Metasurface cylindrical vector light generators based on nanometer holes

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Abstract

A kind of metasurface cylindrical vector light (CVL) generator in the visible region is proposed. This kind of CVL generator consists of nanometer holes etched on silver film, and it can change any linearly or circularly polarized light into the CVL in nanoscale. The order of the generated CVL is controlled by the rotation of the holes and its polarization state changes with the incident polarization condition. The base transformation theory guides is used to design the metasurface. The numerical simulations for the transmission of the proposed CVL generators confirm the validity of the theoretical predictions, and they also provide the available parameters for practical metasurface devices. The experimental results verify the performance of the proposed metasurface CVL generators. This kind of vector light generator has the advantages of thin and compact structure, polarization multiplexing and convenient manufacture. This work paves a new path for designing the miniature devices to generate the vector light field and it will promote the applications of polarization devices in optical integration and micro-manipulation.

1. Introduction

Cylindrical vector light (CVL) refers to the light whose polarization is centrosymmetric in the plane perpendicular to the optical axis [1]. As the typical CVLs, the radial and azimuthal vector light with the polarization direction along the radial and azimuthal direction attract much attention because of the characteristics of the tight focusing [2, 3] and larger longitudinal focal field component [4]. And they have been widely used in particle manipulation [5, 6], laser machining [7, 8], optical imaging [9, 10] and so on. CVLs with different spatial nonuniform polarization provide more possibilities for the optical manipulation.

Till now, various techniques including active and passive methods have been proposed to generate the vector lights. The active methods realize the vector light generation using the laser cavity element to drive the laser oscillation in cylindrical vector mode [11–13]. The passive methods usually act with the help of spatial light modulator or q-plate [14–17] and few-mode fiber [18]. With comparison to the active methods requiring precise adjustment, the passive methods have much more flexibility. Relative to these two above traditional methods, the metasurface consisting of subwavelength structures can control effectively the light field in nanometer scale. Metasurface devices open the way for the optical integration circuit because of its compact structure.

Metasurface can be used to control the polarization state of the light field. Several researches have studied the vector light generation [19–22]. Bomzon et al used spatially varying subwavelength gratings equivalent to quarter wave plates to realize the radial and azimuthal vector light generation [19]. Kang et al proposed a metasurface composed of rectangular nanoholes equivalent to polarizers, and obtained the azimuthal vector light by adjusting the incident circularly polarized light [20]. Among these two works and the recent study [22], the generated vector lights carries extra helical phases. Yu et al obtained the pure radial and azimuthal vector light by using the double-layer rectangular nanoholes with the adjustable separation and size [23]. The single layer metasurface can bring the convenience to the practical manufacture with respect to the multilayer
metastructure. Zhao et al used the single-layer metasurface consisting of the dielectric pillars to obtain the general radial and azimuthal vector light \([24]\), and this work was performed in the near-infrared band. In our former studies, we designed the metasurfaces consisting of nanometer holes and obtain the radial and azimuthal vector light under the different polarized light illumination in visible region \([25–27]\).

This paper aims to generate the pure higher order CVL in nanoscale based on the simple metasurface with the linearly or circularly polarized light illumination. Theoretically, the base transformation method is proposed and the dependence relation of the transmission polarization state with the metastructure parameters and the illumination condition is provided. The metasurface structures to generate the CVLs are designed under the theoretic instruction and optimized on basis of numerical simulation. Our designed metasurface CVL generators consist of nanometer silver holes and they take effect in visible light. The order of CVL can be flexibly adjusted and its polarization state can be easily changed. Theoretic analysis, numerical simulations and practical experiment confirm the performance of the generated CVLs. This study presents the important reference for designing nanometer polarization devices and manipulating the light field in nanoscale.

2. Basic theory

As we know, the CVL in the Cartesian basis can be expressed as,

\[
i_x = \left( \begin{array}{c}
\cos(n\varphi + \varphi_0) \\
\sin(n\varphi + \varphi_0)
\end{array} \right),
\]

where \(\varphi\) is the position angle of the CVL field at one point, \(n\) is the order of the CVL and \(\varphi_0\) is a constant representing the initial phase. As \(n = 1\) and \(\varphi_0 = 0\), it is the so-called radial vector light, and as \(n = 1\) and \(\varphi_0 = 90^\circ\), it is the so-called azimuthal vector light. Here, we call the CVL of any order with \(\varphi_0 = 0\) as the general radial vector light and the case with \(\varphi_0 = 90^\circ\) as the general azimuthal vector light.

The polarization state of the CVL in the space changes with the values of \(n\) and \(\varphi_0\), and figure 1 shows the spatial polarization distributions of the CVL fields on one transverse observation plane. Where the results in figures 1(A)–(D) correspond to the CVLs with the order \(n\) taking 1, 3, 5 and 7, and from left to right, the constant phase \(\varphi_0\) takes 0°, 30°, 60° and 90°. The inserted grayscale patterns in the lower right corners are the \(y\) component of the CVL intensity distributions. It is easy to see that the spatial polarization for CVL has the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Spatial polarization distributions of CVLs with the order of \(n\) taking 1(A), 3(B), 5(C) and 7(D) and the constant phase of \(\varphi_0\) taking 0°, 30°, 60° and 90°, respectively. The inserted grayscale patterns are \(|E_y|^2\) transmitted by CVLs.}
\end{figure}
cylindrical symmetry with respect to the central axis, the CVL field takes on petal-like intensity distributions and the higher order CVL has more petals. Moreover, the polarization direction deflects and the petal-like intensity distribution rotates with increase of the initial phase $\varphi_0$.

In order to generate the high order CVL by using the metasurface, we perform the detailed theoretical analysis. We first construct a polar base, where the light vector in the Cartesian basis can be changed into the form in this polar base through the transformation of $\mathbf{i}_p = \mathbf{A}^{-1} \mathbf{i}_e$, like our former work [27]. The transformation matrix $\mathbf{A}$ and its inverse matrix $\mathbf{A}^{-1}$ take the following forms,

$$\mathbf{A} = \begin{pmatrix} \cos n\varphi & -\sin n\varphi \\ \sin n\varphi & \cos n\varphi \end{pmatrix}, \quad \mathbf{A}^{-1} = \begin{pmatrix} \cos n\varphi & \sin n\varphi \\ -\sin n\varphi & \cos n\varphi \end{pmatrix}. \tag{2}$$

Thus, the orthogonal vectors of $\mathbf{i}_e = (\cos n\varphi, \sin n\varphi)$ and $\mathbf{i}_e = (-\sin n\varphi, \cos n\varphi)$ in Cartesian basis can be rewritten into $\mathbf{i}_p = (0,1)$ and $\mathbf{i}_p = (1,0)$ in polar base, and the general CVL in equation (1) can be expressed by $(\cos \varphi_0, \sin \varphi_0)$.

For the anisotropic metasurface unit with the angle $\alpha$ between its fast axis and the x axis, its Jones matrix $\mathbf{T}_e$ can be expressed by four components of $T_{xx} = a_e \cos^2 \alpha + a_i \sin^2 \alpha e^{i\delta}$, $T_{xy} = T_{yx} = (a_e - a_i) \sin \alpha \cos \alpha$ and $T_{yy} = a_e \sin^2 \alpha + a_i \cos^2 \alpha e^{i\delta}$ in the Cartesian base, where $a_e, a_i$ and $\delta$ denote the amplitudes along the x and y axis and their phase delay.

The corresponding Jones matrix in polar base can be deduced by $\mathbf{T}_p = \mathbf{A}^{-1} \mathbf{T}_e \mathbf{A},$

$$\mathbf{T}_p = \frac{1}{2} \begin{pmatrix} A + B \cos 2(\alpha - n\varphi) & B \sin 2(\alpha - n\varphi) \\ B \sin 2(\alpha - n\varphi) & A - B \cos 2(\alpha - n\varphi) \end{pmatrix}, \tag{3}$$

where $A = a_e + a_i e^{i\delta}$ and $B = a_e - a_i e^{i\delta}$. Then the light vector $\mathbf{t}_p$ passing through the metasurface unit satisfies $\mathbf{t}_p = \mathbf{T}_p \mathbf{i}_p$, with the incident light vector $\mathbf{i}_e$ having two components of $i_1$ and $i_2$ in polar base. After the matrix operation, the transmitted light vector can be derived into,

$$\mathbf{t}_p = \frac{1}{2} \begin{pmatrix} A i_1 + B i_1 \cos 2(\alpha - n\varphi) + B i_2 \sin 2(\alpha - n\varphi) \\ A i_2 + B i_1 \sin 2(\alpha - n\varphi) - B i_2 \cos 2(\alpha - n\varphi) \end{pmatrix}. \tag{4}$$

If the metasurface unit can be taken as an equivalent quarter-wave plate (QWP), namely $A = 0 + j$ and $B = 1 - j$, the transmission polarization can be expressed into $2^{-1/2}(e^{j\pi/2} i_1 - j i_2 \sin 2(\alpha - n\varphi) + j i_2 \cos 2(\alpha - n\varphi))$. For the incident circularly polarized light, it can be written as $2^{-1/2}(e^{j\pi/4} i_1 + j i_2 \sin 2(\alpha - n\varphi) + j i_2 \cos 2(\alpha - n\varphi))$. Then the general azimuthal polarization with any initial angle can be denoted by $\cos(\theta - n\varphi), \sin(\theta - n\varphi)$ in polar base and the transmission light vector can be deduced into $[\cos(2\alpha - \theta - n\varphi), \sin(2\alpha - \theta - n\varphi)]$. Comparing this expression with equation (1), we can easily obtain $[\cos(\theta - n\varphi), \sin(\theta - n\varphi)]$ as $2\alpha = n\varphi$, and it is equivalent to the CVL with $\varphi_0 = -\theta$. Moreover, the general radial polarization $(1,0)$ is obtained as $\alpha = (\theta + n\varphi)/2$ and the general azimuthal polarization $(0,1)$ is generated as $\alpha = (\theta + n\varphi)/2 + \pi/4$. Certainly, two cases of $\theta = 0$ for $\alpha = (\theta + n\varphi)/2 + \pi/4$ and $\theta = \pi/2$ for $\alpha = (\theta + n\varphi)/2$ are equivalent. This indicates that for the same metasurface with $\alpha = n\varphi/2 + \pi/4$, the transmission is the general radial polarization with $\theta = 0$ and changes the general azimuthal polarization with $\theta = \pi/2$. As the incident angle takes other value, it is the general CVL with $\varphi_0 = \pi/2 - \theta$. Obviously, this metasurface structure has the polarization multiplexing and the generated polarization state changes with the incident polarization condition.

Equation (4) exhibits the dependence relation of the transmission polarization with the incident polarization and the metasurface unit. It predicts that the circular polarization light can be changed into the general radial or azimuthal polarization light with zero initial angle and the linear polarization light can be also changed into the general CVL with any initial angle through the desired metasurface. In the following sections, we will give the corresponding simulation and experiment verification.

3. Numerical simulations

We can design the metasurface CVL generator on basis of the above theoretical analysis. The CVL generator consists of the identical nanometer holes etched on the silver film deposited on the glass substrate. Here, two kinds of CVL generators are proposed and their elementary units are the rectangular holes and the cross holes, as
shown in figure 2. Figure 2(A) is for the first kind of CVL generator, where the rectangular holes locate on the spiral trajectory with the radius of \( r = r_0 + n \lambda \varphi / 2 \pi \) so as to delete the additional phase delay. The fast axis of the rectangular hole along its longer edge rotates with the position angle and rotating angle satisfies \( \alpha = n \varphi + \pi / 4 \). This structure can generate the nth order radial CVL with the right-handed circularly polarized light illumination. The magnified picture shows intuitively the orientation of one rectangular hole.

In order to obtain the high order CVL, we first optimize the film thickness and the size of the rectangular hole and make it equivalent to the QWP which can change the linear polarization into the circular polarization. The equivalent amplitudes of \( E_x \) and \( E_y \) and the phase delay \( \pi / 2 \) along the z axis transmitting through one rectangular hole under the linearly polarized light illumination should be satisfied, like the simulated curves in figure 2(A). Meanwhile, the transmission transverse phase distribution of the rectangular hole, as the color pattern shown in figure 2(A), just corresponds to the case of the circular polarization. Where the phase for the incident linear polarization is also inserted in the lower right corner. The optimized parameters for the rectangular hole are the length \( l = 310 \) nm, the width \( w = 200 \) nm and the thickness of the silver film \( h = 200 \) nm with respect to the incident wavelength of 633 nm. The number of rectangular holes is 72 and the duty cycle of the total area of holes in the occupied ring with the width of 366 nm is about 35.7%.

Figure 2(B) is for the second kind of CVL generator, where the cross holes are used as the metasurface units and all cross holes locate on one circle with the radius \( r \). The rotation angle of cross hole and its position angle \( \alpha = n \varphi / 2 + \pi / 4 \), which can be seen clearly from the magnified picture of the cross hole shown in figure 2(B). These identical cross holes are equivalent to half wave plates with the fast axis along the longer edge of the cross hole and they can change the circular polarization into its cross polarization. \( E_x \) and \( E_y \) distributions along the z axis for the optimized cross hole under the left-handed circularly polarized light illumination have the equivalent amplitudes and the phase delay of \( \pi / 2 \), and they prove the transmission field of the optimized cross hole is the right-handed circularly polarized light. The transmission phase distribution is just the cross circular polarization with respect to the inserted incident circular polarization, as shown by the color patterns of figure 2(B). The parameters of the optimized cross hole are the length of \( l_x = 600 \) nm and the width of \( w_x = 150 \) nm for one hole, the length of \( l_o = 220 \) nm and the width of \( w_o = 180 \) nm for the other orthogonal hole and the film thickness of \( h = 220 \) nm. The number of cross holes is 60 and the duty cycle of the holes in the occupied ring with the width of 600 nm is about 21%.

The efficiency of any structure is roughly estimated according to the above-mentioned duty cycle of rectangular holes and yet the practival efficiency of any structure is lower than this value. For our designed CVL generators, we simulate their transmission using the finite difference time domain method [28]. For the incident wavelength of 633 nm, the dielectric constant of silver takes the value given by Palik [29]. Figure 3 shows the structures of the first kind of CVL generators and the simulation results for the distributions of the transmission intensity component \( |E_y|^2 \). Where figure 3(A) is for the case with the relations of \( \alpha = n \varphi + \pi / 4 \) and \( r = r_0 + n \lambda \varphi / 2 \pi \) satisfied and the incident polarization taking right-handed circular polarization. Similarly, figure 3(B) gives the case with the relations of \( \alpha = n \varphi - \pi / 4 \) and \( r = r_0 + n \lambda \varphi / 2 \pi \) satisfied and the incident polarization taking left-handed circular polarization. The initial radius of the spiral takes \( 12 \lambda_{\text{app}} \) with \( \lambda_{\text{app}} = 613 \) nm and the value of \( n \) takes 1, 2 and 3. The observation plane is set 3 \( \mu \)m above the silver film. From the results of figure 3, we can see that the transmission intensity distributions consist of the cylindrical symmetric petal-like spots. The bright spots get more with increase of the order of CVL. Comparing the results in figures 1
and 3, we can see that the results of figure 3(A) just correspond to the ones of figure 1 with \( \varphi_0 = \pi / 2 \), and the results of figure 3(B) just correspond to the ones of figure 1 with \( \varphi_0 = 0 \). These results mean that the general radial and azimuthal vector lights are generated by using this kind of CVL generators with the circularly polarized light illumination. However, these structures only generate the \( n \)-order CVLs with zero initial phase. Furthermore, we design the second kind of CVL generators consisting of the cross holes on one circle with \( r = 7.5 \, \mu m \) and the orientation angle of the cross hole satisfies \( \alpha = n \varphi / 2 + \pi / 4 \), as shown in figure 4. Figure 4(A) gives the structure of the 1-order CVL generator and the transmission light intensities of \( |E_y|^2 \) when the incident polarization angle takes 0°, 30°, 60°, and 90°. Similarly, figures 4(B)–(D) give the structures of the 3-, 5- and 7-order CVL generators and the corresponding transmission intensity distributions with different linearly polarized light illumination. These results are detected at the observation plane of 6 \( \mu m \) above the silver film.

From figure 4, we can see that the more bright spots appear among the patterns of the higher order CVLs. As the incident polarization angle rotates, the pattern seems to rotate too. Comparing these results with the ones shown in figure 1, we can see that the result for the certain incident angle \( \theta \) just corresponds to the polarization state of \( \pi / 2 - \varphi_0 \). These results are the same as the theoretical predictions and they also indicate that the second kind of CVL generators can generate the CVL with any order and any initial phase. Meanwhile, for one metasurface structure, the multiple polarization states can be obtained through changing the incident polarization. Therefore, this design behaves the characteristic of the polarization multiplexing.

4. Experimental measurement

In order to testify the performance of the proposed CVL generators, we manufacture two samples for the second kind of CVL generators with the order of \( n \) taking 3 and 5. Silver film with the thickness of 220 nm is first deposited on a glass substrate by using the magnetron sputtering deposition method, and then the nanometer holes are etched in the silver film with the help of the focused ion beam etching technique. Each sample consists of 60 cross holes etched on the silver film and arranged on the circle with \( r = 7.5 \, \mu m \). The parameters of the cross holes are the same as the above theoretic values. One hole of the cross hole has the length of 600 nm and the width of 150 nm and the other hole has the length of 220 nm and the width of 180 nm.

The scanning electron microscope (SEM) images of the samples are shown in figures 5(b) and (g). Put one CVL generator sample into the experimental setup of figure 5(a), we can measure its transmission intensity distribution with the linear polarization light illumination. The light beam from a He–Ne laser passes through
the combination of a QWP and a polarizer (P1) and changes into the needed linear polarization. Then the light beam illuminates the fabricated sample (S) from the glass substrate, and a microscopy objective (MO) magnifies the generated vector field and a charge-coupled device (CCD) with No. DU-888U3 receives the magnified

Figure 4. Structure diagrams of the second kind of CVL generators and the simulation intensities \( |E_y|^2 \) with the incident polarization angle taking \( 0^\circ, 30^\circ, 60^\circ \) and \( 90^\circ \).

Figure 5. Experimental setup (a), the SEM images of the CVL generator samples ((b) and (g)) and the corresponding experimental results ((c)–(f) and (h)–(k)).
intensity distribution. The polarizer P1 changes the incident polarization direction and the polarizer P2 extracts the y component of the transmission intensity. The density filter DF controls the incident intensity.

Figures 5(c)–(f) show the experimental results for sample 1 with the incident polarization angle taking 0°, 30°, 60° and 90°, and figures 5(h)–(k) show the experimental results for sample 2 under the same illumination conditions. We can see that the measured results are consistent with the simulated results of figure 4 and they also verify the theoretical predictions. These results indicate that our proposed metasurfaces generate the high order CVLs and the performance of the proposed CVL generators is reliable though only the experimental results for two samples are provided. It needs to be pointed out that the theoretical prediction about the metasurface device consisting of rectangular holes can be also verified in a similar way.

5. Conclusions

In summary, two kinds of simple metasurface CVL generators are proposed based on identical nanometer holes etched on silver film, and they can control the polarization state in nanoscale and generate the higher order CVL. The base transformation theory is utilized to provide the design principle for two kinds of CVL generators. The first kind of CVL generators acts under the circularly polarized light illumination and they can obtain the general radial and azimuthal CVLs with zero initial phase. The second of CVL generators takes effect under the linearly polarized light illumination and they can generate the CVL of any order with any initial phase. Most of important, this kind of CVL generators have the properties of polarization multiplexing. The theoretical analysis, numerical simulations and experiment measurement verify the polarization controllable performance of the proposed CVL generators. This work provides a method to manipulate artificially the polarization state of light field by using the simple metastructure, and the advantages including ultrathin thickness, compact structure, convenient fabrication, flexible manipulation and multiple function must expand the applications of metasurface CVL generators in integrated optics and optical micromachination.

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