

Dual Circularly Polarized Crescent-Shaped Slot Antenna for 5G Front-End Systems

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Abstract—This paper introduces a new simple-structured dual circularly polarized (CP) antenna design for fifth-generation (5G) front end systems. The antenna configuration consists of a crescent-shaped slot radiator fed by a pair of rectangular 50-Ohm microstrip lines. The antenna is designed on an FR-4 dielectric substrate with an overall size of $48 \times 48 \times 1.6 \text{ mm}^3$ to operate at 3.5 GHz, a 5G candidate band. A wide dual CP characteristic supporting both left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) is achieved in the frequency of 3–4.2 GHz. In addition, the mutual coupling (S_{21}) between two ports of the proposed antenna is better than 15 dB. A prototype sample of the proposed design is fabricated and measured to validate the design concept. The antenna offers sufficient efficiency, gain level, and axial ratio bandwidth which make it suitable for different 5G front end applications such as cognitive radio, base station, satellite communications, imaging, and radar systems.

1. INTRODUCTION

One of the important issues in communication systems is the provision of the right orientation between the transmitter and receiver antennas. Circularly polarized (CP) antennas are good solutions to this problem. Using the CP antennas, there will be no need to consider the orientation between the transmitter and receiver [1]. Apart from this, overcoming the multipath fading problem, higher performance, and better mobility and weather penetration with respect to the linearly polarized (LP) antennas are of the admirable CP antennas features [2]. In recent years, research on circularly polarized antennas has intensified due to their many advantages compared to linearly polarized antennas. This is mainly due to CP antennas' ability to operate with similar radiation performance despite being installed in various random orientations. Circularly polarized radiation can be realized by exciting two orthogonal modes with equal amplitude and 90° phase difference. Antennas with circular polarization have many advantages including reduced orientation constraints between transmitter and receiver antennas, suppressed multi-path interferences, avoiding the need of polarization alignment for terrestrial, and feeds and mitigated polarization mismatch losses [3, 4]. Hence, the circularly polarized antennas are widely used in front-end systems of wireless communication, satellite communication, and navigation systems [5]. Consequently, various CP antennas with different geometries have been experimentally characterized [6, 7].

With the upcoming fifth generation (5G) of wireless communications, dual CP antennas have attracted much attention, because they can offer both right-hand and left-hand circular polarization (RHCP/LHCP) characteristics and improve inter-channel isolation of future wireless networks [8–10]. Among multiple-function antennas, dual CP antennas are more attractive to a variety of different applications, such as 5G Internet of Things and wireless local area networks (WLAN) [11]. These

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antennas can effectively enhance system performance by reconfiguring the polarization states. Circular polarization diversity can improve the transmission quality levels and increase the available operation bandwidth for high-capacity/high-speed wireless communications [12]. For a 5G front-end which needs to receive the electromagnetic signals with any polarization mode and from any directions on the ground, a dual CP antenna is significant and valuable. It may be utilized to alleviate the channel deterioration caused by multipath fading effects. Therefore, dual CP antennas are promising for miniaturized systems with frequency reuse or polarization diversity and can provide a powerful modulation scheme for microwave tagging systems [13]. Dual CP antennas are also useful for the compactness and lightweight of wireless devices and have become candidates for multiple-input multiple-output (MIMO) systems. The MIMO technology with multiple antennas is a hot spot and promising technology to build the next and future generation of the wireless network due to its advantages of high capacity and spectral efficiency [14–16].

Unlike the circularly polarized antennas, a few studies of dual CP antennas are reported [17–29] (see Table 1 for details). However, all these dual CP designs either suffer from a narrow impedance or axial ratio (AR) bandwidth or occupy huge spaces on antenna systems. Furthermore, some of the reported designs use active elements, which increase the complexity of the system. In this paper, a new compact dual CP antenna is proposed for 5G applications. Its schematic is composed of a crescent-shaped slot antenna fed by rectangular microstrip feeding lines. The configuration of the proposed antenna design can be considered as a 2×2 MIMO. However, replication and a large number of the proposed designs are required to be arranged to offer MIMO capability of 5G communications. The antenna is implemented on a low-cost FR-4 substrate to operate at 3.5 GHz for 5G applications. The proposed dual CP MIMO slot antenna design offers a 33% fractional bandwidth (FBW) and 3-dB AR bandwidth.

2. ANTENNA DESIGN AND CONFIGURATION

Figure 1(a) presents the schematic of the dual CP antenna. Its structure contains a modified crescent-shaped slot radiator in the ground plane. The CST software is used to investigate the properties of the designed antenna [30]. It is fed by a pair of rectangular feeding lines. Its parameters (in mm) are as follows: $W = 48$, $L = 48$, $W_x = 16.25$, $L_x = 3$, $R = 17.5$, $r = 11$. Figure 1(b) shows a circuit model of dual-port CP antenna where V , C , N , L_f , and G_r correspond to the loaded voltage, inductor, turns ratio, capacitor, and conductance of the circuit, respectively. The employed h , v subscripts represent the horizontal and vertical polarizations, and H and L are the high and low levels. It can be observed that dual CP antennas are able to support both vertical and horizontal polarizations in the right hand and left-hand modes simultaneously.

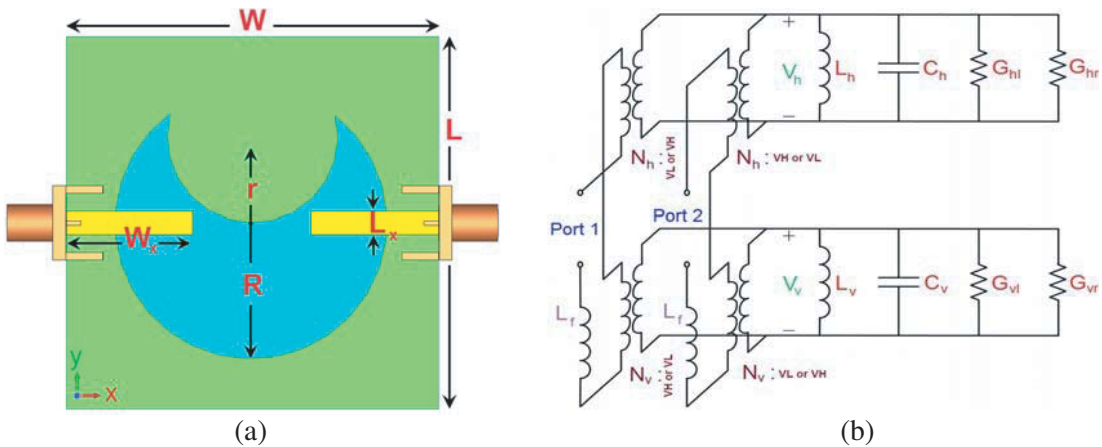


Figure 1. (a) Schematic configuration and (b) circuit model of the designed slot antenna.

3. CHARACTERISTICS OF THE DESIGNED DUAL CP ANTENNA

Figure 2(a) illustrates the simulated S -parameters including the reflection coefficient (S_{11}/S_{22}) and transmission coefficient ($|S_{21}|/|S_{12}|$) characteristics of the proposed dual-port slot antenna. It is shown that the designed antenna exhibits an impedance bandwidth of 3–4.2 GHz. In addition, the antenna offers sufficient isolation (mutual coupling) better than 15 dB. The radiation efficiency (R.E.) and total efficiency (T.E.) characteristics of the design are plotted in Fig. 2(b). It can be observed that the antenna provides very high efficiencies due to its low mutual coupling [31, 32]. More than 80% total efficiency is achieved over the entire operating band. Besides, it has more than 90% radiation efficiency over the entire operation band of the dual CP antenna.

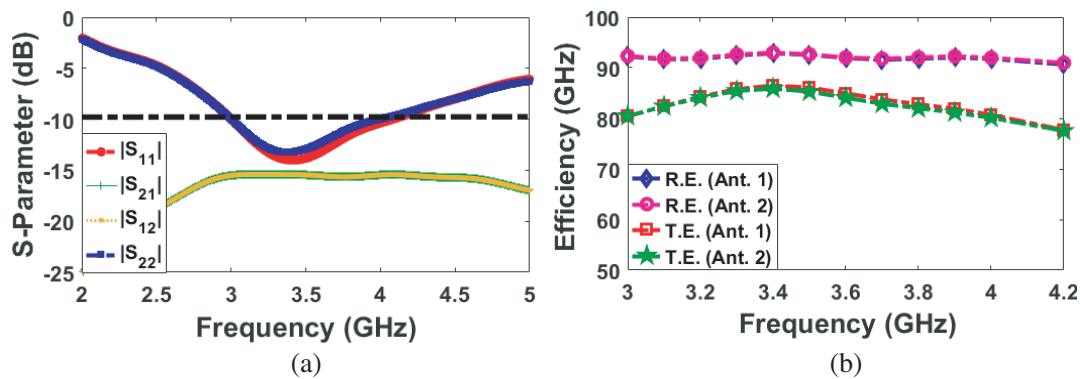


Figure 2. Simulated (a) S -parameters and (b) efficiencies of the antenna over its operation band.

Figure 3 shows the simulated electric current flow and distribution at the resonance frequency of 3.5 GHz on the ground plane of the crescent-shaped slot radiator when each port is excited separately [33, 34]. It should be noted that both current flows are presented at the same temporal instant. It can be observed that the null currents are mainly located at the edges of the crescent-shaped slot. The current densities shown in Figs. 3(a) and (b) rotate with opposite directions, thus radiating RHCP and LHCP modes have been generated for the proposed dual CP slot antenna design. 3D radiation patterns of the crescent-shaped slot antenna at its resonance frequency (3.5 GHz) for different ports are illustrated in Fig. 4. It is evident that the antenna provides good dual-polarization characteristics with a 90° difference and similar radiation pattern performances with 5-dBi gain [35, 36].

In addition, as shown, the antenna provides symmetrical radiations covering both the top and bottom sides of the substrate. In order to demonstrate the dual CP function of the antenna, the right- and left-handed gains of the antenna versus theta are plotted in Fig. 5. As evident from this figure,

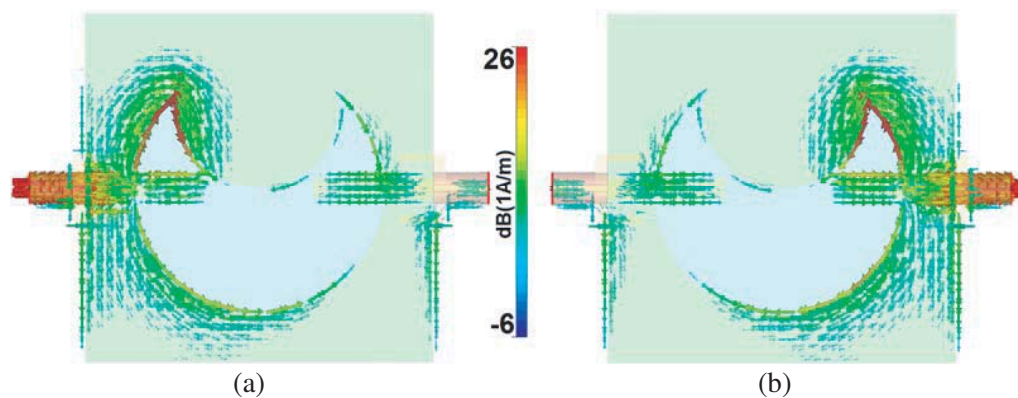


Figure 3. Current flows and distributions at 3.5 GHz for (a) port 1 and (b) port 2.

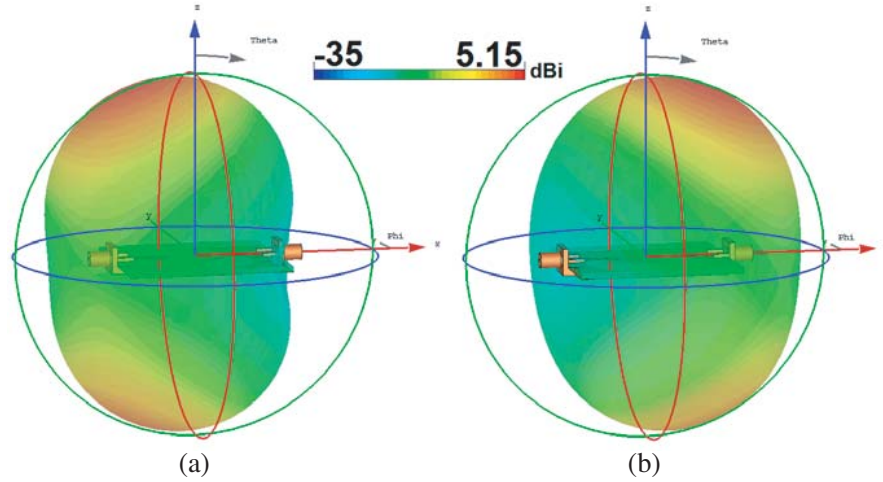


Figure 4. Radiation patterns of the antenna at 3.5 GHz from (a) port 1 and (b) port 2.

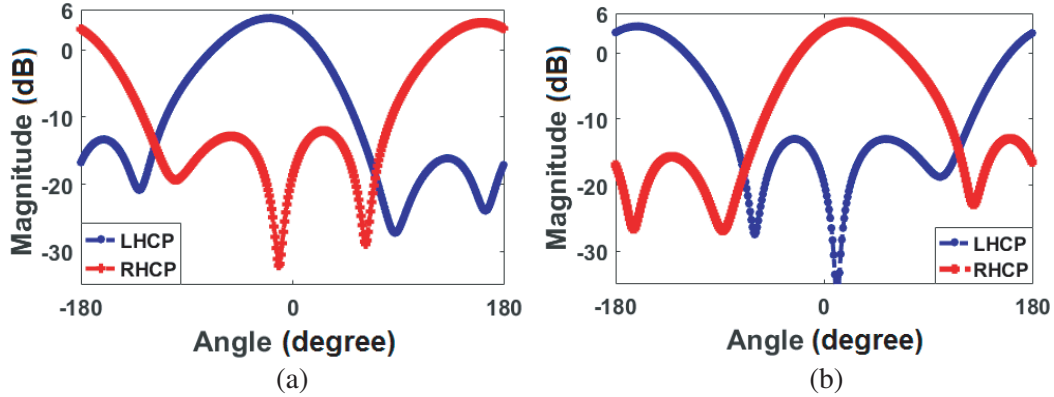


Figure 5. RHCP/LHCP gain magnitudes at 3.5 GHz for (a) port 1 and (b) port 2.

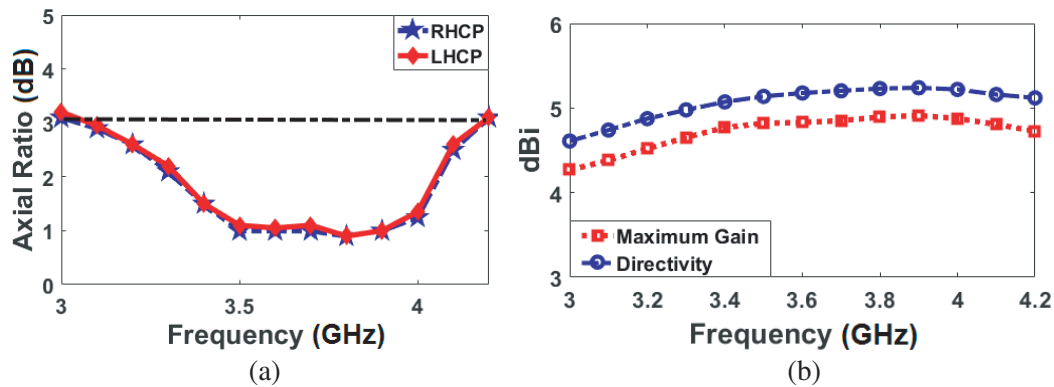


Figure 6. (a) Axial ratio (b) maximum gain and directivity characteristics versus the operation band.

for different feeding ports, the left- and right-handed gains change magnitude reversely which leads to supporting both simultaneously. The axial ratio characteristics of the proposed dual CP antenna are represented in Fig. 6(a). As shown, the antenna provides good dual CP function supporting both RHCP and LHCP characteristics at the same frequency band of the antenna reflection coefficient. Besides, as seen, similar AR performances are achieved for the two feeding ports of the slot antenna. Furthermore,

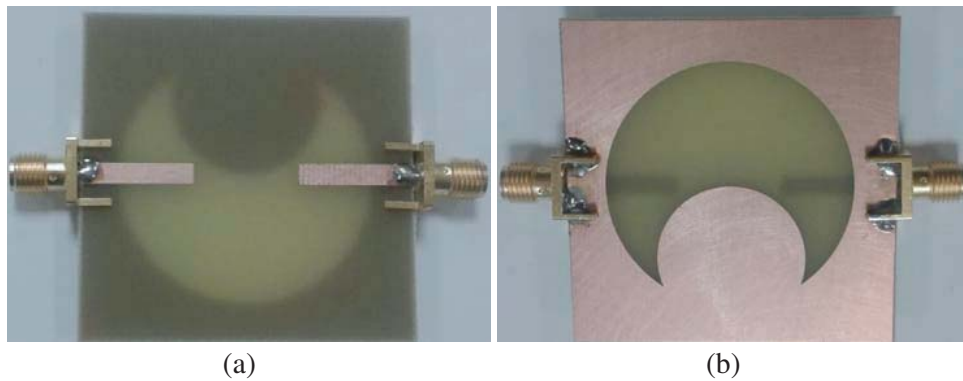


Figure 7. (a) Front and (b) back views of the antenna prototype.

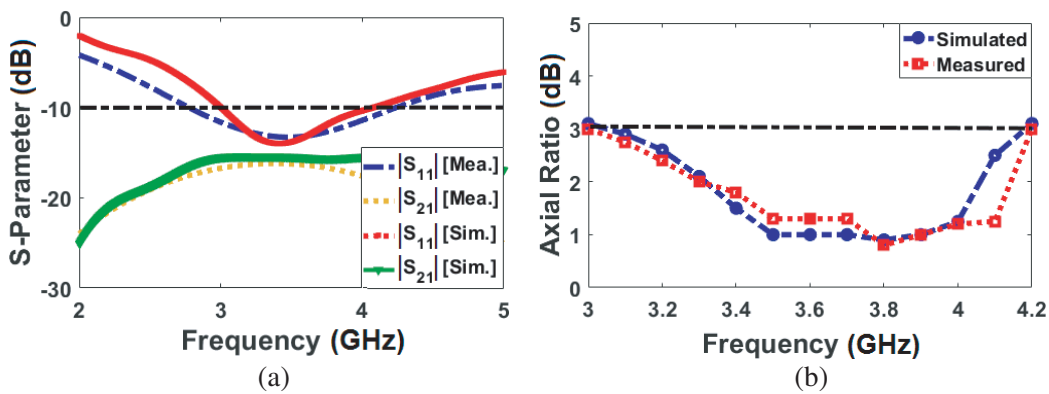


Figure 8. Measured and simulated results of (a) S_{11}/S_{21} and (b) axial ratio characteristics.

as illustrated in Fig. 6(b), the antenna offers sufficient maximum gain and directivity characteristics.

The proposed dual-port slot antenna is properly fabricated on a 1.6 mm FR-4 substrate, and its S -parameters are measured in the antenna lab of the University of Bradford. Fig. 7 illustrates photographs of the fabricated antenna array including top band bottom views. Figs. 8(a) and (b) plot and compare the simulated and measured S -parameters and axial ratio results of the dual-port dual CP slot antenna. A good alignment can be observed for the proposed antenna measurements. As shown in Fig. 8(a), both simulated and fabricated designs cover the operation band of 3–4.2 GHz. Also, sufficient isolation, better than 15 dB, is achieved for the proposed design. Furthermore, it is evident from Fig. 8(b) that the antenna exhibits a broad CP function supporting the whole antenna operation band. The main motive behind the proposed design was to obtain a low-profile and broadband antenna with circular polarization diversity. The frequency response and axial ratio characteristics of the design are very flexible which can be easily adjusted to the desired operation band by changing the values for fundamental antenna parameters such as outer conductor area, substrate thickness, and the size of crescent-shaped slot resonator [37–39].

The 2D-polar radiation patterns of the proposed dual CP antenna at the middle frequency (3.5 GHz) are depicted in Fig. 9, when the ports are excited separately. The consistency of the simulation and measurements verifies the correctness of the proposed slot antenna design [40]. A little misalignment with broadside can be observed on both polarizations which is not significant and harmful for 5G front end applications.

In order to discern the sufficient performance of the proposed antenna, its characteristics are compared with the presented antennas in earlier works and listed in Table 1. It can be observed that the proposed dual CP antenna utilizing a crescent-shaped slot resonator has a compact size and yields a wider impedance and AR bandwidths than the previously reported dual CP antennas. Also,

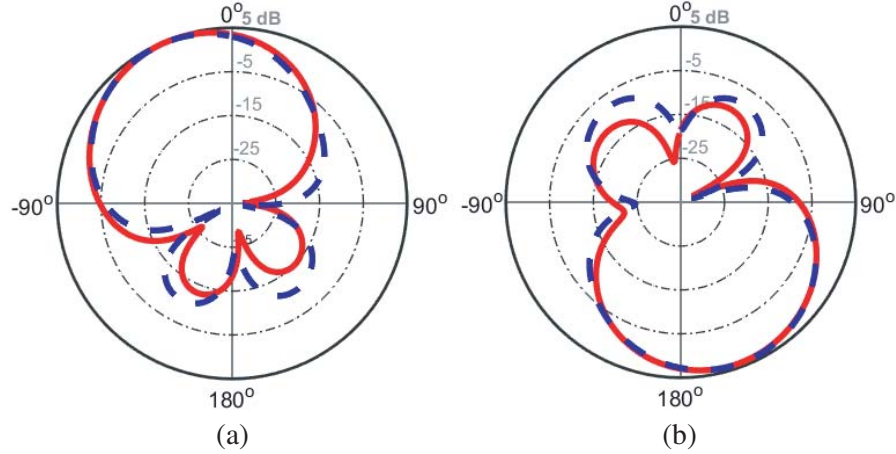


Figure 9. Measured (dashed-line) and simulated (solid-line). (a) RHCP and (b) LHCP radiation patterns at 3.5 GHz for Port 1.

Table 1. Comparison of the design characteristics with the referenced dual CP antennas.

Reference	Impedance Bandwidth	AR Bandwidth	Gain (dBi)	Size (mm ²)	Switching Elements
[17]	12%	24%	6	252 × 252	No
[18]	7%	13%	8.8	140 × 80	Yes
[19]	11%	1.2%	5	135 × 135	No
[20]	18%	12%	9	130 × 130	No
[21]	10%	4.8%	4.9	100 × 100	No
[22]	10%	10%	3.8	100 × 100	Yes
[23]	1.3%	1.3%	9	85 × 80	No
[24]	24%	19%	7.4	76 × 76	No
[25]	12.5%	4.3%	3	85 × 70	No
[26]	6.1%	6.1%	8.7	70 × 70	Yes
[27]	6.7%	1.02%	5.8	60 × 60	Yes
[28]	39.3%	28%		60 × 43	No
[29]	4.3%	1.18%	2.55	43.5 × 31	Yes
This Work	33%	33%	5	48 × 48	No

the antenna provides a quite good gain level of 5 dBi at the center frequency. Furthermore, unlike some of the antennas, the proposed antenna does not require the use of switching elements such as PIN diodes to generate the dual CP function.

4. CONCLUSION

The design and performance of a dual CP slot antenna are investigated in this manuscript. The configuration of the antenna contains a modified crescent-shaped slot radiator in the ground plane, which is fed by a pair of conventional 50-ohm microstrip lines. A wideband dual CP function is effectively excited for the application of the 5G front-end system. The antenna impedance bandwidth, as well as the 3 dB AR characteristics, spans from 3 GHz to 4.2 GHz. In addition, the antenna exhibits high efficiency, gain level, and isolation properties.

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