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High-efficiency broadband vortex beam generator based on transmissive metasurface

SHIWEI TANG,1,3 XIKE LI,1 WEIKANG PAN,1 JUN ZHOU,1 TAO JIANG,1 AND FEI DING2,4
1School of Physical Science and Technology, Ningbo University, Ningbo, 315211, China
2SDU Nano Optics, University of Southern Denmark, Campusvej 55, Odense DK-5230, Denmark
3tangshiwei@nbu.edu.cn
4feid@mci.sdu.dk

Abstract: Vortex beam has attracted growing attention in recent years due to its remarkable abilities in the communication system since it is believed to be an effective way to improve the channel capacity efficiency. However, available vortex beam generators suffer from the issues of complex configurations, low efficiency as well as narrow bandwidths, especially for the transmissive case. Here, we proposed a broadband transmissive metasurface to generate vortex beam with \( l = 1 \) in a broad band ranging from 8GHz to 13 GHz. We enhance the working bandwidth by carefully designing the meta-atoms which provide high transmittances along with similar slopes of the phase responses within a large frequency interval. More importantly, the designed vortex beam generator exhibits very high working efficiencies (more than 83% within the whole working band). Our finding opens a door for the design of high-efficiency broadband transmissive vortex beam generators and operating at other frequency domains.

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1. Introduction

How to efficiently improve the communication capacity is a hot research orientation in modern wireless communication systems [1,2]. However, currently available devices face the challenges of the high profiles and low efficiencies. Nowadays, orbital angular momentum (OAM) vortex beam has attracted interesting attention owing to the spiral phase front carries orbital angular momentum [3–10]. The OAM vortex beam extends the communication capacity by its strictly orthogonal channel with different modes which carrying additional information [3]. A typical feature of a vortex beam is a phase singularity indicating a dark core with zero intensity along the beam-axis together with an annular transverse intensity profile [11–13]. Benefiting from the distinctive electromagnetic properties, vortex beam has led to many fascinating applications in optics, the basic physical properties and radio frequency communication [14–19]. Therefore, how to develop effective methods to produce a vortex beam is one of the key issues.

Nowadays, several methods to generate OAM beams have been continuously proposed, such as spiral plate [20,21], antenna array [22,23], subwavelength gratings and holograms [24]. However, available vortex beam generators suffer from the issues of complex configurations, low efficiency as well as narrow bandwidths. The problems above greatly limit its further development and application in modern wireless communication systems. Very recently, metasurfaces are reported having advantages for generating vortex beams carrying OAM [25–27]. Metasurfaces, as a two-dimensional version of metamaterials, have demonstrated strong capabilities to manipulate electromagnetic (EM) wave-front [28–35]. Therefore, outstanding optical properties of metasurfaces provide a new avenue to developing vortex beam. Generally speaking, there are two methods to implement the agile phases and thus engineer desirable functionalities: varying structural parameters and rotating the principal axes of meta-atoms. In the first approach, the desired phase profile enables achieved under illumination of a linearly polarized (LP) wave [36,37]. The second approach also termed as the Pancharatnam-Berry (PB) metasurface approach, allows dispersionless phase responses within an operation band.
under circularly polarized (CP) wave excitations [38–41]. Although the great progress has been achieved, the majority of vortex beam generators with wide bandwidth and high-efficiency are operating at reflection side of the system. It is not easy to obtain wide phase range in transmissive mode along with high transmission which is reducing the freedom of controlling EM waves. Therefore, it is essential to realize high-efficiency broadband vortex beam generators working in a transmissive mode.

In this paper, we proposed a new strategy to design a high-efficiency vortex beam generator by using transmissive metasurface which can achieve the broadband characteristic. The meta-atoms of the proposed metasurface provide high transmittances and similar slopes of the phase responses within a large frequency interval. The phase and amplitude of transmission can be respectively controlled by the open angle and rotation angle of the meta-atoms. Combining the focusing phase and the spiral phase distributions, a new kind of metasurface is designed to generate an OAM vortex beam. Numerical results illustrate that the proposed vortex beam generator realized a high-efficiency vortex beam conversion over a broad range of 8GHz to 13 GHz.

2. Broadband meta-atom design

We now describe our strategy to design a broadband and high-efficiency vortex beam generator. The key step is to design a collection of meta-atoms with transmission amplitudes of near 1 and tuned transmission phase that covers the 2π range. On the other hand, in order to enlarge the operating bandwidth, the meta-atoms need similar slopes of the phase responses at different frequencies within a broadband, which means that we must satisfy the condition

$$\frac{\partial \varphi(x, y)}{f_1} = \frac{\partial \varphi(x, y)}{f_2} = \frac{\partial \varphi(x, y)}{f_3}$$

where $f_1$ and $f_2$ are the lower and upper frequencies of the working band, $f_i$ denotes an arbitrary frequency within the band and $\varphi(x, y)$ is the transmission phase under normal incidence.

The first step is to find a proper meta-atom that is totally transparent in a broadband, which can ensure the metasurface with wide bandwidth and high efficiency. Such properties can be achieved by means of multiple plasmon resonances, which efficiency can be enhanced greatly by the interference in the Fabry–Perot-like cavity [42–44]. According to such theory, we proposed a transmissive metasurface, which is shown in Fig. 1(a). Each meta-atom is a basic multilayered structure, consisting of three metallic layers and separated by two F4B dielectric substrates (The thickness and permittivity of each dielectric are 3 mm and $\varepsilon_r = 2.65 + 0.01i$). The period of the unit cell is set as $p = 11$ mm. The metallic layers can be regarded as a perfect electric conductor (PEC) in this frequency region. The top layer and bottom layer of the meta-atom are composed of two one-dimensional metal gratings, which are orthogonal to each other. The grating constant of the metal grating is 2.2 mm and the width of the metal bar is 0.8 mm. All the thicknesses of metals we used in the unit cell are set as 0.035 mm. The middle metallic layer composed of a symmetric split ring and a cut wire, where $\alpha$ represents the open angle of the symmetric split ring and $\beta$ is the rotation angle of the meta-atom. $\alpha$ and $\beta$ will be mainly considered in the following discussions. Other dimensions of the structure are listed in the caption of Fig. 1(b). Although the metallic mesh of the middle metallic layer is not an absolutely necessary element in designing a single cell, its presence can significantly reduce the mutual couplings between adjacent cells, which make our design robust and reliable [45,46].

To illustrate the unique EM properties of the meta-atom, we consider its performance under different polarizations. Figure 1(c) depicts the full-wave simulated transmission coefficients as a function of frequency through finite-different time-domain (FDTD) method when we set $\alpha$ as 120° and $\beta$ as 45°. In this figure, $t_{xx}$ and $t_{xy}$ represent the transmission coefficient of the co-polarized and cross-polarized wave when a normal x-polarized incident wave illuminates
onto the meta-atom from -z-direction. Similarly, $t_{xy}$ and $t_{yx}$ represent the transmission coefficients under a normal y-polarized incident wave. We can clearly see that $t_{yx}$ keeps higher than 0.8 within a wide frequency range from 8 to 14 GHz. Meanwhile, $t_{xt}$, $t_{yt}$, and $t_{yy}$ keep a small value approximately equal to zero.

When we turn the rotation angle $\beta$ of the meta-atom into $\beta=135^\circ$, we can find in Fig. 1(d) that the cross-polarized transmissive phases are the same as $\beta=45^\circ$, but with a constant $\pi$ phase difference.

![Fig. 1. The topology of the building block and simulated transmission spectra.](image)

(a) The perspective view of the meta-atom. (b) Middle layer of the meta-atom. The geometrical parameters are: $p = 11$ mm, $r = 4.25$ mm, $w = 1.5$ mm. $\alpha$ represents the open angle of the symmetric split ring and $\beta$ is the rotation angle of the unit cell. (c) FDTD simulated spectra of transmission coefficient $t_{xy}$, $t_{yx}$, $t_{xt}$, and $t_{yt}$. (d) FDTD simulated spectra of phase.

In order to explain these phenomena, we use the Jones Matrix [47] to analyze the optical properties of the transmissive meta-atom, and it works as a guide to identify the desired polarization response. For a transmissive meta-atom within a Cartesian coordinate system, it is assumed that the metasurface slab is illuminated by a plane wave propagating in the positive $z$-direction

$$E_i(r, t) = \begin{pmatrix} t_x \\ i_y \end{pmatrix} e^{i(kz - \omega t)},$$

with $\omega$ being its frequency, $k = 2\pi / \lambda$ being the wave vector, and the complex amplitudes $i_x$ and $i_y$ describing the state of polarization. The transmitted field is then given by

$$E_t(r, t) = \begin{pmatrix} t_x \\ t_y \end{pmatrix} e^{i(kz - \omega t)}.$$
The transmission matrices connect the generally complex amplitudes of the incident and the transmitted field:

\[
\begin{pmatrix}
    i_x \\
    i_y
\end{pmatrix}
= \begin{pmatrix}
    T_{xx} & T_{xy} \\
    T_{yx} & T_{yy}
\end{pmatrix}
\begin{pmatrix}
    i_x \\
    i_y
\end{pmatrix}
= \begin{pmatrix}
    A & B \\
    C & D
\end{pmatrix}
\begin{pmatrix}
    i_x \\
    i_y
\end{pmatrix}
= T
\begin{pmatrix}
    i_x \\
    i_y
\end{pmatrix}.
\]

For convenience, we have replaced the entries \( T_{ij} \) by A, B, C, D, which form the actual T matrix. For the simple anisotropic structure with a mirror plane parallel to the y-axis, we have the T matrix

\[
\begin{pmatrix}
    0 & 0 \\
    0 & 1
\end{pmatrix}.
\]

In addition, rotation by an angle \( \varphi \) can be written as:

\[
D_\varphi = \begin{pmatrix}
    \cos(\varphi) & \sin(\varphi) \\
    -\sin(\varphi) & \cos(\varphi)
\end{pmatrix},
\]

and the new transmission matrix \( T_\varphi = D_\varphi \top T D_\varphi \). Then the anisotropic media is sandwiched by two orthorhombic metallic gratings where the T matrixes of the metallic gratings are described as \( T_\parallel = \begin{pmatrix}
    1 & 0 \\
    0 & 0
\end{pmatrix} \) and \( T_\perp = \begin{pmatrix}
    0 & 0 \\
    0 & 1
\end{pmatrix} \). Therefore, the final transmission matrix is \( T_{\text{final}} = T_\parallel T_\varphi T_\perp \). In especial, when rotation angles are \( \beta=45^\circ \) and \( \beta=135^\circ \), we can get two transmission matrixes which have the equal magnitude but opposite phase:

\[
T_{45^\circ} = \begin{pmatrix}
    0 & A-D \\
    0 & 0
\end{pmatrix}, T_{135^\circ} = \begin{pmatrix}
    0 & -(A-D) \\
    0 & 0
\end{pmatrix}.
\]

From these two transmission matrixes, we can also find that the unit cells with \( \beta=45^\circ \) and \( \beta=135^\circ \) can produce the same cross-polarized transmissions but with a constant \( \pi \) phase difference, which are in good agreement with Figs. 1(c) and 1(d). Thus, we only need to cover the \( \pi \) range when we manage to tune the transmission phase to satisfy the wide phase range \( 2\pi \), which is essential for the design of the Vortex beam Generator. As a result, we can avoid the resonance of the multilayer structure to design the metasurface, and the phase spectra can be almost a straight line and the spectra with different parameters are almost parallel to each other, which will support the broadband performance.

In addition, two mutually orthogonal metal gratings and a symmetric split ring with a cut wire form a Fabry–Perot-like cavity. When y-polarized wave illuminates onto the meta-atom from -z-direction, it can transmit through the front grating and then functions on the symmetric split ring array. As analyzed above, a portion of the y-polarized incident wave converts to the x-polarized transmission. On the one hand, the x-polarized transmitted component \( E_{x,x} \) can penetrate through the back grating, whereas the remaining y-polarized transmitted component \( E_{y,y} \) is reflected by the back grating and goes back to interact with the symmetric split ring array again. On the other hand, the x-polarized reflected component \( E_{x,y} \) is blocked by the front grating and also goes back to interact with the symmetric split ring array again. Afterward, the EM wave reflected and transmitted will be selected by the front and back gratings. Through repeating the above processes, consequently, the cross-polarized transmission can be greatly enhanced in wide range. At the same time, the co-polarized reflection can be drastically reduced. As a result, the transmittance and polarization conversion efficiency can be enhanced largely owing to the Fabry-Perot like resonances.

Based on the aforementioned analysis, we also consider the performance of the meta-atoms with different geometrical parameters when the incident wave is y-polarized. Figure 2 shows the relationship between the cross-polarized transmission coefficient and \( \alpha, \beta \). As is shown in Fig. 2(a), when \( \beta \) is \( 45^\circ \) and \( \alpha \) varies from \( 66^\circ \) to \( 178^\circ \), for the vast majority of these angles, the
amplitudes of cross-polarized transmission coefficients are higher than 0.8 within 8-13 GHz. This offers us the possibility to choose the meta-atom with a high transmission coefficient. According to Fig. 2(b), the phase shift covers a range of more than \( \pi \) in a broadband when \( \beta \) is 45° and \( \alpha \) varies from 66° to 168°. Moreover, the meta-atom is a symmetric structure in Fig. 1(b) when \( \beta \) is 45° and 135°, a mirror structure of the unit cell can produce the same cross-polarized transmission except for a \( \pi \) phase shift. Therefore, it enables to realize the phase shift over 2\( \pi \) by adjusting \( \alpha \) and \( \beta \), as the result shown in Fig. 2(b).

One important phenomenon can be found in Fig. 2(b) is that the phase spectra of different parameters are almost parallel to each other, which guarantee that meta-atoms with different parameters have similar slopes of the phase responses at different frequencies. As a result, both the amplitude and phase of cross-polarized transmission can be controlled in a broadband by adjusting the open angle and rotation angle of the meta-atom. Therefore, it offers us the possibility to satisfy the phase requirements of a vortex beam generator.

![Fig. 2. The cross-polarized transmission coefficients and phase for different \( \alpha \) and \( \beta \) value. (a) magnitude. (b) the phase of cross-polarized for different \( \alpha \) and \( \beta \) value for normal y-polarized incidence.](image)

### 3. Broadband vortex beam generator design

In order to implement a vortex beam generator, a self-made Vivaldi antenna [48,49] is adopted as a feed source, which can radiate quasi-spherical waves with a broad bandwidth (7-18 GHz). The details of the structure, parameters and radiation pattern of the Vivaldi antenna can be found in Ref [48]. Owing to the metasurface should exhibit the helical wavefront, it should combine the focusing phase [36] and the spiral phase [18,19]. The focusing phase distribution can be expressed as

\[
\varphi_f(mp, np) = k_0 \left( \sqrt{F_0^2 + (mp)^2 + (np)^2} - F_0 \right) + \varphi_0
\]

with \( k_0 = 2\pi / \lambda \) being the propagation constant, \( F_0 \) being the focal length which can be chosen freely and arbitrarily, \( \varphi_0 \) denoting the reference phase, and \( m \) and \( n \) represent the number of meta-atoms along x and y-axis. Here we set \( F_0 = 70 \text{mm} \) and \( \varphi_0 = 0^\circ \).

The spiral phase can be calculated as

\[
\varphi_s(mp, np) = l \tan^{-1} \left( \frac{n}{m} \right)
\]

where \( l \) is denoting the mode number of phase singularity (topological charge). Here, we chose \( l = 1 \). Thus, the total phase distribution at each transmissive meta-atom for vortex beam generator can be calculated as
\[ \phi_{\text{total}}(mp, np) = \phi_1(mp, np) + \phi_2(mp, np) \]  

(3)

Then, the calculation process and phase distribution for \( l = 1 \) are presented in Fig. 3(c), where 360° has been subtracted from any phase exceeding 360° for easy realization. The focusing, spiral phase and total phase distributions are shown in Figs. 3(a)-3(c).

According to the 2-D phase profile and phase-parameter relationship in Fig. 2, the meta-atoms satisfying phase distribution with different \( \alpha \) and \( \beta \) can be readily achieved. The metasurface with a center frequency of 10 GHz is designed. The metasurface is composed of a 16 × 16 array of meta-atoms and accommodates a total area of 176 × 176 mm², and the middle metallic layer of the metasurface is shown in Fig. 3(d). The metasurface has a different position-variant \( \alpha, \beta \) and comprises a set of rotational meta-atoms of the same structures and parameters.

4. Result and discussion

After the structure is designed, the next step is to characterize its near-field and far-field EM performances of metadevices. Firstly, we characterize its near-field property. The designed vortex beam generator is excited by a y-polarized Vivaldi antenna which is set at the focus of the metasurface. Referring to the simulated Re(\( E_z \)) and phase distributions which recorded by field monitor at xoy plane (30cm behind the metasurface) shown in Fig. 4, we can clearly see that the proposed vortex beam with \( l = 1 \) performs well in the band, and only vortex mode can be found without any scattering modes. As expected in the design frequency region, the vortex beams exhibited an amplitude null at the center due to the vector singularity, thus revealing their capability of converting plant waves into vortex beams. The inherent physics is that the interferences among the high-efficiency transmitted waves passing through meta-atoms at different positions form the pure vortex beam, and all of the meta-atoms with different parameters have similar slopes of the phase responses at different frequencies.
Secondly, we calculated the far-field radiation performances of broadband OAM vortex beam. Figure 5 presents the numerically calculated 3D far-field radiation patterns of the metasurface with $l=1$ from 8 to 13 GHz in steps of 1 GHz under normal y-polarized incidence. From Fig. 5, we can clearly see that the cross-polarized transmissive vortex beams are dominant and the reflective beams are very low. Moreover, all those 3D far-field radiation patterns at different frequency show a typical doughnut-shaped intensity with a singularity in the center, indicating that the radiation energy in the normal direction is very low, which is completely identical with the far-field distribution of the ideal vortex beam. At the design frequency 10 GHz, the far-field pattern indicate that gain lower than $-15$ dB at the specular direction. Moreover, there is a better performance at high frequencies, such as at 13 GHz, the gain is lower than $-27$ dB at the specular direction. Meanwhile the sidelobe level also enhances with the increase of frequency, especially at the top frequency of the working band, which are mainly caused by the enlarged size of element at the metasurface at higher frequencies. But the radiation gain at specular direction is better than $-10$ dB within the frequency interval of 8-13 GHz.
Fig. 5. Numerically calculated far-field patterns of the metasurface with $l = 1$ from 8 to 13 GHz in steps of 1 GHz under normal y-polarized incidence.

Finally, we also plot the 2-D radiation patterns at different frequencies for the sake of clarity the performance of the vortex beam generator. As shown in Fig. 6, a clear amplitude null existed at the center of the vortex beam with the frequency varied from 8 to 13 GHz in steps of 1 GHz, revealing an OAM vortex beam of broad bandwidth. Moreover, the calculated gain levels in normal direction are extremely lower than those of the main beams within the working band region. Meanwhile, the far-field results further verify the characteristic of the broadband vortex beam generator.

Based on the far-field simulated results, we can also quantitatively examine the working efficiency of the vortex beam generator, which is defined as the ratio between the power carried by the vortex beam and that of the incident wave. The reflection, transmission and incident power can be evaluated by integrating the power in the designed system. Therefore, the calculated numerical efficiencies are more than 83% for all the frequencies varied from 8 to 13 GHz. The high working efficiency indicates that the proposed metasurface is a good candidate in wireless communication system. As a result, this paper only takes the mode number $l = 1$ as an example to demonstrate the feasibility and efficiency of the vortex beam generator. The proposed metasurface can feasibly generate OAM beams with arbitrary OAM modes.
Fig. 6. Simulated 2D far-field radiation patterns characterization of the broadband metasurface with $l = 1$ under normal y-polarized incidence. (a) 8 GHz, (b) 9 GHz, (c) 10 GHz, (d) 11 GHz, (e) 12 GHz, (f) 13 GHz.

5. Conclusions

In summary, we proposed a broadband transmissive metasurface to generate the vortex beams with high efficiency. The metasurface consists of $16 \times 16$ transmissive meta-atoms, which operate in a linear cross-polarization scheme in a broadband. Such cross-polarized transmission phases of the meta-atoms can be respectively controlled by their open angles and rotation angles. Both far-field and near-field characterizations indicate that the proposed vortex beam generator can realize a high-efficiency (83%) vortex beam conversion over a broad range of 8-13 GHz. Our findings provide a new avenue to design a broadband transmissive vortex beam, which is of crucial importance in the modern communication system.

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References

1. R. Niemiec, C. Brousseau, K. Mahdjoubi, O. Emile, and A. Ménard, “Characterization of an OAM Flat-Plate Antenna in the Millimeter Frequency Band,” IEEE Antenn. Wirel. Pr. 13(1), 1011–1014 (2014).
2. M. W. Beijersbergen, R. P. C. Coerwinkel, M. Kristensen, and J. P. Woerdman, “Helical-wavefront laser beams produced with a spiral phaseplate,” Opt. Commun. 112(5-6), 321–327 (1994).
3. G. Gibson, J. Courtial, M. Padgett, M. Vasnetsov, V. Pas’ko, S. Barnett, and S. Franke-Arnold, “Free-space information transfer using light beams carrying orbital angular momentum,” Opt. Express 12(22), 5448–5456 (2004).
4. H. Chen, J. Hao, B. F. Zhang, J. Xu, J. Ding, and H. T. Wang, “Generation of vector beam with space-variant distribution of both polarization and phase,” Opt. Lett. 36(16), 3179–3181 (2011).
5. J. Wang, J. Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, “Terabit free-space data transmission employing orbital angular momentum multiplexing,” Nat. Photonics 6(7), 488–496 (2012).
6. Z. Zhao, J. Wang, S. Li, and A. E. Willner, “Metamaterials-based broadband generation of orbital angular momentum carrying vector beams,” Opt. Lett. 38(6), 932–934 (2013).
7. E. Karimi, S. A. Schulz, I. D. Leon, H. Qassim, J. Upham, and R. W. Boyd, “Generating optical orbital angular momentum at visible wavelengths using a plasmonic metasurface,” Light Sci. Appl. 3(5), e167 (2014).
8. M. Q. Mehmood, S. Mei, S. Hussain, K. Huang, S. Y. Siew, L. Zhang, T. Zhang, X. Ling, H. Liu, J. Teng, A. Danner, S. Zhang, and C. W. Qiu, “Visible-Frequency Metasurface for Structuring and Spatially Multiplexing Optical Vortices,” Adv. Mater. 28(13), 2533–2539 (2016).
40. Z. Wang, S. Dong, W. Luo, M. Jia, Z. Liang, Q. He, S. Sun, and L. Zhou, “High-efficiency generation of Bessel beams with transmissive metasurfaces,” Appl. Phys. Lett. 112(19), 191901 (2018).

41. W. Luo, S. Sun, H. Xu, Q. He, and L. Zhou, “Transmissive ultrathin Pancharatnam-Berry metasurfaces with nearly 100% efficiency,” Phys. Rev. Appl. 7(4), 044033 (2017).

42. Y. J. Chiang and T. J. Yen, “A composite-metamaterial-based terahertz-wave polarization rotator with an ultrathin thickness, an excellent conversion ratio, and enhanced transmission,” Appl. Phys. Lett. 102(1), 011129 (2013).

43. Z. Wei, C. Yang, Y. Fan, Y. Xing, and H. Li, “Broadband polarization transformation via enhanced asymmetric transmission through arrays of twisted complementary split-ring resonators,” Appl. Phys. Lett. 99(22), 221907 (2011).

44. N. K. Grady, J. E. Heyes, D. R. Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. Dalvit, and H. T. Chen, “Terahertz metamaterials for linear polarization conversion and anomalous refraction,” Science 340(6138), 1304–1307 (2013).

45. T. Cai, G. Wang, X. Zhang, J. Liang, Y. Zhuang, D. Liu, and H. Xu, “Ultra-thin polarization beam splitter using 2-D transmissive phase gradient metasurface,” IEEE Trans. Antenn. Propag. 63(12), 5629–5636 (2015).

46. T. Cai, S. Tang, G. Wang, H. Xu, S. Sun, Q. He, and L. Zhou, “High performance bifunctional metasurfaces in transmission and reflection geometries,” Adv. Opt. Mater. 5(2), 1600506 (2017).

47. C. Menzel, C. Rockstuhl, and F. Lederer, “Advanced Jones calculus for the classification of periodic metamaterials,” Phys. Rev. A 82(5), 053811 (2010).

48. Y. Ran, J. Liang, T. Cai, W. Ji, and G. Wang, “High-performance broadband vortex beam generator based on double-layered reflective metasurface,” AIP Adv. 8(9), 095201 (2018).

49. Y. W. Wang, G. M. Wang, and B. F. Zong, “Directivity Improvement of Vivaldi Antenna Using Double-Slot Structure,” IEEE Antenn. Wirel. Pr. 12(3), 1380–1383 (2013).