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Creation of super-length optical tube by phase modulated azimuthally polarized beam with multi-zone phase filter

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ABSTRACT

We suggest a new approach to utilize a multi-zone phase filter along with a high NA lens axicon to accomplish a subwavelength focal hole with large uniform focal depth by means of azimuthally polarized Bessel–Gaussian beam. The intensity distributions are obtained and calculated based on the vector diffraction theory, the recommended system generates a subwavelength super-length optical tube with a sub diffraction beam size of 0.494 λ and long focal depth is approximately 63.6 λ in free space. We also established that the focal depth and sub diffraction beam size is dependent relative on focusing condition of the numerical aperture. The authors presume such a high intense tube beam may perhaps find the applications in atom optics, optical manipulations, optical trapping and optical processing technologies.

1. Introduction

In latest years, a subwavelength optical tube beams with a long depth of focus (DOF) in the focal region has been achieving a research attention for their practical applications. Optical beams with zero on-axis intensity bounded beside the regions of higher intensity in all three directions are popularly known as optical tube beams [1]. This tube beams may have many applications, particularly in atom optics to exact molecule identification, dark regions of zero intensity is necessary [2–4]. Tube beams can be also recognized by placing binary phase plate [5], multi-belt binary optical phase elements [6] or amplitude filters [7] on the lens pupil. A subwavelength light needle have DOF is around 4 λ has been formed by focusing a radially polarized beam with a high numerical aperture (NA) objective lens and binary phase optical element [5,8]. Recently, a effectively created a excellent focal spot, where the spot size, focal depth and the side lobe intensity are 0.41 λ, 9.53 λ and 16.35% by tight focusing of a higher-order radially polarized beam with the seventeen-belt binary phase pupil filters [9]. Creation of a non-diffracting transversally polarized beam by highly focusing an azimuthally polarized Bessel–Gaussian (BG) beam with high NA lens and a multi-belt spiral phase mask is also verified numerically [10].

A subwavelength size focal hole with a relatively long DOF (26 λ) was accomplished near the focus by a double-ring-shaped azimuthally polarized beam with annular filter under the high NA focusing condition [11]. However, the proposed method is easy and liberated from the complex interferometric techniques used in the conventional methods to create focal hole and a lot of energy of the incident light beam is blocked by the middle part of the annular aperture. Conquer this difficulty for the azimuthal polarization counterpart, a subwavelength size (0.5 λ) "dark channel" with a long DOF (48 λ) was more recently achieved by tight focusing of a double-ring-shaped azimuthally polarized beam with the help of high NA lens axicon [12]. Usually the axicon lens and holographic axilens are used to generate long DOF at axial direction [13,14]. Diffractive optical elements (DOE) (phase and amplitude filters) have been also used to achieve long DOFs. It is capable to reduce the concession between the NA and the DOF and it is also verified the lateral and axial resolutions in a predictable optical imaging structure, respectively [15]. In this article, we study the focusing properties of tightly focused azimuthally polarized BG beam using multi-zone phase filter with high NA lens axicon, based on the vector diffraction theory. We surveyed that by carefully designing multi-zone phase filter with high NA lens axicon can generates super-length optical tube with sub diffraction beam size (0.494 λ) that propagates lacking divergence above a long distance (of about 63.6 λ) in free space. However, in the ordinary lens with the same NA, the full width half maximum (FWHM) of the focal hole is created to be 0.672 λ and its resultant focal depth is only 5.2 λ. We also found that the focal depth and beam size is dependent relative

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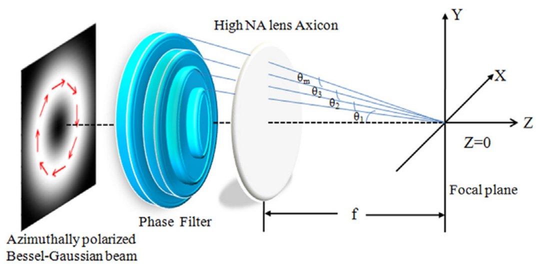

Fig. 1. An azimuthally polarized Bessel–Gaussian beam passes through a multi-zone phase filter and is subsequently focused by a high NA lens axicon.

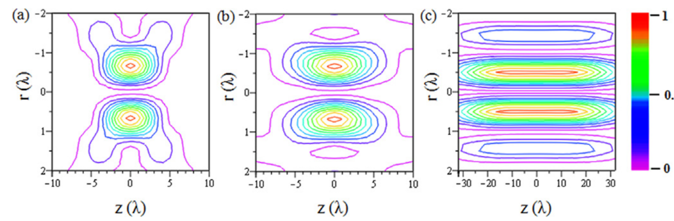

Fig. 2. Intensity distribution of the focused field near focus for tightly focused azimuthally polarized beam focused with (a) high NA lens, (b) multi-zone phase filter with high NA lens and (c) multi-zone phase filter with high NA lens axicon for NA = 0.6.

on focusing condition of the lens and decreases with increments of numerical aperture of an azimuthally polarized BG beam.

2. Theory

The schematic arrangement is shown in Fig. 1. An incident azimuthally polarized BG beam exceeds through a multi-zone phase filter and is consequently focused by a high NA lens axicon. Regard as adopting the cylindrical coordinates r, z, φ in the case of incident azimuthally polarization, the electric field intensity $E(r, \varphi, z)$ can be written as:

$$E(r,\varphi,z) = \begin{bmatrix} E_r \\ E_\varphi \\ E_z \end{bmatrix} = \begin{bmatrix} 0 \\ 2A\displaystyle\int_0^\alpha \cos^{1/2}(\theta)\sin(\theta)P(\theta)A(\theta)J_1(kr\sin\theta)e^{ikz\cos\theta}d\theta \\ 0 \end{bmatrix} \quad (1)$$

Here, $\alpha = \arcsin(NA/n)$ is the maximum aperture angle as well NA is the numerical aperture and n is the index of refraction between the lens and the sample. A is relative amplitude, $J_1(\theta)$ symbolizes the Bessel functions of first kind, k is the wave number and the function $A(\theta)$ expresses the amplitude modulation. $A(\theta)$ stands for the apodization function of an azimuthally polarized BG beam, which is given as [10,16]:

$$A(\theta) = \exp\left[-\left(\frac{\sin\theta}{\sin\alpha}\right)^2\right] J_1\left(2\frac{\sin\theta}{\sin\alpha}\right) \quad (2)$$

In the following simulation results, the unit of coordinates in the entire figures estimates as wavelength (λ).

3. Results and discussion

In this article, initially we illustrate a numerical study about the total electric field intensity distribution in the focal plane in the case of conventional lens is analyzed, based on vector diffraction theory. We carry out the integration of Eq. (1) numerically using parameters $\lambda = 1$, the refractive index $n = 1$, $P(\theta) = 1$, $A = 1$ and the wave number $k = 2\pi/\lambda$. Fig. 2(a) shows the contour profile of the total intensity distribution in the focal plane for the focusing system with high NA objective lens for NA = 0.6. It is observed that the DOF of the focal hole is regarding as 5.2 λ by means of the FWHM is 0.672 λ and the radii of the generated focal holes are almost homogeneous beside the focal hole.

We endeavour to achieve relatively a long DOF azimuthally polarized BG beam based on the above precise formula with added phase modulation (multi-zone phase filter). Here, multi-zone phase filter signifies five-belts in the radial direction with π phase. A π phase shift varies involving the adjacent belts and phase values approximately a loop encompassing the axis change with 2π [10]. The effect of phase modulation on a tightly focused azimuthally polarized BG beam with high NA lens is calculated the function $P(\theta)$, where $P(\theta)$ is given by [17]

$$P(\theta) = \begin{cases} 1, & \text{for } 0 \le \theta \le \theta_1, \theta_2 \le \theta \le \theta_3, \theta_4 \le \theta \le \alpha \\ -1, & \text{for } \theta_1 \le \theta \le \theta_2, \theta_3 \le \theta \le \theta_4 \end{cases} \quad (3)$$

where θ_1, θ_2, θ_3 and θ_4 are radius of the first, second, third and fourth zones of the phase filter, respectively. Based on vector diffraction theory, we select one configuration with random values for θ_1–θ_4 from all possibilities and imitate their focusing properties. For this optimizing structural parameters based on a traditional global-search optimization algorithm where primary values are iterated until a relatively long and smooth beam is attained, as reported in [5]. We give an example by implementing a five-belts phase filter that is described by the following five values are $\theta_1 = 8.98°$, $\theta_2 = 16.39°$, $\theta_3 = 25.59°$, $\theta_4 = 34.77°$ and $\theta_5 = 36.89°$. Fig. 2(b) shows the contour image profile of the total intensity distribution in the rz plane near the focus for multi-belt phase filter and the high NA lens with NA = 0.6, respectively. The other parameters are also same while describing for conventional lens system. It is examined that the radius of the focal holes are exposed to be homogeneous along the optical tube and it has the FWHM of total intensity about 0.692 λ with resulting focal depth is 8.2 λ.

It is also achievable to generate high intense long optical tube with subwavelength size by using multi-belt phase filter and high NA lens axicon. A schematic illustration of the recommended method is shown in Fig. 1. The high NA lens axicon consist a doublet of aberrated diverging lens and a high NA converging lens [18]. If we consider the system, a perfect high NA converging lens and a diverging lens encompass the third-order spherical aberration. The intensity distribution of the lens axicon is evaluated using above explicit formula by substituting the function $P(\theta)$ by the function $P(\theta)\ T(\theta)$, where $T(\theta)$ is written as [17,19]:

$$T(\theta) = \exp\left(Ik\left(\psi\left(\frac{\sin(\theta)}{\sin\alpha}\right)\right)^4 + \left(\frac{1}{2f}\left(\frac{\sin(\theta)}{\sin\alpha}\right)^2\right)\right) \quad (4)$$

In this simulation work we take the numerical values as $k = 2\pi/\lambda$, the focal length $f = 18.4$ mm and the aberration coefficient $\psi = 6.67 \times 10^{-5}\ \text{mm}^{-3}$ and these results in an equiconcave diverging lens which is trouble-free to construct [18]. The contour image profile of total electric field intensity distribution on the focal plane for azimuthally polarized BG beam through multi-belt phase filter subsequently focused the high NA lens axicon is shown in Fig. 2(c). From the figure that the radius of the focal holes is exposed to be homogeneous along the optical tube and generated tube extends up to 63.6 λ and the FWHM of the sub diffraction beam size is measured as 0.494 λ.