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Effect of spherical aberrations in tight focusing of higher order radially polarized beam

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ABSTRACT

The effect of spherical aberration, in higher order radially polarized beam, is investigated theoretically by vector diffraction theory. It is observed that an increase in aberration results in the spreading of the intensity distribution, positional shift and the size of the generated focal pattern.

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]. Recently a double-ring-shaped beam was experimentally observed as a higher-order radially polarized mode (R-TEM_{11}*) directly from a laser cavity [7]. In addition, these higher-order mode beams may be generated by a particular laser cavity designed to oscillate only with radial polarization [8,9]. It was theoretically reported that a double-ring shaped radially polarized beam has the potential to form an optical bottle beam under a particular focusing condition [10], and can generate a sharp focal spot of the longitudinal component under tight focusing [11]. In the case of an R-TEM_{11}* mode, a double ring structure accompanies with π phase shift between inner and outer rings. Therefore, the intensity distribution near the focal point varies drastically with the degree of the truncation of the incident beam by a pupil. Deformation in the size and shape of the focal structure is possible due to perturbation in the focused beam. This perturbation may arise due to the refractive index mismatch between two media, defect or misalignment of the optical. Such a refractive index mismatch produces an important amount of spherical aberration (SA), which strongly degrades the spatial resolution, in the case of confocal scanning microscopy [12–15] or impoverishes the trapping power in the case of the laser trapping technology [16]. Recently, Escobar et al. [17] have investigated the reduction of the spherical aberration effect in a high NA system. 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 system. Structural modification of the focused doughnut beam due to aberration has been mentioned briefly by Willig et al. [19] in the context of STED microscopy. Biss and Brown [20] have investigated the effect of primary aberrations on the focused structure of the radially polarized vortex beam. Recently Singh et al. investigated the effect of primary aberrations of the high NA lens system in the presence of phase vortices [21–27]. However, no detailed studies seem to have been made on the effect of primary aberrations on the tight focusing of a radially polarized double ring shaped beam. In view of the importance of the tight focusing of a higher order LG beam, we have investigated the effect of spherical aberration on the focused structure of higher order radially polarized beams by using the vector diffraction theory.

2. Theory

A schematic diagram of the suggested method is shown in Fig. 1. The incident R-TEM_{11}* beam is focused through a high NA lens system. The analysis was performed on the basis of Richards and Wolf's

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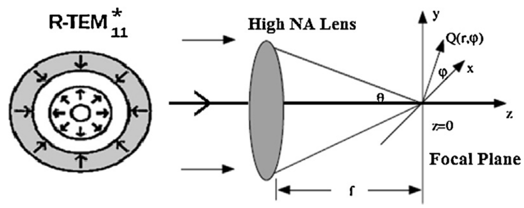

Fig. 1. Focusing of a R-TEM$_{11}$* beam with high NA lens.

vectorial diffraction method [28] widely used for high-NA lens system at arbitrary incident polarization. In the case of the incident polarization, adopting the cylindrical coordinates r, z, φ and the notations of Ref. [1], radial and longitudinal components of the electric field $E_r(r, z)$ and $E_z(r, z)$ in the vicinity of the focal spot can be written as

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

where E_r, E_z are the amplitudes of the two 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

$$E_r(r,z) = A\int_0^{\alpha} \cos^{1/2}(\theta)P(\theta)\sin 2\theta A_2(\theta)J_1(kr\sin\theta)e^{ikz\cos\theta}d\theta \quad (2)$$

$$E_z(r,z) = 2iA\int_0^{\alpha} \cos^{1/2}(\theta)P(\theta)\sin^2\theta A_2(\theta)J_0(kr\sin\theta)e^{ikz\cos\theta}d\theta \quad (3)$$

where $\alpha = \arcsin(NA)/n$ the maximal angle is determined by the numerical aperture of the objective lens, and n is the index of refraction between the lens and the sample. $k = 2\pi/\lambda$ is the 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 $p(\theta)$ describes the amplitude modulation and for illumination by a double ring shaped radially polarized beam with its waist in the pupil, this function is given by Rajesh et al. [29]

$$P(\theta) = \beta^2\frac{\sin\theta}{\sin^2\alpha}\exp\left[-\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right]L_p^1\left[2\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right] \quad (4)$$

where β is the parameter that denoted the ratio of pupil diameter to the beam diameter and L_p^1 is the generalized Laguerre polynomial. If $p = 1$, the incident beam is a R-TEM$_{11}$* beam.

The wave aberration function, which denotes the deviation of the actual wavefront from the ideal wavefront in the presence of primary spherical aberration and defocusing, can be written [30] as

$$A_2(\theta) = \exp\left[ikAs\left(\frac{\sin\theta}{\sin\alpha}\right)^4\right] \quad (5)$$

where As is the spherical aberration coefficient in units of wavelength.

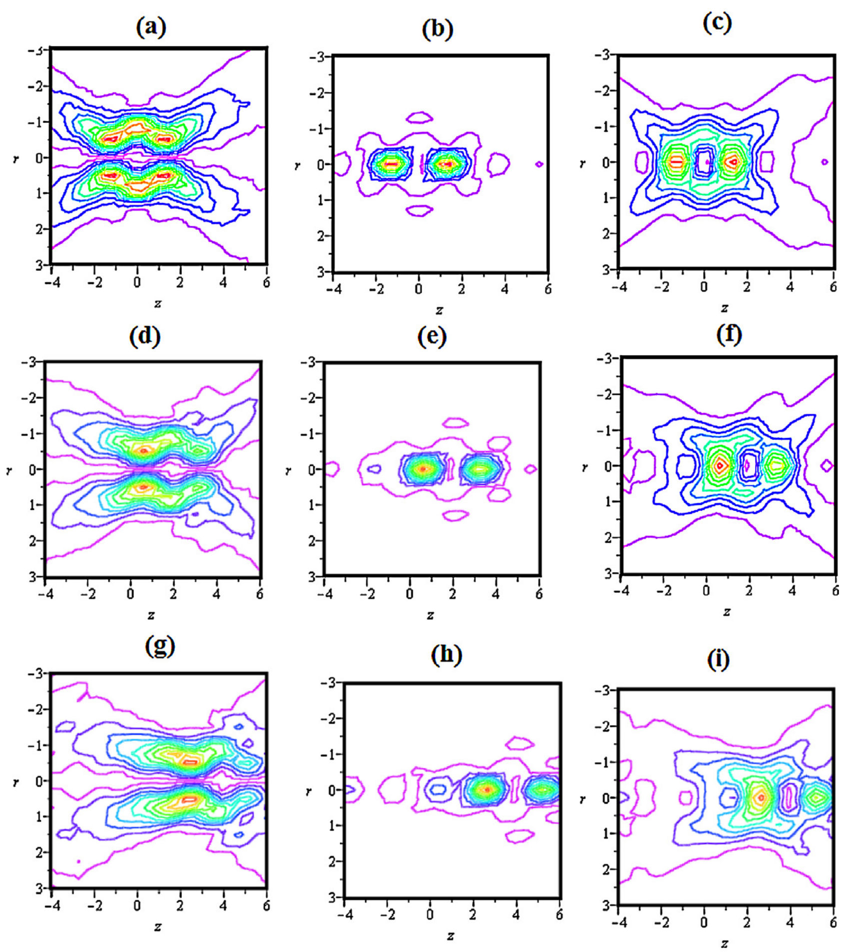

Fig. 2. Calculated intensity distributions of (a, d and g) the radial component and (b, e and h) the longitudinal component (c, e and i). Total intensity in the focal area for $\beta = 1.3$. (a–c) As = 0.0λ, (d–f) As = 1λ and (g–i) As = 2λ.