Synthesis and Measurement of a Circular-Polarized Deflection OAM Vortex Beam With Sidelobe Suppression Array

JUN LIANG¹,², ZHONGLIANG JING², QIANG FENG³, YUSHAN ZHENG³, AND LONG LI³, (Senior Member, IEEE)
¹School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, China
²China Academy of Launch Vehicle Technology, Beijing 100076, China
³Key Laboratory of High Speed Circuit Design and EMC, Ministry of Education, School of Electronic Engineering, Xidian University, Xi’an 710071, China
Corresponding authors: Zhongliang Jing (zljing@sjtu.edu.cn) and Long Li (lilong@mail.xidian.edu.cn)

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ABSTRACT In this paper, a chamfer distribution antenna array is designed to generate a deflecting circular-polarized vortex beam carrying orbital angular momentum (OAM) mode. When the vortex beam is designed with a deflection angle, the sidelobe of the vortex beam will deteriorate. In order to solve this problem, an optimized array design is presented in this paper. Inspired by the Chebyshev distribution array synthesis method, the antenna elements in the four corners of the antenna array are cut out to realize the chamfer distribution array. Therefore, the sidelobe level of the deflected vortex beam can be effectively suppressed. Moreover, a simplified feeding network is designed to reduce the feeding network complexity by using circularly polarized structural center antenna element. The designed antenna array is simulated, fabricated, and measured at center frequency of 4.25 GHz in C-band. The far-field radiation pattern of the deflected vortex beam and the near E-field OAM vortex beam distribution are simulated and measured to verify the effectiveness of the proposed design method for sidelobe suppression array.

INDEX TERMS Chebyshev array synthesis, chamfer antenna array, orbital angular momentum (OAM), sidelobe suppression, circular-polarized vortex beam.

I. INTRODUCTION
Orbital angular momentum (OAM) brings more opportunities in communication and radar detection fields [1]–[5]. The electromagnetic waves carrying the OAM modes are named vortex electromagnetic wave or electromagnetic vortex beam [2]. OAM vortex wave was first introduced to radio domain through the uniform circular array (UCA) antenna [6] and studied in detail later [7]. Many other types antennas to generate OAM vortex beams can be summarized approximately into four types [8] including single microstrip antenna, traveling wave antenna, array antenna, and metasurface antenna. Although the digital coding metasurface antenna and reconfigurable metasurface [9], [10] can be flexibly used to generate the vortex beam, they still have some restrictions for the vortex beam radiation pattern control.

The radiation pattern control of the vortex beam plays an important role in vortex beam applications in wireless communication and radar imaging [11]–[16], especially about the vortex beam consistency collimation, vortex beam steering, and vortex beam sidelobe control [11]–[14].

It is well known that for conventional pencil beams, when a beam scans away from the normal direction, its beam sidelobe will become deteriorated [17]. This problem is more serious for the deflected OAM vortex beam [7], [11], because of the hollow cone beam in the middle. Although some optimization array design methods were presented for UCA antenna, however, they were mainly used for the vortex beam without the beam deflection [13]. When the OAM vortex beam is deflected, its sidelobe level will evidently increase [12], [14], [18]. In [12], the deflected vortex beam was considered. Although the specific vortex beam sidelobe values were not given, it can be found from 3D radiation pattern results that the deflected vortex beam sidelobe gets...
worse. In [14], the deflected vortex beams was simulated with sidelobe of nearly $-5\,\text{dB}$ when the deflection angle of the OAM vortex beam is $20^\circ$. And in [18], the deflected vortex beam with sidelobe level approximately higher than $-5\,\text{dB}$ was reported. It seems that heretofore there are a few attentions to this problem of deflected vortex beam sidelobe level suppression. In this paper, based on the array antenna design theory and phased array technology [19], a planar microstrip antenna array is designed at $4.25\,\text{GHz}$. Chebyshev amplitude distribution array synthesis method is used for the initial array design. Considering the design simplicity and vortex beam symmetry property, the antenna elements in the four corners of the antenna array are cut out to realize a chamfer distribution array [20]. And a circularly polarized microstrip antenna element with structural center feeding is designed, i.e., whose feeding point is at the center of the antenna structure. This property can be used to simplify the feeding network design. By center rotating the designed element with specific angle, the corresponding excitation phase shift of the antenna array element can be obtained [21]. For further simplifying the feeding network design, two-level cascaded feeding network design technique are adopted.

The paper is organized as follows. In section II, the design process of the proposed antenna array is described. Then the whole electromagnetic simulation model including the integrated feeding network is established. The corresponding simulation results of far field radiation pattern and near field vortex beam field distribution are given. In section III, the designed antenna array prototype is fabricated and measured. The corresponding far-field and near-field measurements are performed. The far field radiation pattern and the near field vortex beam field distribution are analyzed and discussed. Section IV is the conclusion.

II. ANTENNA ARRAY DESIGN AND SIMULATION

In this section, the circular polarization microstrip antenna with structural center rotational symmetry is firstly designed as the array element. Then three types antenna array for generating deflected OAM vortex beams are designed and analyzed, respectively, i.e., the conventional antenna array with same amplitude distribution, the Chebyshev amplitude distribution antenna array, and the chamfer antenna array with four corners being cut out. The radiation patterns of three types antenna arrays are simulated and analyzed. Then the complete array models with feeding network are designed. The far field radiation pattern and near field vortex beam electric field distribution of the deflected vortex beam are analyzed as follows.

A. ANTENNA ARRAY DESIGN

The initial geometry of the designed antenna array for generating the deflected OAM vortex beam is shown in Figure 1(a). The center working frequency is $4.25\,\text{GHz}$, and the antenna array has $6 \times 6$ elements. According to the antenna array design theory and the vortex beam generation method [22], [23], the deflected OAM vortex beam can be realized by suitably setting the excitation of each array element. The specific excitation phase-shift of each antenna element can be calculated by the following expression [22],

$$\phi_{mn} = -\frac{2\pi}{\lambda} \vec{r}_{mn} \cdot \hat{u}_k + \Phi_k,$$

where $\phi_{mn}$ is the excitation phase of the $mn$th element, $\vec{r}_{mn} = (x_{mn}, y_{mn})$ is the position of the $mn$th element, $\hat{u}_k = (\cos \theta_k, \sin \theta_k)$ is the vortex beam deflection direction, $\Phi_k$ is the generated
OAM mode, and $\Phi_{k}$ is the azimuthal angle in the rotated coordinate system. The designed vortex beam deflection direction here is $\theta_{k} = 30^\circ$, $\phi_{k} = 180^\circ$ as an example.

In this paper, we design a right-handed circular polarization (RHCP) microstrip antenna element with center feeding structure [24], [25], as shown in Figure 1(b). Circular polarization has advantages in some particular application scenarios such as in satellite communications. Because it can avoid the impact of the electromagnetic wave polarization property as the attitude of the antenna platform changes. On the other hand, in order to simplify the feeding network, a circular polarization center feeding antenna geometry is utilized as the array element. By rotating a certain angle with the center feeding point as the origin, the corresponding space phase shift can be realized for required phase shift. The microstrip antenna element is simulated and optimized through the electromagnetic simulation software HFSS. The corresponding geometry structure parameters are listed in Table 1. The substrate of the microstrip antenna is F4B with $\varepsilon_r = 2.65$. The simulation and measurement results verify that the designed microstrip antenna element works well at the center frequency of 4.25 GHz.

Three types antenna array are designed and analyzed, in order to explain the sidelobe suppression technique for OAM vortex beam. These three types array schematic diagram can be viewed from Figure 1(a). The first-type array is a conventional antenna array with same amplitude distribution. The second-type array is a Chebyshev amplitude distribution array, and the normalized excitation amplitude distributions of each element are listed in Table 2. The third-type array is a chamfer array that is an improved design based on the second array but with four corners being cut out. As shown in Figure 1, the dash lines show that these corner elements are cut out to be a chamfer array.

The 3D radiation patterns of three different arrays are simulated and shown in Figure 2. It can be found that the deflected vortex beams are effectively generated. The OAM mode is 1.

We pay our attention to the sidelobe level of three kinds of arrays. The 2D radiation patterns in yoz plane of three kinds of arrays are compared and shown in Figure 3. It can be seen that the sidelobe level of the Chebyshev amplitude distribution array is obviously better than that of the conventional equal amplitude distribution array. The Chebyshev array obviously decreases the first sidelobe to nearly $-20$ dB.
Furthermore, the chamfer array decreases not only the first sidelobe but also the second sidelobe. The chamfer array can suppress the whole sidelobes under $-15$ dB. It should be noted that the performance of the chamfer array is best. This is because that the original Chebyshev array is a square aperture array, but by cutting out the four elements in the corner of the array, the antenna array itself becomes closer to a circular aperture array. Compared with the square aperture circular array, a circular aperture array can generate more symmetrical vortex beam and higher OAM mode purity [26]. It can be seen that when the radiation elements in the four corners of the square array are removed, the chamfer array is more beneficial to the symmetrical cone vortex beam generation and has good sidelobe performance.

B. SIMULATION RESULTS AND ANALYSIS

In this subsection, the whole electromagnetic simulation model including the first-layer feeding network is designed, as shown in Figure 4. The second-level feeding network is not included here, which is realized through a one-to-four ways power divider module. The first-level feeding network and the second-level feeding network are connected by same radio frequency (RF) cables.

The corresponding far-field 3D radiation pattern and 2D radiation pattern are given in Figure 5(a) and (b) respectively. From Figure 5(a), we can see that the typical vortex beam radiation pattern with OAM mode $l = 1$ is generated, which is consistent with the previous simulation results shown in Figure 2(c). From Figure 5(b), we can see that the deflected vortex beam at $\theta = -30^\circ$ is generated and that the sidelobe of the deflected vortex beam is indeed be suppressed under $-15$ dB by using the chamfer array design method. The whole model simulation results are consistent with the previous array design analysis. The corresponding simulated cross-polarization (LHCP) results is also given in Figure 5(b) which is overall less than $-20$ dB. The simulated co-polarization (RHCP) vortex beam axial ratio (AR) curve versus the angle theta is shown in Figure 5(c), which works well in the main lobe area of the generated vortex beam.

The observation plane of the near-field vortex beam is set and shown in Figure 1. The corresponding near-field vortex beam E-field distributions including the amplitude and phase distributions in the observation plane are shown in Figure 6(a) and (b), respectively. From its symmetrical vortex electric field amplitude distribution and spiral vortex electric field
III. PROTOTYPING AND MEASUREMENT

In this section, the fabricated chamfer array prototype is exhibited and the corresponding far-field vortex beam radiation pattern and near-field vortex field distributions are measured. The fabricated prototype of the designed antenna array is shown in Figure 7. The simulated and measured S parameters of four input ports in the first-level feeding network are shown in Figure 8.

Note that the differences between the measurement and the simulation S parameters results in Figure 8, it could mainly be caused by fabrication processing errors and substrate material errors. The designed array in this paper was processed by lamination of multilayer PCB boards. Constrained by machining accuracy, some slight fabrication errors such as...
FIGURE 9. Far field measurement and near field measurement anechoic chamber environment. (a) The far field measurement environment, (b) the near field measurement environment. The distance between the probe and the antenna array center is 700 mm. The scanning plane is 800 mm x 800 mm with sample period of 16 mm leading to 51 x 51 sampling grids. For measurement convenience, the array antenna prototype is tilted with 30° to align with the probe.

FIGURE 10. (a) Measured results of far field 2D radiation patterns in yoz plane comparing with the simulated results. The RHCP (co-polarization) wave and the LHCP (cross-polarization) wave are given. (b) AR results of the simulated and the measured RHCP vortex beam versus the angle θ.

as PCB layer misalignment may worsen the S parameters results. The substrate of the PCB boards is F4B whose practical permittivity has a little difference from simulation design value, which results in some frequency shifts between the simulation and measurement. Although the measured results are a little difference from the simulated results, the fabricated antenna array can still work well in the operational frequency band.

The far-field measurement environment and near-field measurement environment are shown in Figure 9(a) and (b), respectively. In Figure 10(a), it is the measured far-field 2D radiation pattern in yoz plane. The measurement results and the simulation results are compared together. The co-polarization (RHCP) and the cross-polarization (LHCP) are given. By comparing the measurement results with the simulation results, we can find that the measurement results are in good agreement with simulation results. The measured co-polarization second sidelobe comes to nearly −13 dB. The corresponding AR results between the simulation and the measurement are compared together in Figure 10(b), which are consistent in the main lobe area of the generated vortex beam.

Table 3 gives a comparison between the previous related working about the deflected vortex beam sidelobe problem. By comparing the data listed in Table 3, it is obvious that the vortex beam sidelobe suppression design proposed in this paper is better than the sidelobe level of the related literatures, and the effectiveness of the proposed chamfer array design can be demonstrated.

Additionally, the bandwidth properties of the designed antenna array are analyzed. The corresponding results are shown in Figure 11. It can be found that within the working
TABLE 3: Comparison between the proposed antenna and other similar OAM vortex beam deflection array antenna.

| References | Array form | OAM mode | Deflected angle (°) | Sidelobe level (dB) |
|------------|------------|----------|---------------------|---------------------|
| [12]       | UCA        | 1        | 30                  | Not given exactly   |
|            |            | 2        | 30                  | Not given exactly   |
| [14]       | UCA        | 1        | 10                  | Around -4.5         |
|            |            | 3        | 20                  | Around -3.5         |
| [18]       | UCA        | 1        | 8                   | Around -5.0         |
| This work  | Planar chamfer array | 1   | 30                  | -13.0               |

FIGURE 11. (a) Simulated and measured AR of the antenna array, (b) the main polarization (RHCP) radiation pattern, and (c) AR distributions at three different working frequencies of 4.24 GHz, 4.25 GHz, 4.26 GHz, respectively.

FIGURE 12. Measured near E-field distribution of the vortex beam in the observation plane at center frequency 4.25 GHz. (a) amplitude distribution, (b) phase distribution, and (c) axial ratio distribution in the observation plane, the areas with blue color means that the value of the AR is less than 3 dB.

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band, the vortex beam radiation pattern properties and AR properties are well.

Finally, the planar near-field scanning technology is adopted to measure the vortex beam near field electric field distributions. The corresponding vortex beam phase distribution, amplitude distribution, and axial ratio distribution in the near-field measurement scanning plane are shown in Figure 12, respectively. It is obvious that the deflected circular polarization vortex beam is generated. According to the AR measurement results in Figure 12(c), it can be concluded that the circular polarization property of the generated OAM vortex beam is kept well. From the vortex beam far-field radiation pattern measurement results shown in Figure 10, Figure 11 and the near field electric field distributions in Figure 12, we can see that the sidelobe of the deflected vortex beam is effectively suppressed. It is obvious that the proposed synthesis method for circular-polarization OAM vortex beam is valid and the designed antenna array can realize the deflected vortex beam with low sidelobe.

IV. CONCLUSION

Based on the phased array technology, the chamfer antenna array is designed for generating the deflected circular polarized OAM vortex beam with low sidelobe in this paper. In order to suppress the sidelobe level, the antenna array synthesis method based on the Chebyshev amplitude distribution was adopted, and an improved chamfer array design was
presented. Besides, a circular polarization structural center feeding antenna element is designed to simplify the feeding network. By rotating the specific angle of the array element, the array element relative phase-shift can be achieved. This design approach is also useful and insightful for simplifying the related feeding network design of antenna array. Through the full-wave electromagnetic simulation and prototype measurement, the proposed design was well validated. This design for deflected OAM vortex beam with low sidelobe could bring some advantages in both the vortex beam related wireless communication and radar detection applications.

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JUN LIANG was born in Hunan, China, in 1980. He received the M.S. degree from Beijing University, Beijing, China, in 2004. He is currently pursuing the Ph.D. degree in control science and control engineering with Shanghai Jiao Tong University. He is also with the China Academy of Launch Vehicle Technology. His current research interests include signal processing and communication.

ZHONGLIANG JING was born in Sichuan, China, in 1961. He received the B.S., M.S., and Ph.D. degrees in electronics and information technology from Northwestern Polytechnical University, Xi’an, China, in 1983, 1988, and 1994, respectively. He is currently a Full Professor with the School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, China. His research interests include signal processing, information fusion, and avionics integration.
Qiang Feng was born in Shanxi, China, in 1992. He received the B.E. degree in electromagnetic wave propagation and antenna from Xidian University, Xi’an, China, in 2015, where he is currently pursuing the Ph.D. degree in electromagnetic field and microwave technology with the School of Electronic Engineering. His current research interests include metasurface, antenna array design, and the application of radio orbital angular momentum vortex wave.

Yushan Zheng was born in Shanxi, China, in 1994. She received the B.S. degree from the School of Electronic Information Engineering Technology, Xidian University, Xi’an, China, in 2017, where she is currently pursuing the M.S. degree in electromagnetic field and microwave technology with the School of Electronic Engineering. Her research interests include metasurface, antenna array synthesis method, and orbital angular momentum vortex wave and its applications.

Long Li (Senior Member, IEEE) received the B.E. and Ph.D. degrees in electromagnetic fields and microwave technology from Xidian University, Xi’an, China, in 1998 and 2005, respectively. He was a Senior Research Associate with the Wireless Communications Research Center, City University of Hong Kong, in 2006. He was with Tohoku University, Sendai, Japan, as a JSPS Fellow, from 2006 to 2008. He was a Senior Visiting Scholar with Pennsylvania State University, USA, in 2014. He is currently a Professor with the School of Electronic Engineering, the Director of the Key Laboratory of High-Speed Circuit Design and EMC, Ministry of Education, China, and the Dean of the Hai-Tang No. 9 Academy, Xidian University. He has authored or coauthored over 100 articles in journals. He holds more than 20 patents. His research interests include metamaterials/metasurfaces, antennas and microwave devices, field-circuit collaborative design and EMC, wireless power transfer and harvesting technology, and orbital angular momentum vortex waves.

Dr. Li is a Senior Member of CIE. He is the Vice-President of MTT-Chapter with the IEEE Xi’an Section. He received the Japan Society for Promotion of Science (JSPS) Postdoctoral Fellowship, the Nomination Award of the National Excellent Doctoral Dissertation of China, in 2007, the Best Paper Award with the International Symposium on Antennas and Propagation, in 2008, the Program for New Century Excellent Talents with the University of the Ministry of Education, China, in 2010, the First Prize of Awards for the Scientific Research Results offered by the Shaanxi Provincial Department of Education, China, in 2013, the IEEE APS Raj Mittra Travel Grant Senior Researcher Award, in 2015, the Shaanxi Young Science and Technology Award, in 2016, and the Outstanding Young Foundation of Shaanxi Province of China. He is a TPC Co-Chair of APCAP2017 and the General Co-Chair of AWPT2019. He serves as an Associate Editor for ACES Journal and the Guest Editor for the IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology Special Issue.

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