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# Effect of spherical aberration on tightly focused cylindrically polarized vortex beams

G. Therese Anita [a], C. Amala Prathiba Janet [b], K. Prabakaran [c], T.V.S. Pillai [c], K.B. Rajesh [d,*]

[a] *Department of Physics, Arunachala College of Engineering for Women, Nagercoil, Tamil Nadu, India*
[b] *Department of Physics, St. Xavier's Catholic College of Engineering, Nagercoil, Tamil Nadu, India*
[c] *Department of Physics, Periyar Universit- PG Extension Centre, Dharmapuri, Tamil Nadu, India*
[d] *Department of Physics, Chikkanna Government Arts College, Tiruppur, Tamil Nadu, India*

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ABSTRACT

In this paper attention is given to the effects of primary spherical aberration 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 spherical aberration generates structural modification and positional shift of the generated focal structure.



## 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 [8–13]. 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 wave front aberrations even for the well corrected objectives [14–16]. When a tightly focused laser propagates through an interface of two different materials, spherical aberration will be induced due to refractive-index mismatch. Marcinkvcius et al. [17] reported that this interface SA increase the size and distorts the shape of photo damaged regions and thus reduces the spatial resolution of micro fabrication, where the focusing depth inside the glass is no more than 250 μm. 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 [19] 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 of primary aberrations on the tight focusing of cylindrical vortex beam. In view of the importance of the high NA focusing of CVB, in this paper we present the results of our investigation of effect of spherical aberration, on cylindrical vortex beam.

## 2. Theoretical model

A schematic diagram of the suggested method is shown in Fig. 1. The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method [20] 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 $\varphi_0$ 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. [21]. The focal field of a cylindrically polarized vortex beam can be written as:

$$\vec{E}(r,z) = E_r\vec{e}_r + E_z\vec{e}_z + E_\varphi\vec{e}_\varphi \quad (1)$$

* Corresponding author.
*E-mail address:* rajes@gmail.com (K.B. Rajesh).

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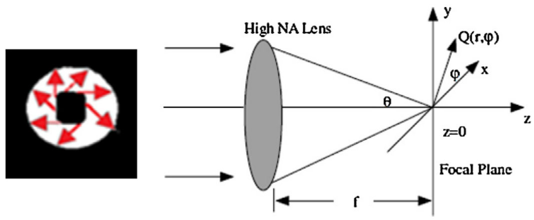


**Fig. 1.** Schematic diagram of generalized cylindrical vortex beam.

where $E_r$, $E_z$ are the amplitudes of the three orthogonal components and $\vec{e}_r$, $\vec{e}_z$ are their corresponding unit vectors. The two orthogonal components of the electric field is given as:

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

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

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

where $r$, $\varphi$ and $z$ are the radial, azimuthal and longitudinal coordinates of the observation point in the focal region respectively. $k = 2\pi/\lambda$ is wave number, and $\alpha = \arcsin(\mathrm{NA})$, is the maximal angle determined by the numerical aperture of the lens. $A_1$ denotes the wave front aberration function in the beam which can be expressed as [22]:

$$A_1 = \exp\left[I.k.As\left(\frac{\sin(\theta)}{\sin(\alpha)}\right)^4\right] \quad (5)$$

where the spherical aberration coefficient $As$ is in units of the wave length of the beam.

## 3. Results

### 3.1. Radially polarized vortex beam

Fig. 2(a) shows the 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 spherical aberrations. The generated focal structure agrees well with Fig. 2(d) of [23]. 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 is non-zero at the optical axis which is in contrast to the $n = 1$ case, where the longitudinal component distribution has an on-axial maximum. Fig. 2(b–d) shows the intensity distribution at the focus for different $As$ values. It is observed from the figure, that the intensity distribution in the focal plane undergo significant changes in the presence of spherical aberration. It is noted, that the spherical aberration not only changes the focal structure and intensity distribution of the generated focal segment but also shifted it away from the aperture. It is clearly observed, that as the value of spherical aberration coefficient increases, the shifting of generated focal segment along $z$-axis is also increased. Fig. 2(b) shows the position of maximum intensity of the generated focal spot at $z = 0.5\lambda$ when $As = 0.5\lambda$. However further increasing of $As$ to $1.5\lambda$ shifted the focal segment axially to $z = 3\lambda$. It is also observed when $As$ increases, the generated focal segment undergoes structural modification such that the size of the generated focal segment squeezing towards aperture. The modification of the structure is visible when the value of $As$ increases to $1.5\lambda$. Fig. 2(e–h) shows the corresponding two dimensional intensity distribution calculated at the position of maximum intensity.

### 3.2. Azimuthally polarized vortex beam

Fig. 3(a) plots the intensity distribution in the focal plane for $\Phi_0 = 90°$, which correspond to an azimuthally polarized vortex incident beam without spherical aberration. Azimuthally polarized vortex beam has no radial and longitudinal component and the total intensity distribution on the optical axis has a maximum which is in contradiction to $n = 0$, case where the generated focal segment is a focal hole. We measured the FWHM of the generated focal spot is ($0.31\lambda$) and agrees well with the result of [23]. Hence, such azimuthally polarized vortex beams can obtain a highly confined focal spot. However, it is noted that the presence of spherical aberration generates focal shifting and structural modification. Fig. 3(b)

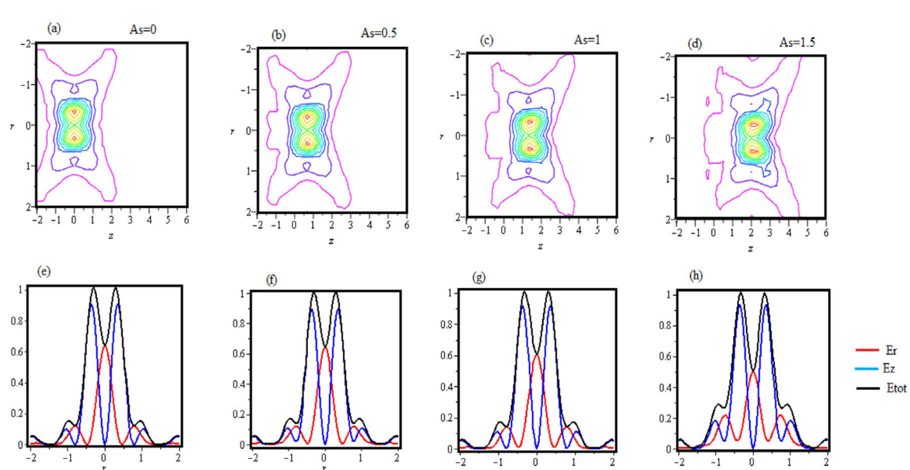


**Fig. 2.** Total intensity distribution of radially polarized cylindrical vortex beam (a) $As = 0.0\lambda$, (b) $As = 0.5\lambda$, (c) $1.0\lambda$, (d) $As = 1.5\lambda$ and two dimensional intensity distribution at the focal plane (e) $As = 0.0\lambda$, (f) $As = 0.5\lambda$, (g) $As = 1.0\lambda$, (h) $As = 1.5\lambda$.