A Dual-band uniform circular array for Generating vortex electromagnetic waves

Cheng Yang¹,a, Wang Haitao²,b, Fan Qin³,c*, Yi Liu⁴,d, Cheng Tao Wan⁵,e
¹,²China Coal Xi’an Design Engineering Co., Ltd., Xi’an, China
³,⁴,⁵State Key Laboratory of Integrated Services Networks (ISN), Xidian University, Xi’an, China
a4658886@qq.com; bhtwang1980@126.com; c* fqin@xidian.edu.cn
⁴yliu@xidian.edu.cn; ectwan@stu.xidian.edu.cn

Abstract—A novel dual-band uniform circular array (UCA) is presented to generate vortex electromagnetic waves. The proposed antenna is designed to operate in C- and X-bands with center frequency of 5.8 GHz and 10 GHz, respectively. To construct a shared-aperture structure, two UCAs operating in different frequencies are combined in a common aperture with different radius. Each UCA is composed of 8 antenna elements in the proposed design. The specific phase shifts for generating vortex waves are obtained by carefully designing the feed networks at the two working frequencies. One prototype is simulated, fabricated and measured to verify the concept. Good agreement between simulated results and measured results are obtained. +1 mode vortex beams are successfully penetrated with the gain of 12.3 dBi in both C- and X-bands with good vortex phase fronts.

1. INTRODUCTION
With the rapid development of 5G, beyond 5G/6G and internet of things (IOT) technologies, wireless communication with high-speed, high-capacity and high spectral efficiency has experienced many challenges. In theory, vortex electromagnetic waves or orbital angular momentum (OAM) can provide infinite number of orthogonal modes for information transmission, leading to dramatic increase of channel capacity. Therefore, vortex waves are considered as a promising candidate to support large capacity transmission without occupying additional spectrum resource in future wireless communications.

Antenna systems play a significant important role in communication systems based on vortex waves, which can generate single- or multi-mode vortex beam. There are many methods having been investigated to achieve vortex beam. It is a typical method to use planar or helical phase plates and helical parabolic antennas to obtain vortex beam [5-7]. However, Single-mode vortex beam can be generated by using only helical phase plates or helical parabola, which is difficult to meet the requirements of multi-mode vortex beam in some special communication based on vortex waves. Because of its simple structure and easy phase control, the concept of antenna array is a promising approach to generate single- or multi-mode vortex beam. In [8], for example, employing a patch array with a circular phase shifter has generated a single-mode vortex beam. Furthermore, [9] has presented a dual-polarization dual-mode vortex beam with broadband phase-shift feed network. Other approaches have also been presented, such as the discrete lens [10], the period reflectarray [11], the travelling-wave
ring-slot structure [12], the elliptic patch antenna and substrate integrated waveguide (SIW) antenna based on orthogonal high order mode of the appropriate combination resonant antenna [13].

Implementing single- or multi-mode vortex beam having been considerably researched. However, few investigations of dual-band vortex beam antennas are found in previous literatures. The versatility of the communication system can be significantly improved by dual-band or multi-band operation. On the other hand, it can be foreseen that if the communication system based on vortex beam can operate at dual or multi-frequency, the communication capacity will be greatly increased. At the same time, it is necessary for different frequency operations to reduce the cost and weight of the RF frontend by sharing the same aperture in some special applications [14-15].

Our recent work on a dual-band shared aperture uniform circular array (UCA) producing vortex waves is presented in this paper. Two UCAs with a common aperture operating at C band and X band respectively are designed. The feeding network with proper phase shift for each antenna element is also introduced in detail. A prototype is then manufactured and measured to validate the design concept.

2. DUAL-BAND UCA FOR GENERATING VORTEX WAVES

Fig. 1 shows the whole configuration of the proposed dual-band UCA with common aperture. As can be seen, a X-band UCA (inner circle) and C-band UC (outer circle) are combined in the same aperture, where each UCA consists of 8 antenna elements. The distance between two adjacent elements in X-band and C-band is optimized as 19 mm and 40 mm, respectively. The radius of X-band UCA and C-band UCA is selected as 24.5 mm and 50 mm, respectively. The feeding network at each band is realized by employing 7 two-way power dividers. The required phase shift is achieved by designing different lengths of the microstrip lines.

![Figure 1. The configuration of dual-band antenna array with feeding network](image)

As shown in Fig. 2, both the X-band and C-band antenna elements are composed of a driven patch and a parasitic patch, which are etched in different substrate layers. To improve the impedance bandwidth, an air space between the driven patch and parasitic patch is employed in the proposed design. Rogers 4350B ($\varepsilon_r=3.48$) with the thickness of 0.508 mm is selected as the substrate. The antenna elements for each band are carefully simulated and the optimized parameters are listed in Table I.

| TABLE 1. OPTIMIZED PARAMETERS OF THE ANTENNA ELEMENT |
|---------------------------------------------|
| Unit(mm) | $a_1$ | $a_2$ | $L_1$ | $L_2$ | $h$ |
|---------|-------|-------|-------|-------|-----|
| C-band  | 17    | 13    | 5     | 9.6   | 4   |
| X-band  | 9     | 7.5   | 2.7   | 5     | 2.5 |
Figure 2. The details of the antenna element.

The antenna elements are designed and simulated using the full-wave commercial software HFSS. Fig. 3 shows the simulated S parameters, where a wideband impedance matching is achieved due to the employment of parasitic patch. Simulated results show that the X-band element can operate from 9.4 GHz to 11.5 GHz with 2.1 GHz bandwidth. Meanwhile, the C-band element can work from 5.4 GHz to 6.4 GHz with 1 GHz bandwidth. The normalized radiation patterns in E-plane and H-plane are plotted in Fig. 4, showing that the radiation patterns have peak gain at boresight direction.

Figure 3. The simulated S11 of the proposed antenna elements.

Figure 4. Simulated radiation patterns: (a) 5.8 GHz; (b) 10 GHz.

For a N-elements UCA generating vortex waves, the antenna element should be fed with same magnitude with incremental phase shift. The required phase is depended on the function of $2\pi l/N$, where the integer $l$ is the mode number of vortex waves.

All radiation elements are fed with same magnitude but incremental phase shift. The element phase shift can be calculated using the function of $2\pi l/N$, where the integer $l$ is the OAM mode number. The phase can be incremented by $2\pi l$ radians in one geometrical rotation around the array axis by applying the required phase distribution. In our design, due to 8 antenna elements existing in each UCA, $+45^\circ$ phase difference is necessary between two adjacent elements to generate $+1$ mode vortex waves.
Fig. 5(a) shows the phase distribution in a general 8-elements UCA producing +1 mode vortex waves. As can be seen, a clockwise phase rotation of 360° is observed with the phase step of 45°. While, in the proposed design, the 5-8 antenna elements are mounted as the mirror image of 1-4 antenna elements, which can lead to an additional 180° phase shift compared to the original placement of 5-8 antenna elements shown in Fig. 5(a). Thus, the arrangement of antenna elements in Fig. 5(b) has more compact structure and also can simplify the design of feeding network.

The feeding networks, shown in Fig. 1, consists of 7 two-way power dividers in each operating band. To obtain the required phase shift, the length difference of the microstrip between two adjacent elements is designed to be λ/8, where λ is the wavelength on the substrate at the operating frequency. As can be seen, the X-band feeding network is placed in the center and is surrounded by the C-band feeding network. Fig. 6 shows the simulated S-parameters of the proposed feeding network. Both of the C and X-bands feeding networks have good impedance matching. More importantly, the feeding network can provide uniform power magnitude to each antenna element. Around -9.5 dB transmission magnitude are obtained at X- and C-bands. Meanwhile, the phase difference at each element meet the required value with small error of 4°. Therefore, the designed feeding network can well satisfy the required specification to generate vortex waves in dual-band.

To verify the generation of vortex waves at C- and X-bands, the dual-band UCAs combined with the feeding networks are simulated. The phase fronts and electric field distributions at 5.8 GHz and 10 GHz are simulated and shown in Fig. 7. In the simulation, a plane (x-y plane) area with the dimension 560
mm × 560 mm is selected to plot the phase and electric field distributions, where the plane is mounted above the proposed array with the distance of 90 mm at 5.8 GHz and 50 mm at 10 GHz, respectively. It can be observed that a typical clockwise phase distribution is successfully generated by the proposed antenna array. Meanwhile, the electric field intensity shows a doughnut shape with null energy in the center.

![Figure 7](image)

**Figure 7.** The simulated near-field results of the proposed antenna array: (a) phase front at 5.8 GHz; (b) phase front at 10 GHz; (c) electric field distribution at 5.8 GHz; (d) electric field distribution at 10 GHz.

3. EXPERIMENTAL RESULTS

To verify the design, a prototype is fabricated and measured, as shown in the Fig. 8. Two SMA connectors are soldered to the antenna array as the feeding ports. Hexagonal nylon spacers are placed to support the substrate of the parasitic patches layer and create an air space between the driven patches and parasitic patches. They are also modeled and taken into consideration during the full-wave simulation in HFSS.

![Figure 8](image)

**Figure 8.** The antenna prototype: (a) the proposed antenna array; (b) antenna measurement in anechoic chamber.

The measured reflection coefficient at C- and X-bands is shown in Fig. 9, with the simulated results as comparison. Good impedance matching is obtained. For lower band, the proposed antenna array can
work from 5 GHz to 6.2 GHz with 24.5% impedance bandwidth. Meanwhile, for higher band, the proposed antenna array operates from 9 GHz to 11.5 GHz with 24.3% impedance bandwidth.

![Simulated and measured S parameters: (a) C band; (b) X band.](image1)

Radiation patterns are measured as well. To compare with the simulated radiation patterns, Fig. 10 plots the measured and simulated normalized radiation patterns in the both of E-plane and H-plane. As can be seen, the radiation patterns at both the 5.8 GHz and 10 GHz show a deep null along the boresight, which is the unique features of vortex waves. The measured gain reaches to around 12.3 dBi at 5.8 GHz and 10 GHz in our design. Due to small phase error and equipower provided by the feeding networks, the radiation patterns have good symmetry along boresight direction. Fig. 11 shows the E-field of the radiation patterns along the direction of boresight, where the divergence angle of the OAM beams is about 15° and 16° at 5.8 GHz and 10 GHz, respectively.

![The measured radiation patterns (a) E-plane at 5.8 GHz; (b) H-plane at 5.8 GHz; (c) E-plane at 10 GHz; (d) H-plane at 10 GHz.](image2)

![The E-field along the direction of boresight at 5.8 GHz and 10 GHz.](image3)
4. CONCLUSION
In this paper, an antenna array generating vortex waves at dual-band with a common aperture is proposed. Wideband antenna elements at C- and X-bands are carefully designed. To produce +1 mode vortex waves, two UCAs with same center operating at different frequencies are constructed. The feeding network with specific phase shift is designed and simulated. The phase fronts and E-field intensity of the proposed antenna array are studied as well. To verify the design, a prototype is fabricated and measured. The measured results agree well with the simulated ones, indicating that the vortex waves can be obtained by our designed antenna array. The proposed antenna can be a promising candidate in future wireless communication systems based on vortex waves.

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