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LETTER

An Improved Design and Implementation of a Broadband and Wide Axial Ratio Beamwidth Circularly Polarized parallel plate Antenna

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Abstract This paper presents an improved design and implementation of broadband circularly polarized (CP) antenna that features a broad bandwidth and wide axial ratio (AR) beamwidth. First, the relationship between the three parallel plates (rectangular, semicircular, and semieliptical) and θ is analyzed. The semieliptical parallel plates (PP) used to obtain a wider 3dB AR-beamwidth (104°×110°×102°×118° at φ= 0°, 45°, 90°, 135°, respectively) compared with rectangular and semicircular PP. Secondly, orthogonal crosses with 43° inclination are used to generate orthogonal fields, and broadband characteristics can be obtained by adjusting the arm of orthogonal crosses. The semieliptical CP-PP antenna prototype was verified by ANSYS HFSS simulation. According to the measurement results, the -10 dB return loss is about 20% (24.3-29.7GHz). A gain of 9.22 dBi at 27 GHz and a 3 dB AR-beamwidth of 106°×105° at φ=0° and φ=90° are obtained. The designed semieliptical CP-PP antenna can be more beneficial to 5G millimeter wave applications.

Keywords: Circular polarization, Parallel Plate Antenna, Broadband

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

The millimeter wave has the characteristics of broadband and is used for wireless communication, radar, ADAS and imaging[1][2][3][4]. The antenna is an essential device for circuit and free space information exchange. The CP antennas have made much progress in research and development and are widely known as the critical technologies of various wireless systems, including mobile communications, global navigation satellite systems (GNSS), wireless local area networks (WLAN) and other applications. It is because CP antennas have essential advantages over linear polarized antennas[5][6][7][8][9][10].

Basic CP antennas include microstrip patch antennas (MPA), helical antennas, dielectric resonant antennas (DRA), and horn antennas[11]. The reported CP- MPAs are mainly used in lower frequency bands[12][13][14][15][16][17][18]. However, few CP-MPAs are reported for mmWave, and the 3dB-AR beamwidth is not enough for wireless communication[19][20]. For wireless communication applications, CP-DRAs are similar to CP-MPAs applications, and the industry mainly focuses on lower frequencies [21][22][23][24]. Reference [23] reported a wideband CP antenna with a stair-shaped dielectric resonator (DR) and an open-ended slot ground, which obtained 3 dB AR-bandwidths of 46.0% (4.15-6.63GHz) and 92% radiation efficiency. Reference [24] uses four sequentially rotated metal plates to use a single-fed broadband CP dielectric resonator antenna (DRA) and achieves a -10dB impedance bandwidth of 46.9% and an average gain within the passband of 4.7 dBi. However, the radiation efficiency of the MPA and DRA can be significantly reduced at mmWave frequencies due to the surface-wave, metallic, and dielectric losses.

The CP horn antenna not only has a radiation efficiency of more than 95% but also has a moderate size to meet the manufacturing tolerance in the millimeter wave frequency [25][26][27][28][29][30][31][32][33]. However, the 3dB AR-beamwidth of the CP horn antenna is relatively small, so the application of the CP horn antenna is severely restricted by the range of the 3dB AR-beamwidth[25][26][33].

This paper analyses the radiation characteristics of three PP (rectangular, semicircular, and semieliptical). The semieliptical PP used to obtain a wider 3dB AR-beamwidth (104°×110°×102°×118° at φ= 0°, 45°, 90°, 135°, respectively) compared with rectangular and semicircular PP. Additionally, the 3dB AR-beamwidth of the semieliptical PP is balanced and symmetrical at φ= 0°, 45°, 90°, 135°, respectively. The orthogonal crosses with 43° inclined to generate orthogonal fields, and broadband characteristics can be obtained by adjusting the arm of the crosses.
2. Antenna Design

2.1 Antenna Geometry

Fig. 1(a) shows the HFSS 3D model in Cartesian coordinates. With reference to the figure, it consists of two parts, namely the polarizer and feeding structure (WR34). For the polarizer part, two vertical rectangular PP separated by a distance of \( d \) are connected at the bottom by a horizontal ground plane with a thickness of \( w_0 \). Each vertical plate has a length of \( a \), height of \( h_1 \). Fig. 1(b) is a side view of a semielliptical CP-PP. With reference to the figure, the vertical plates are chamfered with a radius \( r_1 \), and the height of the feeding waveguide is \( h_2 \). The feeding probe has an offset of \( h_3 \) from the opened-end of the waveguide. To generate the CP orthogonal field (TEM and TE modes), an orthogonal cross with a 43° inclination was placed at the opened-end ground of the waveguide as shown in Fig. 1(c). The lengths of the orthogonal cross are \( L_1 \) and \( L_2 \), and the size of the WR34 is 8.64mm × 4.32mm. The parameters of the semielliptical CP-PP antenna are labelled in Table 1.

![Fig.1 Antenna Geometry. (a) 3D model, (b) Side view, (c) Top view.](image)

### Table 1 Semielliptical CP-PP Antenna Parameters

| Parameters | Value (mm) |
|------------|------------|
| \( a \)    | 32         |
| \( h_1 \)  | 17.6       |
| \( r_1 \)  | 13.5       |
| \( h_2 \)  | 12.8       |
| \( h_3 \)  | 9.25       |
| \( d \)    | 10         |
| \( L_1 \)  | 6.9        |
| \( L_2 \)  | 3          |

2.2 Broad 3dB AR-beamwidth

Due to the difference of \( r_1 \), three PP polarizers (rectangular, semicircular, semielliptical) can be produced, and \( r_1 = 0 \)mm, 16mm, 13.5mm represent rectangular, semicircular and semieliptical polarizers respectively. Fig. 2(a) depicts the 3dB AR-beamwidth of the rectangular (\( r_1 = 0 \)mm) polarizers versus \( \theta \) at \( \phi = 0°, 45°, 90°, 135° \), and yielding a good 3dB AR-beamwidth characteristics at \( \phi = 0 \), but around \( \theta = \pm 22° \) and \( \pm 24° \) for \( \phi = 45, 90, 135 \) has local maximum. The rectangular PP polarizer (\( r_1 = 0 \)mm) produces a 3dB AR-beamwidth of 90° × 100° × 28° × 28° at \( \phi = 0°, 45°, 90°, 135° \). Fig. 2(b) shows the 3dB AR-beamwidth (60° × 52° × 92° × 102° at \( \phi = 0°, 45°, 90°, 135° \)) of a semicircular polarizer (\( r_1 = 16 \)mm), which extends the 3dB AR-beamwidth for \( \phi = 90° \) and \( 135° \) compared with rectangular PP polarizer (\( r_1 = 0 \)mm).

As \( r_1 \) increases from 0 to 16mm (rectangular to semicircular polarizer), the 3dB AR-beamwidth for \( \phi = 0° \) and \( \phi = 45° \) shrinks by 33.3% and 48%, respectively. However, the 3dB AR-beamwidth of \( \phi = 90° \) and \( \phi = 135° \) is expanded by 228% and 264%, respectively. Therefore, a suitable \( r_1 \) is crucial for the 3dB AR-beamwidth. As shown in Fig. 2(c), the 3dB AR-beamwidth (104° × 110° × 102° × 118° at \( \phi = 0°, 45°, 90°, 135° \)) of the semielliptical polarizer (\( r_1 = 13.5 \)mm) obtains the advantages of the rectangular PP (\( \phi = 0° \) and \( 45° \)) and semicircular polarizer (\( \phi = 90° \) and \( 135° \)), which
outperforms the semicircular \((r_1=16\text{mm})\) and rectangular PP \((r_1=0\text{mm})\). Additionally, the 3dB AR-beamwidth of the semielliptical polarizer is balanced and symmetrical at \(\varphi=0^\circ, 45^\circ, 90^\circ, 135^\circ\), respectively.

![Fig. 2](image)

**Fig. 2** 3dB AR-beamwidth vs. \(\theta\). (a) Rectangular CP-PP polarizer, (b) Semicircular CP-PP polarizer, (c) Semielliptical CP-PP polarizer.

The semielliptical polarizer also has broad 3dB AR-beamwidth for different frequencies, as shown in Fig. 3. The 3dB AR-beamwidth has local maximum at 25GHz for \(\theta=\pm 24^\circ\) and \(\varphi=90^\circ\), since the AR of 1.56dB is obtained in the boresight \((\theta=0^\circ\text{ and } \varphi=0^\circ)\), the local maximum will be degraded by 3dB AR-beamwidth. In addition, the 3dB AR-beamwidth has a local minimum at 28GHz for \(\theta=\pm 18^\circ\) and \(\varphi=90^\circ\), although the AR of 1.08dB in the boresight \((\theta=0^\circ\text{ and } \varphi=0^\circ)\) is obtained, it still maintains small value within \(\theta=\pm 45^\circ\). Finally, the 3dB AR-beamwidths of \(104^\circ \times 104^\circ\) and \(102^\circ \times 100^\circ\) at \(\varphi=0^\circ\) and \(90^\circ\) were obtained at 25 and 28 GHz, respectively. It is worth mentioning that 25GHz-29GHz is the 5G communication frequency.

![Fig. 3](image)

**Fig. 3** 3dB AR-beamwidth vs. \(\theta\) at 25GHz and 28GHz.

2.3 Wideband Semielliptical CP-PP antenna

Fig. 4(a) depicts the real part of the input impedance with \(L_2\) of the inclined orthogonal cross. The real part of the impedance is around 50 \(\Omega\) at \(L_2=3\text{mm}\). Fig. 4(b) shows the imaginary part of the input impedance with \(L_2\). Reasonable adjustment of the length of \(L_2\) keeps the imaginary part close to 0 \(\Omega\) in the broadband.

![Fig. 4](image)

**Fig. 4** (a) The impedance Real Part and (b) imaginary Part vs Frequency.
3. Fabrication and measurements

In order to verify the semielliptical CP-PP Antenna, a prototype was manufactured. The size of the fabricated antenna is 22×32×17.3 mm$^3$, and the antenna is made of aluminums. Fig. 5 shows the picture of the prototype. Both measured and simulated S11 of the proposed antenna are presented in Fig. 6. The Agilent N5225B vector network analyzer was used in the measurement. The simulation of S11<-10 dB is 18.5% from 24.5 to 29.5 GHz, and the measurement result from 24.3 to 29.7 GHz is 20%.

![Fabricated antenna photograph.](image)

**Fig. 5** Fabricated antenna photograph.

![Measured and simulated reflection coefficients of the semielliptical CP-PP Antenna.](image)

**Fig. 6** Measured and simulated reflection coefficients of the semielliptical CP-PP Antenna. The parameters are the same as table 1.

![Sim. Meas.](image)

**Fig. 7** Measured and simulated realized antenna gains of the semielliptical CP-PP Antenna.

![Sim. Meas.](image)

**Fig. 8** Measured and simulated AR of the semielliptical CP-PP Antenna.

Fig. 7 shows the measured and simulated realized boresight gains ($\theta = 0^\circ$ and $\phi = 0^\circ$) that have included impedance mismatch and obtained a gain of 9.22dBi at 27GHz. Fig. 8 shows the measured and simulated AR in the boresight ($\theta = 0^\circ$). Regarding the figure, the bandwidths entirely cover the -10dB impedance bandwidth, making the impedance bandwidth entirely usable. More importantly, a minimal AR of 0.28dB is obtained at 27GHz.

![Normalized Pattern (dB)](image)

**Fig. 9** Measured and simulated normalized radiation patterns in XOZ and YOZ at 25 GHz, 27GHz and 29GHz, respectively, and the co-polarization is RHCP. The half-power beamwidth (HPBW) is $74^\circ \times 99^\circ$, $66^\circ \times 74^\circ$, $65^\circ \times 66^\circ$ at 25 GHz, 27GHz and 29GHz, respectively. Additionally, the radiation patterns are stable and symmetrical in both XOZ and YOZ.
crosses can achieve broadband matching. According to the measurement results, the -10 dB return loss is about 20% (24.3-29.7GHz). A gain of 9.22 dBi at 27 GHz and a 3 dB AR-beamwidth of 106°×105° are obtained. Compared with the previously reported waveguide CP antenna, the proposed semieliptical CP-PP antenna is more favorable for 5G mmWave communication.

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4. Conclusion

This paper analyses the radiation characteristics of a semieliptical CP-PP antenna. The semieliptical PP obtains the advantages of the rectangular and semicircular PP at φ=0°, φ=45° and φ=90°, φ=135°. By placing 43° inclined orthogonal crosses at the waveguide opened-end to generate TEM and TE orthogonal modes, a reasonable adjustment of the arm of the orthogonal

Table 2 Performance comparison.

| Ref.  | BW (%) | Peak Gain(dBi) | Pol. structure |
|-------|--------|----------------|----------------|
| [25]  | 12.5   | 7.5            | PP polarizer   |
| [26]  | 37.8   | 9.8            | Circular waveguide |
| [27]  | 94.5   | 18.3           | <30°×30°        | AETS** |
| [32]  | 37     | 9              | 60°×60°        | Rotated tapering rod |
| [33]  | 7.4    | 14.2           | 40°×30°*       | Metasurface Polarizer |
| This work | 20     | 9.22           | 106°×105°      | Semieliptical PP polarizer |

* Measured Co-polar 3dB AR-beamwidth (θ3dB). Estimated values are used for those references which have no exact beamwidths.
** Waveguide loaded with antipodal exponential tapered slots(AETS).

Fig. 10 Measurement and simulation: AR vs. θ at 27 GHz.
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