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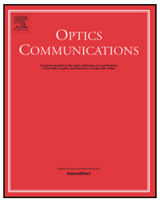

High-performance broadband vortex beam generator using reflective Pancharatnam–Berry metasurface

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ABSTRACT

Vortex beam generators, especially for broadband working ones, are essential in recent communication systems, since it is believed to be a key to improve the channel capacity efficiently. However, available vortex beam generators surfer from narrow bands, low efficiencies as well as complex configurations. In this paper, we propose an ultra-broadband reflective Pancharatnam–Berry metasurface to generate the vortex beams within 12-18 GHz. The metasurface consists of 20×20 single-layered rotated reflective elements A Ku-band Archimedes spiral antenna is placed at the focal point of the PB metasurface as a feed source which is used to emit a right-handed circularly polarized wave. Then, the metasurface is fabricated, simulated, and measured. Numerical and experimental results coincided well, indicating that the proposed vortex beam generator demonstrated several improvements, including wideband working (12-18 GHz), high efficiency (75.76%), and simple fabrication. Our findings open up a new avenue for the design of high-performance broadband vortex beam generators.

1. Introduction

In modern wireless communication systems, how to efficiently improve the channel capacity as well as enlarge the communication accuracy have been an urgent problem [1,2]. Nowadays, the orbital angular momentum (OAM) vortex beam has been applied in the area of optics due to its strictly orthogonal channel with different modes and excellent characteristics of transmission capability [3]. OAM vortex beams carry with a kind of azimuthal phase factor $\exp(il\varphi)$, with φ being the azimuthal angle and l being the topological charge which can be integer or noninteger [4]. Vortex beams can travel helically forward, and the intensity of the beam center is near zero [4–6]. With the unique electromagnetic properties and potential applications in optics, atomic physics and communications, vortex beams have attracted a lot of attention.

Since Allen. L discovered the OAM vortex beam, methods of generating vortex waves have been continuously proposed by scientists, for instance spiral phase plate [7,8], holographic diffraction gratings [9,10], spiral reflectors [11–13], and antenna arrays [14–16], etc. However, these vortex beam generators suffer from a lot of disadvantages, such as large size, complex structure, high cost, and narrow working band, which restrict their further development and applications. In 2011, Yu et al. [17] arranged the V-antennas into an array to generate the vortex beams by using the metasurface for the first time, which opened a new prelude to the development of vortex beams. Generally speaking, two methods are involved to implement the agile phases and thus engineer the desirable functionality: varying structure parameters and rotating the orientation of the meta-atoms. In former case, the desired phase profile was achieved under illumination of a linearly-polarized (LP) wave [18,19], The second approach, also termed as Pancharatnam–Berry (PB) metasurface, afforded achromatic phases within the operation band under circularly-polarized (CP) wave excitations [20,21]. Up to date, fruitful progress have been achieved to generate OAM carrying vortex beams, which provided new ideas for the generation and applications of OAM vortex [22–29].

In this paper, a single layer Pancharatnam–Berry reflective element is proposed to achieve the wideband characteristic, and the phase gradient on the metasurface is obtained by rotating the element according to the PB metasurface. Based on the proposed element, a metasurface is designed, fabricated, and experimentally demonstrated to generate an OAM vortex wave. The metasurface is excited by a wide Archimedean spiral antenna. The paper is arranged as follows. Section 2 shows the structure of the proposed element and demonstrates its wide bandwidth. A wideband vortex beam generator is designed based on the well optimized element. Section 3 discusses the simulated and measured results of the vortex generator. Finally, the paper is summarized briefly in Section 4.

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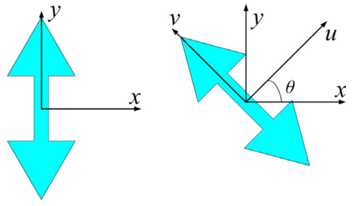

(a) (b)

Fig. 1. Diagram of spin element in (a) xyz coordinates and (b) rotated coordinates.

2. Design of broadband vortex beam generator

2.1. PB meta-atom design

For a reflection meta-atom under Cartesian coordinate system, as shown in Fig. 1, the reflection matrix after a rotation angle θ can be written as:

$$\mathrm{R}_{\theta}^{XY}=\begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix}^{-1}\begin{bmatrix}r_{xx} & r_{xy}\\ r_{yx} & r_{yy}\end{bmatrix}\begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix} \tag{1}$$

where the subscripts x and y denote the polarization of incidences. Then the reflection matrix under CP wave can be obtained as:

$$\mathrm{R}_{\theta}^{LR}=\frac{1}{2}\begin{bmatrix}1 & -j\\ 1 & j\end{bmatrix}\mathrm{R}_{\theta}^{XY}\begin{bmatrix}1 & -j\\ 1 & j\end{bmatrix}^{-1}. \tag{2}$$

By substituting Eq. (1) into Eq. (2), we derive the following reflection matrix under CP incidence as follows

$$r_{LL}=\frac{1}{2}[(r_{xx}-r_{yy})-j(r_{xy}+r_{yx})]\mathrm{e}^{-j2\theta} \tag{3a}$$

$$r_{RR}=\frac{1}{2}[(r_{xx}-r_{yy})+j(r_{xy}+r_{yx})]\mathrm{e}^{j2\theta} \tag{3b}$$

$$r_{LR}=\frac{1}{2}[(r_{xx}+r_{yy})+j(r_{xy}-r_{yx})] \tag{3c}$$

$$r_{LR}=\frac{1}{2}[(r_{xx}+r_{yy})-j(r_{xy}-r_{yx})]. \tag{3d}$$

We can obtain from Eq. (3) that when $\left|r_{xy}\right|\approx\left|r_{yx}\right|\approx 1$, and $r_{xx}\approx r_{yy}\approx 0$, no phase difference exists between two cross-polarizations. In this case, Jones matrix of the reflection coefficient equals to $\boldsymbol{R}=\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$, and the polarization of the reflective wave is in accordance with the incident wave, meaning that its phase shift is as twice as the rotated angle under CP wave.

In order to broaden the working bandwidth of the system, the phase profile of the designed meta-atom needs to have similar slopes at different frequencies within a broadband range, and it can be expressed as

$$\frac{\partial\varphi(L,L)}{\partial f_1}\approx\frac{\partial\varphi(L,L)}{\partial f_i}\approx\frac{\partial\varphi(L,L)}{\partial f_2} \tag{4}$$

where f_1 and f_2 are the lower and upper frequencies of the working band, respectively, and f_i indicates an arbitrary frequency within the band, $\varphi(L,L)$ is the reflection phase under LCP wave illumination. It is similar for the RCP excitation. To achieve a wide operating band, we need to realize a large frequency interval of (f_2–f_1).

Following the mentioned PB theory, we can design a broadband and high-efficiency reflective meta-atom, as shown in Fig. 2(a). Each element consists of a F4B ($\varepsilon_r = 2.65$) intermediate dielectric layer with a double arrow-shaped metallic layer printed on it and the metallic ground. The period of the unit cell is $p = 8$ mm, the other geometrical parameters are listed as $r = 2.6$ mm, $b = 4$ mm and $h = 3$ mm. The period of the element is mainly determined by the central frequency. The other parameters, including r, b, h are obtained through full wave simulation to obtain the best bandwidth. By rotating the double arrow-shaped structure, the unit cell has a continuous reflection phase range with 360°. It is necessary to emphasize that the electric size of the element is only $0.4\lambda_0$ at the center frequency of 15 GHz.

In order to demonstrate the EM response of the element, we have fabricated a homogeneous metasurface with 70 × 70 elements with its picture shown in Fig. 2(b). Broadband performances of our PB element are plotted from Fig. 2(c) and (d). Fig. 2(c) shows the reflection coefficients of co-polarized and cross-polarized waves under normal incidence of LP and CP waves. The simulated and measured bandwidth, ordered by co-polarized reflection coefficients higher than 0.9 ($|r_{xx}| > 0.9$ & $|r_{LL}| > 0.9$), can be calculated as 10–20 GHz under both LP and CP excitations. Most importantly, from Fig. 2(d), the phase response is parallel as expected within the frequency interval for different rotation angles, where the phase variation is precisely twice of the rotation angle.

Owing to the 45°-symmetry of the element, the co-polarized and cross-polarized reflection coefficients under the y-polarized illumination are the same as those of x-polarized wave excitation. Thus, the meta-atom satisfied the requirements of the reflection coefficient matrix $\boldsymbol{R}=\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$ and generated the phase shift under the circularly polarized wave by rotating the double arrow-shaped structure. The perfect phase as well as the high co-polarized reflection efficiency makes the element a good candidate for reflective metasurface to realize wide working bandwidth.

2.2. Broadband vortex beam generator design

In order to design a low-profile vortex beam generator, an Archimedes spiral antenna is used as the feed antenna for its small size. In addition, Archimedes spiral antenna is one of the typical ultra-wideband antennas, which exhibits the advantages of wide band, circularly polarization radiation as well as compact size. Compared with the horn antenna, the aperture of the Archimedes spiral antenna is reduced significantly, and the bandwidth of the antenna could cover the whole 10–20 GHz band.

When the Archimedes spiral antenna is placed at the focal point as the feed source, the emitted spherical wave can be transformed into a plane wave. To produce the helical wavefront, it is necessary to combine the phase distributions of focusing and vortex.

The focusing phase distribution can be expressed as

$$\varphi_1(m,n)=k_0\left(\sqrt{F_0^2+(mp)^2+(np)^2}-F_0\right)+\varphi_0 \tag{5}$$

where $k_0=\frac{2\pi}{\lambda_0}$ is the propagation constant, F_0 is focal length and can be selected arbitrarily. In our design, it is set as $F_0 = 70$ mm, φ_0 is the reference phase and is selected as $\varphi_0 = 0°$, and m and n represent the index of elements in the x and y directions, respectively.

The phase distribution of vortex can be calculated as

$$\varphi_2(m,n)=l\tan^{-1}\left(\frac{n}{m}\right) \tag{6}$$

where l is the OAM mode number of phase singularity, which is also known as the number of topological charge. This paper takes $l = 2$ as an example to explain the principle.

Therefore, the phase-shift required at each reflective element for an OAM vortex wave can be obtained by

$$\varphi_{tot}(m,n)=\varphi_1(m,n)+\varphi_2(m,n). \tag{7}$$

The phase-distribution of focusing, vortex and total are illustrated in Fig. 3.

According to the total phase-distribution required by the vortex beam generator, the elements with different rotation angles are calculated and arranged, and a metasurface with a center frequency of 15 GHz is fabricated by the standard print circuit board (PCB) technology with the photograph shown in Fig. 4(a). In fact, the fabrication process of the metasurface and the feed antenna is well-rounded based on the standard print circuit board (PCB) technology [18–24]. The layout is a square array with the dimension of 160 mm × 160 mm ($8\lambda_0 \times 8\lambda_0$,