Generation of vector beams with different polarization singularities based on metasurfaces

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Abstract

In view of wide applications of vector beams and powerful light manipulation ability of metasurfaces, this paper studies the generation of two kinds of vector beams with different polarization singularities based on metasurfaces. One kind of vector beams are the linearly polarized vector beam with uncertain polarization orientation and the other kind of vector beams are the elliptically polarized vector beam with hybrid polarization states with uncertain polarization orientation, ellipticity and handedness. These vector beams can be decomposed into two or more uniform polarization states carrying the spiral phases. The metasurfaces consisting of rotated cross nanoholes are designed to generate vector beams on basis of the decomposition of vector beams and phase modulation of nanoholes. The simulation results verify the availability of the designed metasurfaces and the experiment results validate the generation of two kinds of vector beams. The generation of complex vector beams based on compact metasurfaces can bring more application possibilities of vector beams in classical physics and quantum sciences.

1. Introduction

Polarization is an important property of light and it is widely applied in imaging, spectroscopy, microscopy, particle trapping, micromechanics, quantum memories and communications. With comparison to scalar beams with the uniform polarization like the linear, circular and elliptical polarization, vector beams have spatial varying polarization [1]. The non-uniform polarization of vector beam can bring tight focusing [1, 2], high resolution imaging [3, 4], high precision sensing [5] and high quality machining [6]. Therefore, vector beams have attracted significant attention recently and their applications have entered into a wide variety of fields as biology, chemistry, physics and materials [7, 8].

Some vector beams may be the nature solutions of vector Helmholtz equation and other compound vector beams can be not obtained through solving vector Helmholtz equation. Moreover, the practical beams emitted from the light sources are usually scalar. The generation of vector beams has attracted much attentions. The common method to generate vector beam is the superposition of two orthogonal polarization scalar beams [9–12]. Typically, two orthogonal circularly polarized beams are often utilized to form one vector beam. Many generation techniques have been developed in parallel to realize the superposition of circularly polarized states, and they include forked gratings [12], cylindrical lenses [13], spiral phase plate [14], q-plate [15], spatial light modulator [16, 17] and optical metasurface [18–25].

Metasurface consisting of nanounits possesses the advantages of ultra-thin thickness, high spatial resolution, convenient operation and ease to integrate, and it becomes an effective tool in many fields like spin–Hall effect [26], invisible light propagation [27], wave–front shaping [28, 29] and structured vortex generation [30]. Meanwhile, with the help of polarization effect of anisotropic nanounits, metasurfaces have been also utilized to generate simple cylindrical vector lights [31–34]. Till now, one can obtain the vector beams with the identical ellipticity or the same polarization type at any position in the transverse plane using optical metasurfaces [22, 31, 35]. The generation of vector fields with polarization types varying with
the spatial positions is difficult for one metasurface only using the metasurface design based on polarization effect of anisotropic nanounits.

Here, we propose the study about the vector beams with the same and different polarization type at any spatial position based on metasurface. Different from our former studies about the generation of vector light based on the polarization conversion of nanounits [31–34], the metasurfaces are designed based on the phase modulation of nanounits and the superposition of scalar vortex beams. Two practical metasurface samples are fabricated to generate the linearly polarized vector beam (LPVB) and the elliptically polarized vector beam (EPVB). Section 2 describes these vector beams and gives the design principles of metasurfaces. Section 3 provides the experiment and simulation results for the vector beams generated by the metasurface samples. The discussions about the polarization distribution variations of vector beams with different parameters are performed in section 4. In the end, the conclusions of this paper are given. The compact metasurface realizes the polarization conversion of the linearly polarized light to the vector beam with diverse polarization states. This work is helpful for promoting the development of metasurface devices and expanding the applications of vector beams.

2. Design principle

As we know, the vector beam has varying spatial polarization, where the polarization direction and the ellipticity may be changed with the spatial position. In this paper, we study two kinds of complex vector beams with diversity polarization states. One is the LPVB with the polarization direction of linear polarization state changing with the angular coordinate, and its expression can be expressed by

\[ E(\varphi) = \begin{pmatrix} \cos(q\varphi + \phi) \\ \sin(q\varphi + \phi) \end{pmatrix}, \quad (1) \]

where \( q \) denotes the polarization order of vector beam and the angle of \( \phi \) determines the initial polarization state. This vector beam has one polarization singularity at the center of light field and the polarization orientation at the singular point is uncertain. The other is the EPVB with the polarization type changing with the angular coordinate, and its expression can be expressed by

\[ E(\varphi) = \begin{pmatrix} \cos(q\varphi + \phi) \\ j \sin(q\varphi + \phi) \end{pmatrix}, \quad (2) \]

This vector beam also has one polarization singularity at the center of light field and the polarization orientation, the polarization ellipticity and the handedness at the singular point are uncertain. Therefore, these two kinds of vector beams have different polarization singularities.

The cosine and sinusoidal functions in equations (1) and (2) for these two kinds of vector beams can be written into the sum of two exponential terms, namely, \( \exp[j(q\varphi + \phi)] \pm \exp[-j(q\varphi + \phi)] \). Thus, the LPVB can be changed into the superposition of two orthogonal circularly polarized vortex beams and the EPVB can be changed into the superposition of two orthogonal linearly polarized vortex beams, where the orientations of two linearly polarized lights are along the diagonal and anti-diagonal directions. Therefore, one can obtain the vector beam with the help of the phase modulation and beam superposition. As we know, the rotated anisotropic nanounit with circularly polarized light illumination can introduce one phase delay, which is carried by the cross circularly polarized light, and the introduced phase is just twice of the rotation angle of nanounit [35, 36]. Here, we use the metasurface consisting of cross nanoholes etched silver film to generate these vector beams.

In order to increase the working efficiency of metasurface, we first optimize the parameters of cross nanohole and the optimized cross nanohole can be equivalent to one half wave plate so as to obtain the maximum polarization conversion efficiency. The parameters of cross nanohole include the thickness of silver film and the size of cross hole. This process can be performed according to the finite-difference time-domain method. For the illumination wavelength of 633 nm, the thickness of silver film is determined as 220 nm, and the sizes of two rectangular holes equaling to one cross hole take 600 nm \( \times \) 150 nm and 180 nm \( \times \) 220 nm [37]. Then the cross nanoholes are arranged on concentric circles with the separation of 613 nm and the rotation angle of cross nanohole at spatial coordinates \( (r, \varphi) \) satisfies the following relation

\[ \alpha = \sigma \left[ \frac{\pi}{\lambda} \left( \sqrt{r^2 + f^2} - f \right) + \frac{q\varphi + \phi}{2} \right], \quad (3) \]

where \( \sigma = \pm 1 \) depends on the handedness of the incident circular polarization, \( f \) is the distance away from the metasurface and \( \lambda \) is the illumination wavelength. Thus, this metasurface with the circularly polarized
light illumination can generate the cross circularly polarized vortex light carrying the spiral phase of $q\phi + \phi$. Similarly, the orthogonal circularly polarized vortex light carrying the spiral phase of $-q\phi - \phi$ can generate through rotating nanoholes along the opposite direction and choosing the opposite chiral circularly polarized light illumination. Then, the LPVB is formed by the compound metasurface consisting of two suits of nanoholes under the horizontal linearly polarized (HLP) light illumination. As for the EPVB, it can be finally decomposed into four circular polarization states carrying different spiral phases of $\pm (q\phi + \phi \pm \pi/4)$ and four suits of nanoholes are needed to generate EPVB. Certainly, the structure of compound metasurface may be simplified when the chosen nanounits directly generate linearly polarized beam.

3. Experiment verification

We manufacture practically two metasurface samples and measure experimentally the generated vector beams. We first deposit the silver background layer onto a glass substrate by using the magnetron sputtering deposition method. Then, the nanoholes are fabricated using the focused ion-beam etching technique. In practical experiment, we mount the manufactured metasurface sample on a translation stage and let the collimated beam emitted from He–Ne laser impinge upon the metasurface sample at normal incidence from the glass substrate. A polarizer and a quarter wave plate are utilized to generate the needed polarization state. With the magnification by a microscopy objective, the intensity pattern of the transmitted field is captured using a two-dimensional CCD camera. Another polarizer is placed at front of CCD to analyze the generated vector beam.

Figure 1(a) shows the scanning electron microscopy (SEM) images of the first metasurface sample and the lower image is the magnification of the part squared by yellow line. This metasurface with the HLP light illumination can generate the LPVB with $\phi = 0$ and $q = 2$ at the distance of $f = 6 \mu m$. The generated vector beam can be simplified into $(\cos 2\phi, \sin 2\phi)$ in terms of equation (1). Figure 1(b) gives the theoretical and simulation polarization distributions at the designated plane of $f = 6 \mu m$ above the metasurface. The simulated result is obtained under HLP light illumination. It is easy to see that the simulated polarization distribution of the vector beam transmitted from the designed metasurface is almost the same as the theoretical one and the polarization state of LPVB at any position is linear polarization.

Figure 1(c) shows the simulated (color patterns) and measured (dark patterns) intensity distributions of the metasurface sample under HLP and left-handed circularly polarized (LCP) light illumination. The arrows inserted at the left of the intensity patterns denote the incident polarization states. It is easy to see
that the measured intensity distributions are consistent with the simulated ones. Under the HLP light illumination, the x components of intensity distributions abide by the rule of $\cos^22\phi$ and the y components of intensity distributions abide by the rule of $\sin^22\phi$. These results testify the generation of LPVB. As this metasurface is illuminated by the LCP light, the RCP vortex beam generates because only one suit of nanoholes takes effect. Therefore, one can see the intensity distributions of the x and y components close to annular shapes. In fact, they are two order optical vortices. These results further testify the optical performance of the metasurface in the phase modulation and polarization conversion.

Figure 2(a) shows the SEM images of the second metasurface sample and the EPVB with $\phi = 0$ and $\psi = 2$ can be generated by this metasurface with the HLP light illumination. Theoretically, the vector beam generated by this metasurface is $(\cos 2\phi, j\sin 2\phi)$ through inserting the given parameters into equation (2). Figure 2(b) gives the theoretical and simulation polarization distributions at the designated plane of $f = 6 \mu m$ above the metasurface, and the simulated result is obtained with the metasurface illuminated by HLP light. It is easy to see that the simulated polarization distribution is almost the same as the theoretical one and the polarization type changes with the angular position, where the polarization types include the vertical and horizontal linear polarization, and the circular and elliptical polarization.

Figure 2(c) gives the simulated (color patterns) and measured (dark patterns) intensity distributions at the distance of $f = 6 \mu m$ above the metasurface under the HLP light illumination. For further verifying the performance of this metasurface, we also simulate and measure the intensity distributions under the LCP light illumination. The black arrows inserted at the left of the intensity patterns denote the incident polarization states. In order to compare the intensity distributions with those under HLP light illumination, we insert the white arrows denoting the polarization analysis directions in the simulated intensity patterns.

One can see that the measured intensity distributions are consistent with the simulated ones. For the HLP light illumination, the intensity patterns of the x and y components are just consistent with the rules of $\cos^22\phi$ and $\sin^22\phi$. These results testify the generation of EPVB. As the illuminating light changes into the LCP, only two suits of nanoholes for this metasurface take effect, and theoretically, the output beam turns into $\cos(2\phi + \pi/4)e_i$ through superposing two LCP beams. With respect to the results for HLP light illumination, one can see that the intensity distributions just rotate $\pi/4$ along clockwise directions. These results further testify the optical performance of the designed metasurface. Furthermore, comparing the polarization and intensity distributions shown in figures 1 and 2, one can easily distinguish two kinds of vector beams generated by two metasurfaces.
4. Discussions

For two metasurface samples, the parameter of \( q \) takes an integer and the angle of \( \phi \) takes zero. In fact, for two kinds of vector beams, one can let the parameter of \( q \) to take any value including the fraction and the negative value, and the angle of \( \phi \) may take nonzero value. In order to further contrast two kinds of vector beams, \( q \) = 1, 3/2, 2 and \(-2\). The patterns in figure 3(a) are for LPVBs and the ones in figure 3(b) are for EPVBs. For clearness, the color shapes are used to differentiate the chirality of elliptical or circular polarization states. The blue ones denote the right-handed polarization states and the red color ones denote the left-handed polarization states. The black ones denote the linear polarization states.

From the results in figure 3(a), one can see the polarization state of LPVB at any position is linear polarization. As the parameter of \( q \) takes an integer, the polarization distributions are cylindrical symmetric and it is the reason that they are called as cylindrical vector beams [1, 3, 32]. As the parameter of \( q \) takes a fraction, the polarization distribution is not cylindrical symmetric. For the case of \( q \) taking positive value and \( \phi = 0 \), one can see that the polarization direction at a certain angular position rotates the opposite angle with respect to the case of \( q \) taking positive value. Generally speaking, the polarization direction with \( q \) taking negative value rotates the angle of \( 2q \phi \) with respect to the case with \( q \) taking positive value. As \( \phi \neq 0 \), the polarization direction at any position rotates the angle of \( \phi \) with respect to the case with \( \phi = 0 \).

From the results in figure 3(b), one can see the polarization state of EPVB at any position is always hybrid polarization including linear polarization state, circular polarization state and elliptical polarization state. As the parameter of \( q \) takes an integer, the polarization distribution is also cylindrical symmetric, and as the parameter of \( q \) takes a fraction, the cylindrical symmetry disappears. For the case with \( \phi = 0 \) and \( q \) taking a negative value, one can see that the left-handed polarization changes into right-handed polarization, and the right-handed polarization changes into left-handed polarization. For the case with \( \phi \neq 0 \), one can see that the ellipticity, polarization orientation and even the handedness of polarization state may change with the angular position.

These vector beams can be obtained by designing the corresponding metasurfaces and more simulation results give the powerful verification. It needs to be pointed out that all the simulated results are obtained in...
terms of the finite-difference time-domain technique [37]. In practical simulation, the complex dielectric constant of the silver film with the illuminating wavelength set at 633 nm takes the value given by Palik [38]. The calculation region takes $30 \mu m \times 30 \mu m \times 10 \mu m$, the minimum mesh cell takes 2 nm and the perfectly matched layer is chosen as the adsorbing boundary.

5. Conclusions

In summary, we study the generation of two kinds of vector beams based on metasurfaces. The physical mechanism including the decomposition of vector beams and the phase modulation of nanounits brings the convenience for the metasurface design. The well-designed metasurfaces can not only generate the LPV Bs with the polarization direction of linear polarization state varying with the spatial position, but also form the EPV Bs with the polarization type changing with the spatial position. This kind of vector beams with hybrid polarization states is difficult to directly realize the polarization conversion only depending on the polarization effect of nanounits. The choice of cross nanoholes equivalent to half wave plates ensures the working efficiency of metasurface although the transmittance of the transmission metasurface is relatively lower. The simulation and experiment results verify the physical conception for the generation of two kinds of vector beams. The obtained results also confirm the association of the polarization conversion and phase modulation. The most important is that the simple metasurface realizes the conversion from uniform linearly polarized state into hybrid polarization state, and the plentiful polarization information of complex vector beam brings more facilitation to the encryption, imaging and detection. Therefore, this work plays the foundation for the wider applications of complex vector beams.

Disclosure

The authors declare no conflicts of interest.

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Data availability statement

All data that support the findings of this study are included within the article.

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