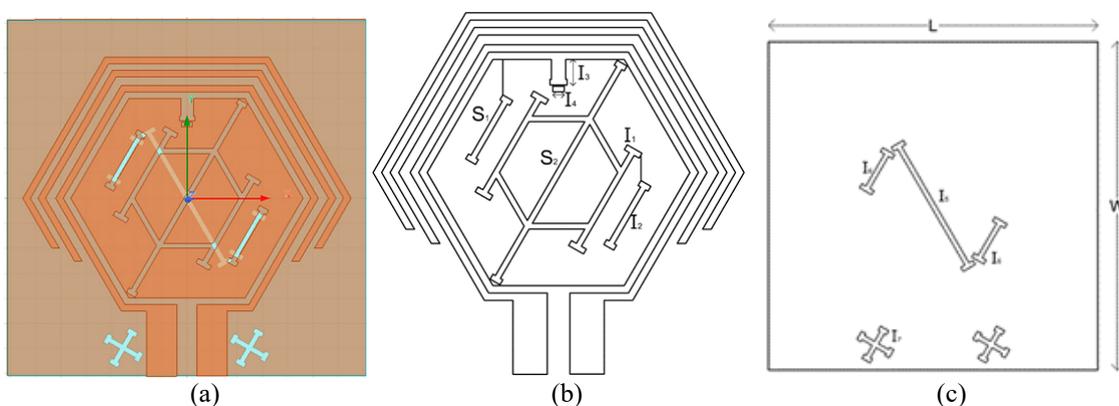

| (a) | (b) | (c) |

Figure 3 (a) Simulated design of circularly polarized hexagonal patch antenna with coplanar proximity feed. (b) Design of circularly polarized hexagonal patch antenna with dimensions in mm. (c) Design of ground with dimensions in mm.

Table 2 The dimensions of the ground slot and patch slots.

Dimension	Value in mm	Dimension	Value in mm	Dimension	Value in mm
L	1.42	I_1	3.7	W	1.42
S_1	4.6	I_2	2.2	I_5	3.8
S_2	2.3	I_3	0.8	I_6	1.6
W_t	1.2	I_4	0.5	I_7	0.6

Results and discussion

The proposed antenna is fabricated on a FR4 substrate (substrate thickness 'h' = 1.6 mm, ε_r = 4.4, tan δ = 0.02). as shown in **Figure 4**. The measured and simulated results of the return loss versus frequency are shown in **Figure 5**, which are found in good agreement with each other. The antenna now behaves as a multi- band broad band antenna with a central frequency of 2.76 GHz (with the bandwidth of 2.42 - 3.22 GHz or 28.37 %), 5.667 GHz (with the bandwidth of 4.94 - 6.4 GHz or 45.25 %), and 11.52 GHz (with bandwidth of 8.19 -11.9 GHz or 33.56 %). The introduction of 2 side slots in the patch gives circular polarization in the 5 GHz band (with a bandwidth of 0.1460 GHz or 14.60 %.). The introduction of 3 slots in the ground generate circular polarization in the 2 GHz band (with a bandwidth of 0.1214 GHz or 12.14 %.) as shown in **Figure 6**.

(a)   (b)

Figure 4 (a) Hardware design of circularly polarized hexagonal patch antenna with coplanar proximity feed. (b) Picture of the antenna with VNA at the time of antenna testing of circularly polarized hexagonal patch antenna with coplanar proximity feed.
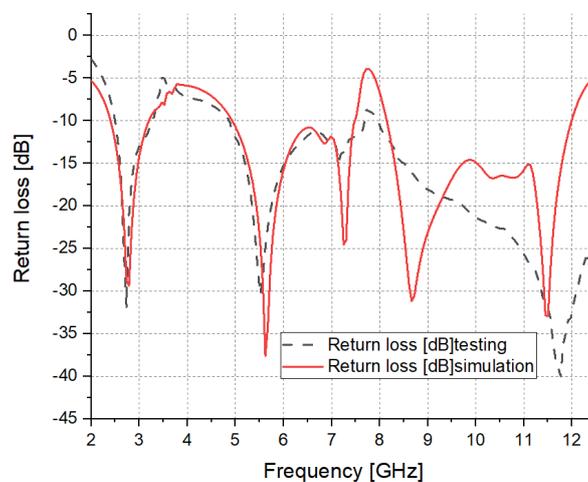

Figure 5 The return loss graph as a function of frequency for circularly polarized hexagonal patch antenna.
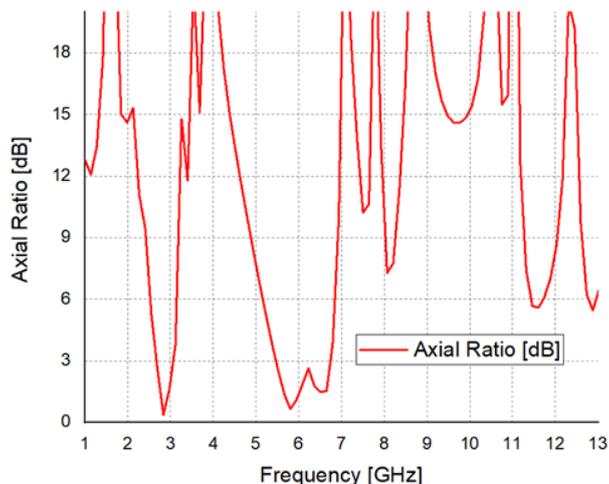
Figure 6 The axial ratio plot of the of the circularly polarized hexagonal patch antenna.

The simulated and measured 2-D gain patterns in y-z and x-z planes at 5.66 GHz are shown in **Figures 7(a) - (d)**, which achieves good agreement. The peak gain of the antenna varies from 18.1 - 34.22 dBm. Its value in the 2 GHz band is 20.23 dBm, in 5 GHz band is 24.98 dBm and at 11.5 GHz is 31.83 dBm as shown in **Figure 8**. The compound total efficiency is also plotted in Figure 7. It is found that its value at 2.8 GHz band is 29.6 %, at 5.6 GHz is 32.7 % and in 11 GHz band is 23.3 % as shown in **Figure 8**.
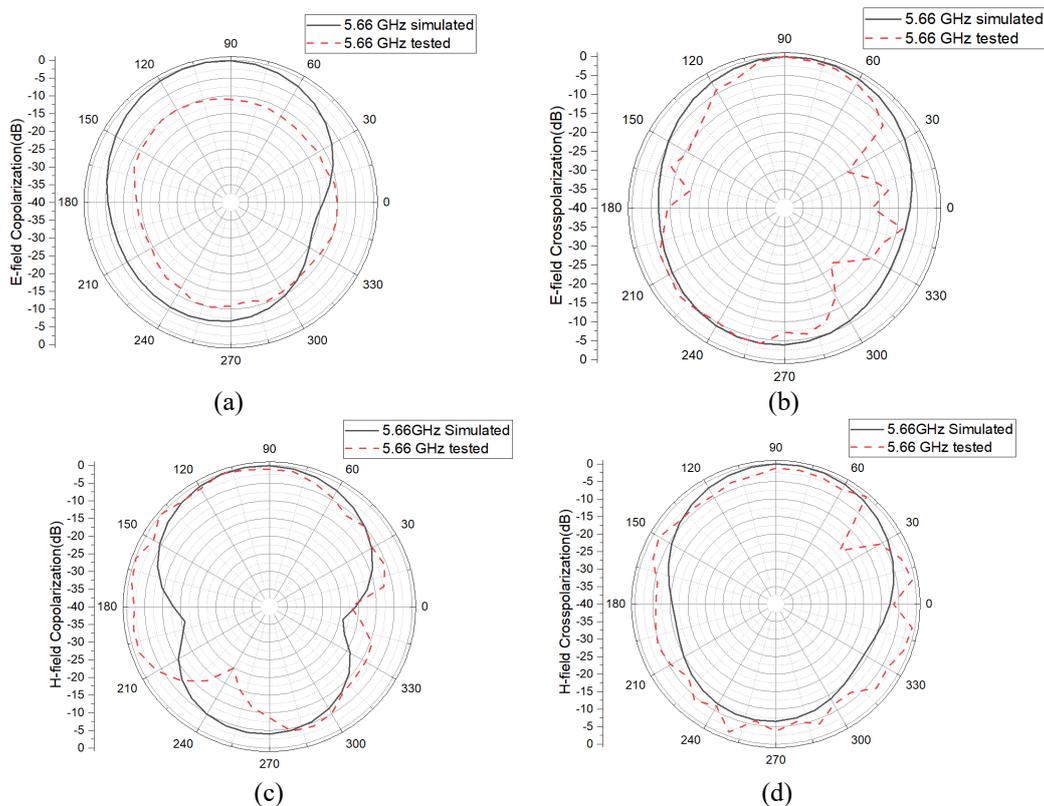

Figure 7 Simulate and measured E field (a),(b) and H field (c),(d) radiation pattern at 5.66 GHz frequency.
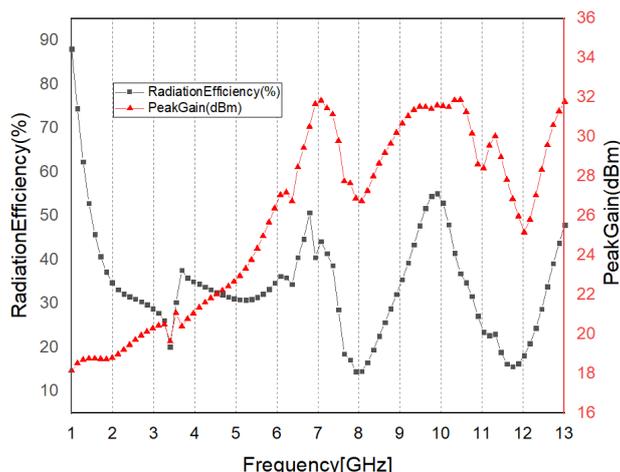
Figure 8 The gain plot and efficiency plot of the of the circularly polarized hexagonal patch antenna.
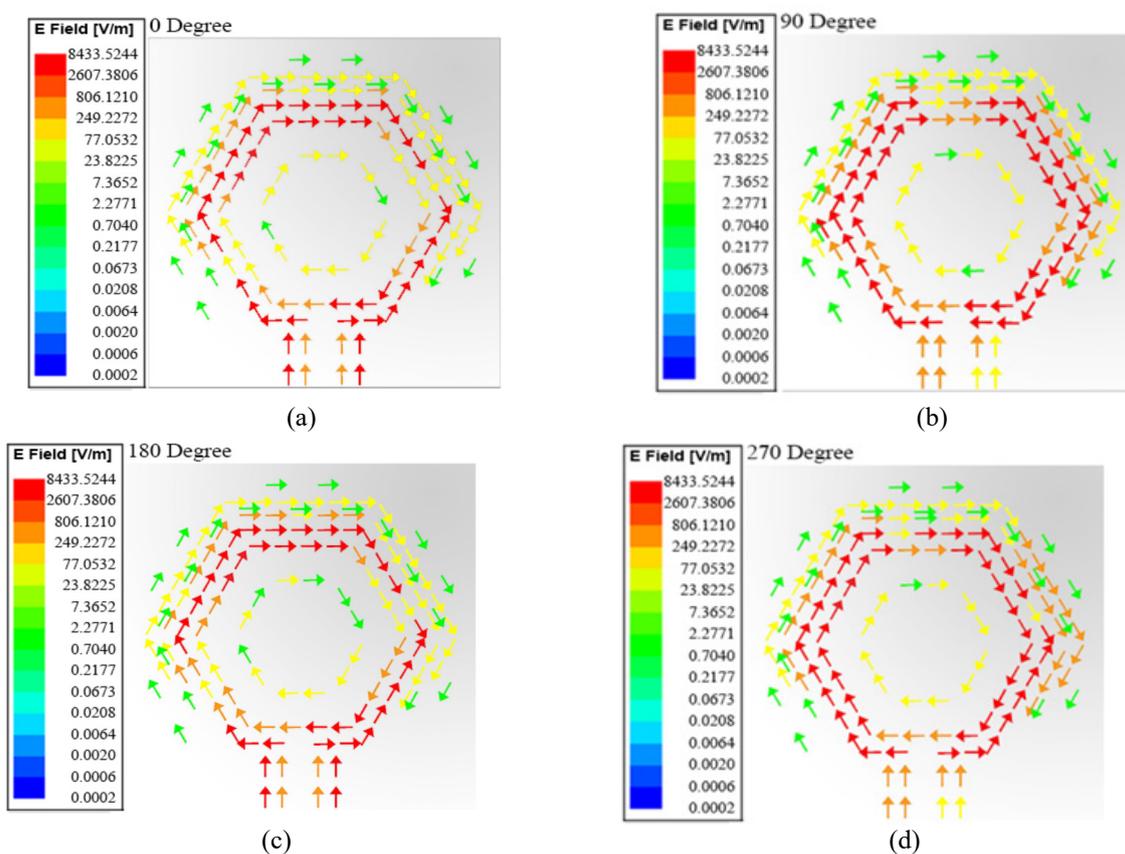

Figure 9 The current distribution pattern of the circularly polarized hexagonal patch antenna with different phase angles of E field (a) 0, (b) 90, (c) 180 and (d) 270 ° at 5.66 GHz frequency.

The surface current distribution of the antenna at the 5.66 GHz frequency is shown in **Figure 9**. It is observed that the hexagonal feed line carries a large amount of current and on the edges of the hexagonal patch structure. At this point, the electric field has been generated. On the ground plane, the current is mainly distributed along the center below the patch structure. At these points, the electric field has been generated. These points contribute to generate the electric _eld *Ex* and *Ey* on the x axis and y axis respectively. When the electric _eld *Ex* and *Ey* have the same magnitude, antenna achieves the CP

operation. Moreover, the surface current vectors are moving clockwise, which means the antenna works in the RHCP mode. The surface current distribution is observed at various phase angles of 0, 90,180 and 270 ° as shown in **Figure 9**. It is observed that the surface current distributions rotated in a clockwise circular manner from 0°to 360° indicating a RHCP patch antenna and the intensity is concentrated on the edges of the hexagonal patch structure.

Comparison of antenna dimensions, bandwidth, polarization and gain of the proposed antenna with other reported proximity coupled feed antennas is shown in **Table 3**. The proposed antenna is capable of achieving lower dimensions and higher bandwidth in the C band.

Table 3 Table of comparison of various parameters for different antennas.

S no.	Dimension mm	Bandwidth GHz	Polarization	No. of elements	Reference number
1	100×100×1.6	2.3 - 3.5, 3.4 - 3.6	Linear	4	[10]
2	63×63×0.79	8.0 - 8.5, 8.9 - 11.4	Circular	7	[11]
3	172×172×1.6	6.7 - 7.2	Circular	11	[12]
4	173.6×63.7×1.6	4.1- 9.2	Circular	10	[13]
5	119×44.1 ×1.6	4.8 - 5.6	Circular	5	[20]
6	182×116×25.6	1 - 2	Linear	6	[21]
7	30×30×3.2	2.5 - 2.6	Circular	8	[22]
8	40×40×1.6	1.41 - 2.26	Circular	1	[23]
9	42×42×23.3	9.48 - 10.8	Circular	10	[24]
10	**14.2×14.2×1.6**	**2.5 - 3.2, 4.8 - 7.6, 8.1 - 11.9**	**Circular**	**1**	**Proposed work**

Conclusions

A circularly polarized hexagonal patch antenna with coplanar proximity feed of size 14×14×1.6 mm^3 is reported in this work. The coplanar proximity feed supports in generating a wide bandwidth without any increase in the thickness of the structure. The introduction of hexagonal slot and I slot in the patch make this structure a multiband broadband antenna. In proposed structure, I-shaped slots are inserted in the ground plane, this results in a circularly polarized antenna with 12 and 14 % CP bandwidths. The simulated and measured results show good agreement for the impedance bandwidth ($|S11| < -10$ dB). This single layered antenna structure can be easily integrated into any portable wireless devices and can be used in MIMO antenna and phased arrays.

Acknowledgement

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