Generation of optical chains by phase-modulated radially polarized beams based on polarization-insensitive metalenses

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ABSTRACT

Optical chains have received widespread attention due to their unique characteristics of high intensity and multiple potential wells. Many methods have been used to generate optical chains, such as using diffractive optical elements or 4Pi systems to modulate vector beams. But these methods require additional phase elements or more complex optical systems. In this work, a single-layer polarization-insensitive metalens with phase distribution of the binary optical element was used to focus the radially polarized beam to generate optical chains. The Richards-Wolf vector diffraction theory was employed to calculate the focal field distribution of the radially polarized beam. Optical chains generated by both the simulated and theoretical calculation are composed of alternating solid points and bubbles which indicates that the theoretical results are in agreement with the simulation results. The introduction of metalens reduces the volume of the optical system, which is conducive to the miniaturization and integration of the optical system. This work may contribute to particle trapping and manipulation, optical micro-nano processing, etc.

Keywords: Optical chains; radially polarized beam; polarization-insensitive metalens

1. INTRODUCTION

The special focal field distributions, such as needle beams [1], optical chains [2], and bottle beams [3], by tightly focusing vector beams through high numerical aperture (NA) lenses have received particular attention. Due to their unique focal field distribution, optical chains have great potential in particle trapping [4] and manipulation [5-7], optical micro-nano processing [8, 9], etc. In recent years, many methods have been used to generate optical chains, such as using diffractive optical elements [10-12] or 4Pi systems [13-16] to modulate vector beams. But these methods require additional phase elements or more complex optical systems.

Metasurface can not only modulate the amplitude, polarization, and phase of the incident light but also achieve miniaturization and integration of optical elements. The functions of some elements such as lenses [17], polarization converters [18], etc., can be achieved by metasurface. Among these polarization-insensitive (PI) metalenses can modulate the phase of incident light to produce special optical fields [19,20], which may provide a new possibility to generate optical chains.

In this work, a single-layer PI metalens with phase distribution of the binary optical element (BOE) was used to focus the radially polarized (RP) beam to generate an optical chain. In addition, the Richards-Wolf vector diffraction theory was employed to calculate the focal field distribution. The generating optical chain may as an effective tool for the capture, transfer, and self-assembly of multiple particles.

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2. THEORY AND METHOD

2.1 Theoretical study of focused RP beams

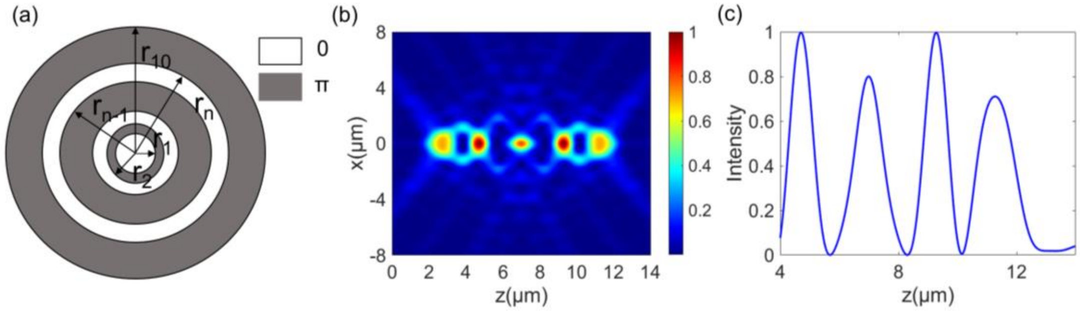

Figure 1. (a) structural diagram of the 10-ring BOE. The gray and white areas indicate phase values of π and 0, respectively. Mathematical calculations of highly focused RP beam. (b) refers to the focal field distribution in the x-z plane. (c) refers to the intensity distribution on the optical chain z-axis.

According to the Richards-Wolf vector diffraction theory [21], under the illumination of RP beams, the electric field near the focus can be expressed as:

$$\vec{E}(r,\phi,z)=\begin{bmatrix}E_r\\E_z\\E_\phi\end{bmatrix}=\begin{bmatrix}A\sum_{i=1}^{10}\int_{\theta_{i-1}}^{\theta_i}\sqrt{\cos\theta}\sin(2\theta)P(\theta)l(\theta)e^{ikz\cos\theta}J_1(kr\sin\theta)d\theta\\2iA\sum_{i=1}^{10}\int_{\theta_{i-1}}^{\theta_i}\sqrt{\cos\theta}\sin^2(\theta)P(\theta)l(\theta)e^{ikz\cos\theta}J_0(kr\sin\theta)d\theta\\0\end{bmatrix}, \quad (1)$$

In Eq. (1), A is a constant, θ_i is the angle between the converging ray and the optical axis ($\theta_{\max}=\arcsin(\mathrm{NA})$, where NA is 0.83), k is the wave number, $P(\theta)$ is the pupil function, J_n denotes the nth-order of Bessel function of the first kind, and $l(\theta)$ is the amplitude distribution of the incident beam. For incident Bessel-Gaussian beam, the $l(\theta)$ can be expressed as:

$$l(\theta)=\exp[-\beta^2(\frac{\sin\theta}{NA})^2]J_1(2\beta\ \frac{\sin\theta}{NA}). \quad (2)$$

In Eq. (2), β represents the ratio of the pupil radius to the beam width, whose value is 1. After the BOE is introduced, $l(\theta)$ in Equation 1 becomes $l(\theta)T(\theta)$, and $T(\theta)$ ($T(\theta)=\exp(i\varphi_{\mathrm{BOE}})$, φ_{BOE} is the phase of the BOE) is the transmissivity which can be expressed as:

$$T(\theta)=\begin{cases}1, & \theta_{i-1}<\theta<\theta_i\\-1, & \theta_{i-2}<\theta<\theta_{i-1}\end{cases}. \quad (3)$$

Among them, the relevant parameters of BOE are as follows:

$$\begin{gathered}\theta_1=4.65^\circ,\theta_2=11.25^\circ,\theta_3=11.66^\circ,\theta_4=22.28^\circ,\theta_5=30.60^\circ,\\\theta_6=36.78^\circ,\theta_7=38.10^\circ,\theta_8=44.44^\circ,\theta_9=48.19^\circ,\theta_{10}=56.10^\circ\end{gathered}. \quad (4)$$

Corresponding radial position can be expressed as $r_i=\sin\theta_i/NA$. The 10-ring BOE structure diagram is shown in Figure 1(a), where the phases of the gray and white areas are π and 0, respectively. Figure 1(b) shows the focal field distribution obtained by theoretical calculation. It is obvious that the focal field presents the shape an of optical chain, with alternating solid points and bubbles. The intensity distribution on the optical chain axis obtained by theoretical calculation is shown in Figure 1(c). It can be seen that the field intensity of each solid point is relatively consistent.

2.2 Design of PI metalens

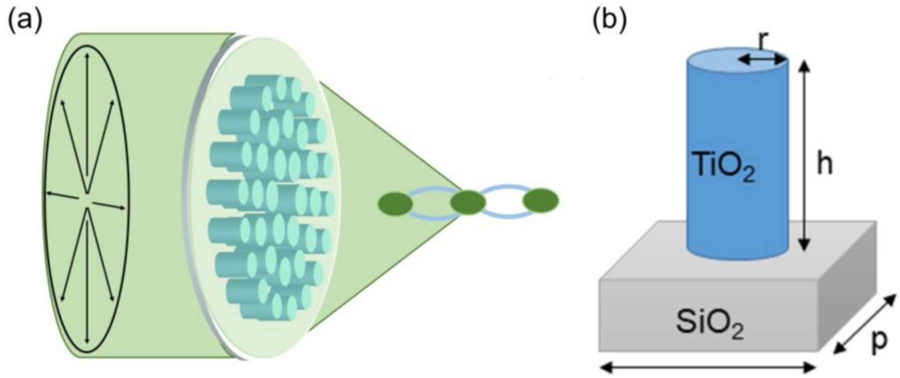

Figure 2 (a) Schematic diagram of the optical chain generated by the PI metalens. (b) Side view of a nanopillar. h and p represent the height and lattice constant of the nanopillar and the values are 600 nm and 370nm, respectively.

The designed metalens with an illumination of the RP beam can form the optical chain, as shown in Figure 2(a). The metalens consists of SiO_2 substrates and TiO_2 arrays of nanopillars, as shown in Figure 2(b). The wavelength of incident light is 532 nm, and the corresponding refractive indices of SiO_2 and TiO_2 are 1.46 and 2.46, respectively. The interaction between light and nanopillars of metalens leads to the local phase change, which is related to the geometric shape, size, and material characteristics of the nanopillars. In order to realize the beam focusing, the abrupt phase generated by each nanopillar at an arbitrary position (x, y) meets:

$$\varphi_f(x,y) = k(\sqrt{x^2+y^2+f^2} - f), \tag{5}$$

here, f is the focal length of metalens. In order to make the focal field of the beam appear the distribution of the optical chain, it is also necessary to load the phase distribution of BOE on the metalens. Next, the phase of the arbitrary point on the metalens can be expressed as:

$$\varphi = \varphi_f(x,y) + \varphi_{BOE}. \tag{6}$$

To sum up, the designed metalens can generate optical chains by phase-modulating RP beam.

3. RESULTS AND DISCUSSIONS

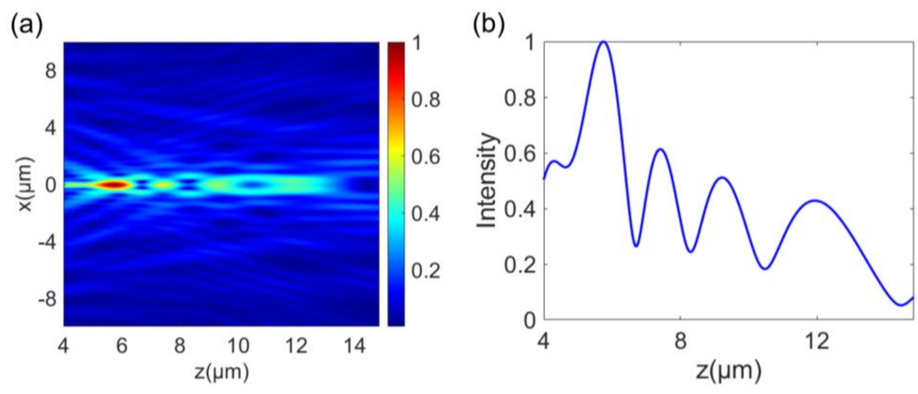

Figure 3 Simulated calculations of highly focused RP beam under NA = 0.83. (a) refer to the focal field distributions on the focal x-z plane. (b) refers to the intensity distribution on the optical chain axis.

The electric field distribution on the propagation plane is simulated by the FDTD method. In the following simulation, the radius R of the metalens is 10 μm, NA is 0.83, the mesh step size is 30 nm in the x, y, and z directions, and the perfectly matched layers are set along the x, y, and z directions. As shown in Figure 3(a), it can be seen that the optical chain can be generated by our designed metalens. The intensity distributions of the solid points are not as uniform as shown in Figure 3(b), this may be due to the inconsistent transmissivity of nanopillars. The results of focal field distribution are in good agreement with those in Figure 1(b). Therefore, the PI metalens loaded with BOE phase distribution can generate optical chains through a phase-modulated RP beam.

4. CONCLUSIONS

In conclusion, the designed single-layer PI metalens combined with the BOE phase modulated the RP beam successfully and generated the optical chains. The simulation results of focal field distribution were consistent with the theoretically calculated results based on the Richards-Wolf vector diffraction theory. The generating optical chains are composed of multiple solid points and bubbles. The single-layer metalens was introduced to simplify the optical system required to generate the optical chains, which may contribute to particle trapping and manipulation, optical micro-nanofabrication, etc.

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