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Effect of coma on tightly focused cylindrically polarized vortex beams

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ABSTRACT

In this paper attention is given to the effects of primary coma on the cylindrical polarized vortex beam based on the vector diffraction theory. It is observed that by properly choosing the polarization angle and topological charge one can obtain many novel focal patterns suitable for optical tweezers, laser printing and material process. However, it is observed that the focusing objective with coma generates structural modification and positional shift of the generated focal structure.

Contents

1. Introduction

In modern optics study and applications of the optical vortex beam have recently generated great research [1–7]. Recently the focusing properties of a circularly, radially, azimuthally or linearly polarized vortex beam by a high numerical-aperture lens have been discussed [8–14]. The radially and the azimuthally polarized beams are of particular importance in many application fields due to unique cylindrical symmetry of polarization. The size and shape of the focused structure of the vortex beam play an important role in many applications such as in microscopy, lithography, data storage, particle trapping, etc. A deformed focused structure may cause serious problems in optical trapping and microscopy. Deformation in the focused structure can be due to aberrations. Under realistic experimental conditions, it is inevitable to suffer wavefront aberrations even for the well corrected objectives [15–17]. An important investigation was initiated by Braat et al. [18] who used extended Nijboer–Zernike representation of the vector field in the focal region of an aberrated high NA optical beam. Biss and Brown [15] have investigated the effect of primary aberrations on the focused structure of the radially polarized vortex beam. However no detailed studies seem to have been made on the effect

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of primary coma on the tight focusing of cylindrical vortex beam (CVB). In view of the importance of the high NA focusing of CVB, we have considered focusing of a radially and azimuthally polarized beam by a focusing system in the presence of primary coma by using a vectorial Debye integral. In this paper we present the results of intensity distribution of cylindrical vortex beam with and without coma. Our results have been compared with those others in the absence of coma, and found to be in reasonably good agreement.

2. Theoretical model

A schematic diagram of the suggested method is shown in Fig. 1.The analysis was performed on the basis of the Richards and Wolf's vectorial diffraction method [19] widely used for high-NA focusing systems at arbitrary incident polarization. Instead of a radial polarization or an azimuthally polarization, each point of the optical vortex beam has a polarization rotated by ϕ_0 from its radial direction.In this paper, we assume that the cylindrically vortex beam is incident upon a high NA lens. Since this beam can be expressed as a linear combination of the focal fields of radial polarization and azimuthally polarization, we adapted the same analysis method as that in Ref. [20]. The focal field of a cylindrically polarized vortex beam can be written as

$$\vec{E}(r, z, \varphi) = E_r\vec{e_r} + E_z\vec{e_z} + E_\varphi\vec{e_\varphi} \tag{1}$$

where E_r, E_zE_φ are the amplitudes of the three orthogonal components and $\vec{e_r}$, $\vec{e_z}\vec{e_\varphi}$ are their corresponding unit vectors. The three orthogonal components of the electric field is given as

$$Er = -iA/2\pi \times \cos(\phi_0)\int_0^\alpha\int_0^{2\pi}\sqrt{\cos(\theta)}\sin(2\theta)A_1\ \cos(\phi-\varphi)$$
$$\exp(in\phi)\times\exp[ik(z\ \cos(\theta)+r\ \sin(\theta)\cos(\phi-\varphi)]d\phi\, d\theta \tag{2}$$

$$Ez = iA/\pi \times \cos(\phi_0)\int_0^\alpha\int_0^{2\pi}\sqrt{\cos(\theta)}\sin^2(\theta)A_1\ \exp(in\,\phi)$$
$$\times\exp[ik(z\ \cos(\theta)+r\ \sin(\theta)\cos(\phi-\varphi)]d\phi\, d\theta \tag{3}$$

$$E\varphi = -iA/\pi \times \sin(\phi_0)\int_0^\alpha\int_0^{2\pi}\sqrt{\cos(\theta)}\sin(\theta)A_1\ \cos(\phi-\varphi)$$
$$\exp(in\phi)\times\exp[ik(z\ \cos(\theta)+r\ \sin(\theta)\cos(\phi-\varphi)]d\phi\, d\theta \tag{4}$$

where r, φ and z are the radial, azimuthal and longitudinal coordinates of the observation point in the focal region respectively. $k = 2\pi/\lambda$ is the wave number and $\alpha = \sin^{-1}(NA)$ is the maximal angle determined by the numerical aperture of the lens. A_1 denotes the wavefront aberration function in the beam which can be expressed as [21]

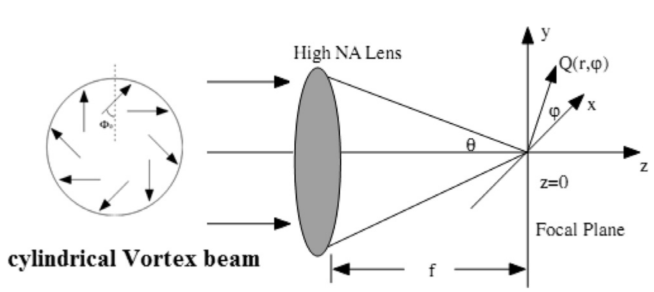

Fig. 1. Shematic diagram of generalized cylindrical vortex beam.

$$A_1 = \exp\left[i.\ k.\ A_c\left(\frac{\sin(\theta)}{\sin(\alpha)}\right)^3\ \cos(\phi)\right] \tag{5}$$

where the coma coefficient A_c is in units of the wave length of the beam.

3. Results

3.1. Radially polarized vortex beam

We perform the numerical integration of Eq. (1) using the midpoint Riemann sum method with 100 partitions. Fig. 2 (a) shows the calculated 3D intensity distribution in the focal plane for $\phi_0 = 0°$, $NA = \sin(80°)$and topological charge $n=1$ which corresponds to radially polarized vortex incident beam without coma. The generated focal structure agrees well with the Fig. 2d of [22]. The total intensity is the sum of the radial intensity and longitudinal intensity. In this case, the azimuthal component disappears and only the radial and longitudinal components are present. It is observed that the total intensity has a bumpy structure which is in contrast to the $n=0$ case, where the longitudinal component distribution has an on-axial maximum and results in a highly confined focal spot. However it is observed that by using proper annular obstruction one can generate a highly confined focal spot of good circular symmetry for the incident radially polarized vortex beam and was recently demonstrated in 4Pi configuration by Chen et al. [23]. It is also noted that the experimental verification of tight focusing of radially polarized vortex beam paves the way for some practical applications such as in optical trapping, near-field microscopy, and material processing [24]. Since no objective is free from aberration, the effect of coma on tight focusing of radially polarized beam is found to be very important in all the above applications. Fig. 2(b–d) shows the intensity distribution at the focus for different A_c values. It is observed from the figure, that the intensity distribution in the focal plane undergoes significant changes in the presence of coma. It is noted, that the coma not only changes the focal structure and intensity distribution of the generated focal segment but also shifted it in the radial direction. It is clearly observed, that as the value of coma coefficient increases, the shifting of generated focal segment along radial axis is also increased. Fig. 2(b) shows the position of maximum intensity of the generated focal spot located at $r=-0.75\lambda$ when $A_c=0.5\lambda$. However further increasing of A_c to 1.5λ shifted the focal segment axially to $r=-1.5\lambda$ and is shown in Fig. 2(d). It is also observed when the value of A_c increases, the generated focal segment undergoes structural modification such that the size of the generated focal segment squeezing in the radial direction and broadens near the focus ($z=0$). The modification of the structure is visible when the value of A_c increases to 1.5λ and a new residual intensity spot begins to appear in the radial direction. Fig. 2(e–h) shows the corresponding two dimensional intensity distribution calculated at the position of maximum intensity. It is observed from the figure, that the increase of A_c value decreases the radial component intensity.

3.2. Azimuthally polarized vortex beam

Fig. 3(a) plots the intensity distribution in the focal plane for $\phi_0 = 90°$, $NA = \sin(80°)$ and $n=1$, which correspond to an azimuthally polarized vortex incident beam without coma. Azimuthally polarized vortex beam has no radial and longitudinal component and the total intensity distribution on the optical axis has only the azimuthal component. It is observed that the generated focal segment has a maximum which is in contradiction to