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Tight focusing of phase modulated radially polarized hollow Gaussian beam using complex phase filter

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ABSTRACT

We propose a new approach for generating multiple focal spot segment of sub wavelength size, by tight focusing of phase modulated radially polarized hollow Gaussian beam. The focusing properties are investigated theoretically by vector diffraction theory. We observed that focal segment with multiple focal spots structure separated with different axial distance can be generated by properly tuning the phase of the incident radially polarized hollow Gaussian (HGB) beam. Potential applications of this focal shaping technique are also discussed.

1. Introduction

Recently, radially polarized light has been gaining great attention due to its novel properties. Laser beams with radial polarization are characterized by a strong longitudinal electric field [1] and a smaller spot size [2] at the focal point when the beams are tightly focused. The existence of a strong longitudinal field of tightly focused radially polarized beam has many attractive applications such as particle acceleration [3], fluorescent imaging [4], second harmonic generation [5] and Raman spectroscopy [6]. It is reported that radial polarization to be the preferred approach for pupil masks for super resolution and apodization at high NA [7]. Recently, hollow Gaussian beam (HGB) has attracted much attention due to its properties and applications [8–19]. It was found that the area of the dark region across the HGBs can be easily controlled by proper choice of the beam parameters [11]. The propagation, far-field intensity distribution, and M2 factor of HGB through paraxial systems have been investigated in detailed [12–15]. In addition, the nonparaxial propagation of vectorial HGBs in free space is also studied based on the vectorial Raleigh–Summerfield diffraction integral [16], and the analytical vectorial structure of HGB is investigated in the far field based on the vector plane wave spectrum and the method of stationary phase [17]. On the other hand, singular optics studying optical vortices, or phase singularities, has grown rapidly recently because optical vortices have some interesting properties [18–20] and promising applications [21–24], for instance, optical vortices can be used to construct highly versatile optical tweezers. Arrays vortices can also assemble micro-particles into dynamically optical pumps [24]. Recently we have introduced the possible design of high NA lens to generate multiple focal spot with sub wavelength size [25,26]. In our knowledge, the focusing properties of the radially polarized HGB with complex phase wavefront are not studied. In fact, the polarization and phase wavefront are very important characteristics to alter propagating and focusing properties of beams [27,1,28,29]. The present paper is aimed at studying high refractive index particles trapping by using phase modulate radially polarized hollow Gaussian beam by vector diffraction theory. It is observed that by properly tuning the phase of the incident radially polarized hollow Gaussian beam using complex phase plate (CPF), it is not only possible to generate sub wavelength focal spot with long depth of focus, but we can also generate multiple spot focal patterns with different sub wavelength dimension and focal depth suitable for optical trapping application. The principle of the focusing of phase modulate radially polarized HGB is given in Section 2. Section 3 shows the simulation results and discussions. The conclusions are summarized in Section 4.

2. Principle of the optical focusing phase modulated radially polarized HGB

A schematic diagram of the suggested method is shown in Fig. 1. The radially polarized beam is phase modulated with complex

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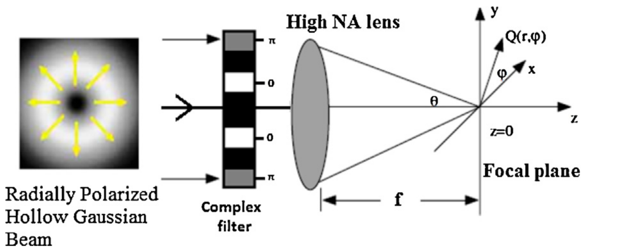

Fig. 1. Focusing of a phase modulated radially polarized hollow Gaussian beam with high NA lens.

phase filter (CPF) and then focused through a high NA lens system. The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method [30] widely used for high-NA lens system at arbitrary incident polarization. Therefore, in the cylindrical coordinate system $(r, \varphi, 0)$ the field distribution $E_0(r, \varphi, 0)$ of the radially polarized HGB at its waist plane is written as:

$$\vec{E_0}(r, \varphi, 0) = E_0(r, \varphi, 0) \cdot \vec{n_r} \quad (1)$$

where $\vec{n_r}$ is the radial unit vector of polarized direction of the HGB. And term $E_0(r, \varphi, 0)$ is optical field value distribution and can be written in the form:

$$\vec{E_0}(r, \varphi, 0) = C \cdot \left(\frac{r^2}{w_0{}^2}\right)^n \cdot \exp\left(-\frac{r^2}{w_0{}^2}\right)\theta \quad (2)$$

where C is a constant, ω_0 is the waist width of the Gaussian beam and φ denotes wavefront phase distribution. Using the same analysis method as that in Refs. [1,28], the electric field in focal region of radially polarized HGB is:

$$\vec{E}(r, z) = E_r\vec{e}_r + E_z\vec{e}_z \quad (3)$$

where $\vec{e}_r$ and $\vec{e}_z$ are the unit vectors in the radial and propagation directions respectively. E_r and E_z are amplitude of two orthogonal components and can be expressed as

$$E_r(r, z) = A\int_0^\alpha \cos^{1/2}(\theta)P(\theta)\sin 2\theta J_1(kr\sin\theta)e^{ikz\cos\theta}d\theta \quad (4)$$

$$E_z(r, z) = 2iA\int_0^\alpha \cos^{1/2}(\theta)P(\theta)\sin^2\theta J_0(kr\sin\theta)e^{ikz\cos\theta}d\theta \quad (5)$$

where r and z are the radial and longitude coordinates of observation point in focal region, respectively. k is wave number and $J_n(x)$ is the Bessel function of the first kind with order n. r and z are the radial and z coordinates of observation point in focal region, respectively. $Q(r, \varphi)$ is an observation point in the focal plane. Note that all components are independent of φ, which means the field maintains cylindrical symmetry. Parameter is the tangential angle with respect to the z axis, and it denotes the radial coordinate of point in incident pupil of the focusing system $\alpha = \arcsin(\text{NA})$ is convergence angle corresponding to the radius of incident optical aperture, where NA is numerical aperture of the focusing optical system. In order to make focusing properties clear and simplify calculation process, after simple derivation, Eq. (2) can be rewritten as:

$$P(\theta) = C\left(-\frac{\sin^2(\theta)}{w^2 \times \text{NA}^2}\right)^n \cdot \exp\left(-\frac{\sin^2(\theta)}{w^2 \times \text{NA}^2}\right) \quad (6)$$

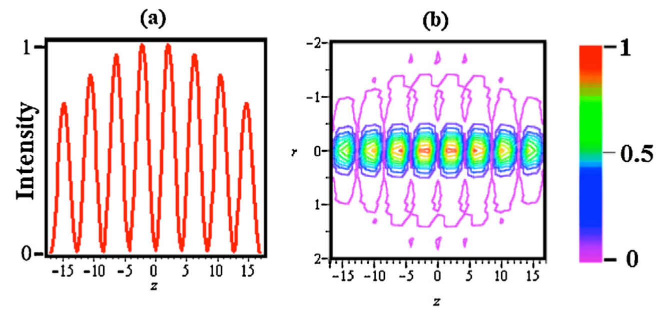

Fig. 2. Intensity distributions at the focus of the lens for (a) at $r = 0$ and (b) are the corresponding contour plot for the total intensity distribution in the r–z plane.

The effect complex phase filter on the input radially polarized hollow Gaussian beam is evaluated by replacing the function $P(\theta)$ by $P(\theta)\text{CPF}(\theta)$. Where $\text{CPF}(\theta)$ is given by

$$\text{CPF}(\theta) = \begin{cases} 0, & \text{for } 0 < \theta < \theta_1, \theta_2 < \theta < \theta_3, \\ 1, & \text{for } \theta_1 < \theta < \theta_2, \\ -1, & \text{for } \theta_3 < \theta < \alpha \end{cases} \quad (7)$$

The optical intensity in focal region is proportional to the modulus square of Eq. (3). Basing on the above equations, focusing properties of radially polarized HGB with complex phase plate can be investigated theoretically.

3. Results and discussion

In the investigation of radially polarized hollow Gaussian (HGB) beam, without loss of validity and generality, it is proposed that the numerical aperture of the focusing optical system NA = 0.9 and relative waist width $w = 1$, $\lambda = 1$. Here, for simplicity, we assume that the refractive index $n = 1$ and $A = 1$, $C = 1$. For all calculation in the length unit is normalized to λ and the energy density is normalized to unity. The intensity distribution for a radially polarized HBG beam, one can achieve a eight sub wavelength focal spot shaving FWHM of 0.43λ and are axially separated by the distance of 2λ between them as shown in Fig. 2(a and b) The set of angles of complex phase filter (CPF) optimized for the above mentioned focal segment using are $\theta_1 = 46°$, $\theta_2 = 47.96°$, $\theta_3 = 63.03°$, $\alpha = 64.19°$. However, from Fig. 3(a) we observed that series of two sub wave length focal spots each having FWHM of 0.55λ and are axially separated by a distance of 1.5λ. The DOF of the each focal spot is measured as 2λ and is shown in Fig. 3(b). The set of angles of complex phase filter (CPF) optimized for the above mentioned focal segment using are $\theta_1 = 21.1°$, $\theta_2 = 51.14°$, $\theta_3 = 58.71°$, $\alpha = 64.19°$. Fig. 4(a and b) shows the focal segment generated for the CPF optimized with angles are $\theta_1 = 21°$, $\theta_2 = 32.7°$, $\theta_3 = 58.78°$, $\alpha = 64.19°$. We observed from the figure, it is possible to generated series of four sub wave length

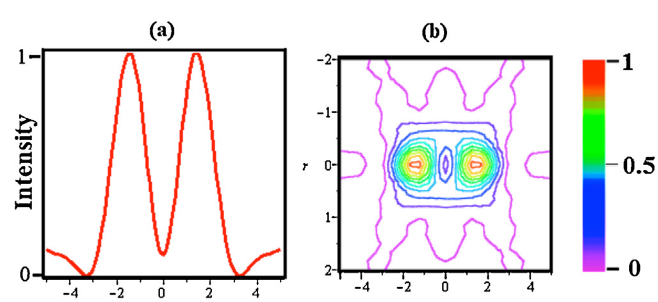

Fig. 3. Intensity distributions at the focus of the lens for (a) at $r = 0$ and (b) are the corresponding contour plot for the total intensity distribution in the r–z plane.