Compound Vector Light Generator Based on a Metasurface

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Abstract: In view of wide applications of vector light with a non-uniform polarization state, a compound vector light generator is proposed to generate compound vector light. One compound vector light contains two or more non-uniform polarization modes and several annular intensities, which can carry more polarization information and possess higher dimensional singularity. The proposed compound vector light generator consists of cross nanoholes with high polarization conversion efficiency; it works under linear polarized light, and the mode of the generated compound vector light can be adjusted through rotating cross nanoholes. The structure parameters of the compound vector light generator are optimized with the aid of numerical simulation, and the simulation results for the generated light fields verify the performance of the proposed device. The advancement of the compound vector light and metasurface design of the compound vector light generator can assist in the exploration of novel singular properties of light fields and the broadening of applications of vector light fields.

Keywords: metasurface; vector light; polarization; singular optics

1. Introduction

Polarization is one of the most important natural properties of light, and the familiar polarization states of light include spatial uniform linear and circular polarization. In comparison to these uniform polarization states, the spatial non-uniform polarization states, namely vector beams, show high polarization sensitivity and possess the ability to manipulate particles, encode information and focus light beams [1]. Studies on vector beams have aroused widespread interest, and vector beams have been widely applied in many fields, such as free space optical communication [2], quantum communication [3], optical information encryption [4], high-resolution microscopy [5], particle trapping [6], laser material processing [7] and beam shaping [8].

As two simple vector beams, the radially and azimuthally polarized vector beams have attracted much attention because of smaller focusing spots and larger longitudinal components of the light field. Until now, many methods, with the help of common devices such as cylindrical lenses [9], optical fiber [10], spatial light modulators [11], birefringent devices [12] and subwavelength grating [13], have been advanced to generate vector beams. With the application expansion of vector beams, two problems arise. One is that the utilization of volume optical elements or complex optical systems makes the integration difficult. The other is that vector beams with the multiple and complex functions have not been generated. The development of nanotechniques [14,15], especially the advancement of metasurfaces composed of sub-wavelength scatterers like nanoantennas [16], nanoslits [17,18], nanoholes [19,20] and absorbers [21], paves the way for solving these related problems.

The powerful light manipulation ability of metasurfaces and the advantages of small size, ultra-thin thickness, convenient operation, and ease to manufacture and integrate are benefits of the design of multiple function elements. Zhang et al. designed a polarization
multiplexing metasurface consisting of nanoholes and generated radially and azimuthally polarized vector beams at the nanoscale under two orthogonal linearly polarized light illuminations [22]. Yue et al. proposed a multichannel full-dielectric metasurface and generated four vector beams with four polarization modes in different spatial positions [23]. Lv et al. obtained a high-order cylindrical vector beam using a metasurface consisting of rectangular nanoholes [24]. Teng et al. proposed a uniform theory for the generation of vector beams, with the help of the base transformation [25]. All these studies refer only to the generation of vector beams with a single polarization mode. So far, compound vector lights (CVLs) with multiple polarization modes distributed in different regions, like the double-ring vector beam [26–28], have been rarely studied using the metasurface.

In this paper, we propose the model of CVL and design the compound vector light generator (CVLG) based on a metasurface, which can generate the CVL with two or more spatially non-uniform polarization modes. The proposed CVLG consists of rotated cross nanoholes, and it works under linearly polarized light illumination. The cross nanoholes with the optimized parameters can realize 100% circular polarization conversion, and they effectively ensure the transmittance of a metasurface. The polarization modes of the generated CVL can be adjusted through changing the rotation angles of cross nanoholes. The design principle for CVLG is detailed in Section 2. The numerical simulations give the sound verification for the performance of the proposed CVLG. The generated compound vector beams have the advantage of parallel output, and they can provide more possibilities for the applications of vector lights in optical communication and optical micro-manipulation.

2. Design Principle

As we know, one cylindrical vector light can be expressed by two components of $\cos(m\varphi + \varphi_0)$ and $\sin(m\varphi + \varphi_0)$ in Cartesian coordinate, where $\varphi$ represents the azimuthal angle, $m$ denotes the order of vector light and $\varphi_0$ is the initial angle of the vector light [24]. Figure 1A gives the intensity and polarization distributions of the vector light with $m = 2$ and $\varphi_0 = 0$. The proposed compound vector beam consists of two or more vector modes distributed in different radial regions. Here, we choose the CVL consisting of two vector modes as an example to illustrate the design principle of CVLG, and it can be described as follows:

$$V_C = \begin{cases} A_1[\cos(m\varphi + \varphi_0)e_x + \sin(m\varphi + \varphi_0)e_y] & r < R \\ A_2[\cos(n\varphi + \varphi_0)e_x + \sin(n\varphi + \varphi_0)e_y] & r > R \end{cases}$$

(1)

where $A_1$ and $A_2$ represent the amplitudes of two vector lights, $e_x$ and $e_y$ denote the unit vectors along $x$ and $y$ directions, respectively, $m$ and $n$ are integers, and the radius of $R$ denotes the boundary of two radial regions. Figure 1B shows the intensity and polarization distributions for the CVL with $m = 2$, $n = 15$, $\varphi_0 = 0$ and the radius of $R$ taking 0.86 μm. The arrows inserted in the intensity patterns of Figure 1A,B denote the polarization states of the light field. One can see that the intensity and polarization distributions and the $x$ and $y$ components of intensity for the CVL have rotational symmetry.

In order to conveniently generate the CVL, we rewrite the expression of Equation (1) into the following form:

$$V_C = \begin{cases} B_1[\exp[j(m\varphi + \varphi_0)]e_R + \exp[-j(m\varphi + \varphi_0)]e_L] & r < R \\ B_2[\exp[j(n\varphi + \varphi_0)]e_R + \exp[-j(n\varphi + \varphi_0)]e_L] & r > R \end{cases}$$

(2)

where $B_1$ and $B_2$ represent the amplitudes, and $e_R$ and $e_L$ denote the unit vectors of the right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) light, respectively. This means that the CVL can be superposed by two RCP lights and two LCP lights, which carry the spiral phases with different topological charges (TCs). Figure 1C shows the phase distributions for RCP and LCP components, where two RCP components carry the spiral phases, with TCs taking 2 and 15, and two LCP components carry the spiral phases, with TCs taking $-2$ and $-15$. The superposition of these light beams can form the CVL, and the right pattern is the phase distribution of the generated CVL, where the region
with \( r < R \) is composed of four patches and the region with \( r > R \) is composed of 30 patches, and two adjacent patches have the phase of \( \pi \).

Figure 1. (A) Intensity and \( x \) and \( y \) components of intensity for the vector light with \( m = 2 \) and \( \varphi_0 = 0 \); (B) intensity and the \( x \) and \( y \) components of intensity for the CVL with \( m = 2, n = 15 \) and \( \varphi_0 = 0 \); (C) phase distributions for RCP and LCP components of the CVL and the phase distribution of CVL.

According to the above superposition principle, we designed the CVLG; Figure 2A shows the schematic diagram for the generation of CVL. The uniform linearly polarized (LP) light passes through the CVLG, and then the CVL appears at the propagation distance of \( f \) away from the CVLG. The designed CVLG consists of two sets of nanometer cross nanoholes etched on silver film, which are distributed in different radial regions. Figure 2B shows the structure of the CVLG, where the yellow circle with the radius of \( R \) denotes the borderline of two regions. As we know, the phase delay of the rotated nanohole equals twice the rotation angle of the nanohole, as seen in Figure 2C. Therefore, the phase distribution for the designed CVLG can be obtained through rotating nanometer holes. The rotation angle of the nanohole with the radial and azimuthal coordinates of \( r \) and \( \alpha \) satisfies the following expression:

\[
\theta = \frac{\pi}{\lambda} \left( \sqrt{r^2 + f^2} - f \right) + \frac{\pi}{\lambda} r \sin \beta + \frac{l \alpha}{2}
\]  

(3)

where \( \lambda \) represents the illumination wavelength, \( l \) takes an integer and \( \beta \) denotes an angle. The first term corresponds to the focusing phase of one equivalent lens with the focal length of \( f \), the second term corresponds to the focusing of one equivalent axicon with the deflection angle of \( \beta \) and the third term is with respect to the vortex with TC taking \( l \). For two sets of cross nanoholes of the CVLG, the value of \( f \) is the same, and yet the value of \( l \) and the value of \( \beta \) in two radial regions take different values.
Figure 2. (A) Schematic diagram for the generation of CVL. (B) P-B phases introduced by the rotated cross nanohole. (C) Schematic illustration of the proposed CVLG with $m = 2$ and $n = 15$. (D) Magnified part of the CVLG.

Figure 2D shows the magnified part of the CVLG, where the parameters of each cross nanohole, including the thickness of silver film and the size of cross nanohole, are optimized through the numerical simulation such that the cross nanohole can be taken as a half wave plate for the given wavelength of 632.8 nm. The same intensities and the phase difference of $\pi/2$ for the two orthogonal components of the transmission field through the cross hole are utilized to ascertain the parameters of the cross hole. Thus, through the optimization, the thickness of silver film takes 220 nm, and the size of the cross nanohole takes $L_1 = 600$ nm, $L_2 = 150$ nm, $L_3 = 220$ nm and $L_4 = 180$ nm. The cross nanohole can turn the incident circular polarization into the cross circular polarization, and the polarization conversion efficiency can reach almost 100% [29]. In our practical design, the cross nanoholes are arranged on the concentric rings, and the distance between two rings is set at 0.613 µm. The boundary of two sets of cross nanoholes takes $R = 15.5$ µm, and the position of the observation plane is set at $f = 10$ µm.

3. Simulation Verification for the CVL

In order to test the performance of CVLG, we constructed the metasurface structure and numerically simulated the intensity and phase distributions of CVLG. First, we designed one vector beam generator and simulated the generation of the simple vector beam, which can be expressed by $[\cos(mp), \sin(mp)]$, namely the part of Equation (1) with $r < R$. Figure 3 shows the simulated intensity and phase distributions of the generated vector beam with $m = 2$ under different polarization light illuminations. Figure 3A,B give the results for the generated vector light with LCP and RCP light illumination, and Figure 3C,D give two orthogonal components for the generated vector light with LP light illumination. The inserted white arrows denote the illumination polarization, and the red arrows represent the detection polarization.
From Figure 3A, one can see that, with LCP light illumination, the transmission intensity takes an annular shape and the spiral phase changes two times $2\pi$ along the anti-clockwise direction. This indicates that a vortex of 2 order exists. Similarly, the results in Figure 3B show the transmission intensity with RCP light illumination also takes an annular shape, and yet the spiral phase changes two times $2\pi$ along the clockwise direction. This means a vortex of $-2$ order forms. Obviously, these results are consistent with the former theoretical predictions. Under the LP light illumination, four symmetric bright spots appear in the intensity distributions of Figure 3C,D, and the adjacent regions have the phase step of $\pi$, which is the same as in the case of Figure 1A. These results show the generated light is just the simple vector light.

We designed the CVLG, with a structure similar to that shown in Figure 2C, and then simulated the diffraction intensity and phase distributions with different polarization light illumination. Figure 4 gives the simulation results of the CVLG with $m = 2$, $n = 15$, $\beta_1 = 30^\circ$ and $\beta_2 = 70^\circ$. Figure 4A,B give the diffraction intensity and phase distributions with LCP and RCP light illumination, and Figure 4C,D give two orthogonal components for the generated CVL with LP light illumination, where the inserted white arrows denote the illumination polarization and the red arrows represent the detection polarization direction. For convenience of observation, the boundary of two regions for the CVLG is highlighted by a dark ring.
Figure 4. (A) Intensity and phase distributions of vortex beam under LCP light illumination; (B) intensity and phase distributions of vortex beam under RCP light illumination; (C) intensity and phase distributions of vector beam under LP light illumination and with the detection along the vertical direction; (D) intensity and phase distributions of vector beam with the detection along the horizontal direction. Note: white arrows represent the polarization state of incident light, and red arrows represent the detection polarization direction.

From Figure 4A, one can see the compound vortex with concentric annular intensities that is generated and that the spiral phases in inner and outer regions have different TCs. With LCP light illumination, the inner phase changes two times $2\pi$ along the anti-clockwise direction, which means the TC of vortex is 2. The outer phase changes 15 times $2\pi$ along the anti-clockwise direction, which indicates the TC of vortex is 15. Similarly, the results in Figure 4B show a compound vortex, with TCs of inner and outer vortices of $-2$ and $-15$ with RCP light illumination, because the inner phase changes two times $2\pi$ along the clockwise direction and the outer phase changes 15 times $2\pi$ along the clockwise direction. These results correspond to the contributions of LCP and RCP parts at two regions of Equation (2). Under the LP light illumination, the symmetric bright spots located on two concentric circles of Figure 4C or Figure 4D are the same as the case of Figure 1B. The phase step of $\pi$ between the adjacent regions also indicates the generation of the CVL.

The parameters of cross nanoholes for the proposed CVLG are only available for the wavelength of 632.8 nm, and if the illuminating wavelength changes, the parameters of cross nanoholes must change too so as to be equivalent to the half wave plate with respect to the corresponding wavelength [30]. During the practical design of any CVLG, it should be noted that the order of the vector beam in the outer region should be much bigger than that in the inner one. This is because the interference of the inner and outer vector beams results in the CVL being damaged or even invisible, as their orders are close. Moreover, in order to avoid the interference of the diffraction rings, the equivalent axicon must be added in the design of the CVLG. Otherwise, the secondary annular intensity of the inner vector light modulates the vector light, and it makes the annular intensity discontinuous [31]. Though one simple CVL consisting of two vector modes is presented here, the design principle is also available for the generation of the complex CVL. This work lays the basis for the generation of more complex CVLs.

It should be pointed out that the simulated results in this paper are obtained using the finite difference time domain method [32,33]. The complex dielectric constant of silver is
$\varepsilon = -15.92 - j1.075$ for the wavelength of 632.8 nm, which is taken from the value given by Palik [34]. The perfectly matched layer is chosen as the adsorbing boundary to prevent non-physical scattering at the boundary; the mesh type is set at the auto non-uniform mode, and the minimum mesh cell is 2 nm. The calculation region is set at 40 $\mu$m $\times$ 40 $\mu$m $\times$ 13 $\mu$m, and the monitor plane is set at 10 $\mu$m above the silver film. Moreover, considering the peak intensity for the high-order vector light is lower than that of the low-order vector light with the same transmittance, more nanoholes are utilized to form the high-order vector light. The inner region for the CVLG is from about 4 $\mu$m to 15 $\mu$m, and the outer region is from about 16 $\mu$m to 33 $\mu$m.

The practical experiment can be also achieved if the metasurface sample for the CVLG is prepared. As for the preparation of the metasurface sample, a silver film with the default thickness should be first deposited on the glass substrate using any film growth technique, like the magnetic-controlled sputtering method. The sputtering power, the vacuum degree, the argon partial pressure and the time should be adjusted according to the structure parameter of sample. The fabrication process can be done by means of a nanofabrication technique like the focused ion beam etching method, where the voltage and the current should be reasonably set. The parallel light impinges on the fabricated CVLG sample, and the intensity distribution at the observation plane can be detected by two-dimensional CCD.

4. Conclusions

In this paper, we propose a model of CVL and design the CVLG based on cross nanoholes. In order to improve the working efficiency of the proposed CVLG, the cross nanoholes equivalent to the half wave plates are chosen to construct the CVLG. The structure of the CVLG is built, and transmission intensity and phase distributions for CVLG are simulated with the help of the finite-difference time-domain technique. The simulation results for the generated CVL verify the performance of the proposed CVLG. The proposed CVLG works under linear polarized light illumination, and the order of CVL can be controlled by the rotation of cross nanoholes. Therefore, our proposed CVLG has the advantages of ultra-thin thickness, compact structure, high working efficiency and simple operation. Our work provides the foundation for complex structured light generation, and it contributes to expanding the applications of vector lights. In our following work, we will further generate different CVLs with high quality and form the more complex CVLs, where the metasurface holography can be utilized [35].

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