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Tight focusing properties of radially polarized Lorentz–Gaussian beam

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ABSTRACT

Focusing properties of radially polarized Lorentz–Gauss beam with one on-axis optical vortex was investigated by vector diffraction theory. Results show that intensity distribution in the focal region can be altered considerably by charge number of the optical vortex and the beam parameters. Many novel focal patterns may occur, Such as Peak-centered, donut focal shapes which is potentially useful in optical tweezers, material processing and laser printing.

1. Introduction

Recently, the Lorentz–Gauss beam has been introduced as a new kind of realizable beam [1]. The Lorentz beam can be regarded as a special case of Lorentz–Gauss beams. With the spatial extension being the same, the angular spreading of a Lorentz–Gaussian distribution is higher than that of a Gaussian description [2]. Therefore, the Lorentz–Gauss beam provides an appropriate model to describe certain laser sources, e.g., double heterojunction Ga1−xAlxAs lasers, which produce highly divergent fields [3]. Recently, a new type of optical beam called Lorentz–Gauss beam has attracted a great deal of interest. The existence of Lorentz–Gauss beam is demonstrated both in theory and in experiment. In theory, the Lorentz–Gauss beam is proved a closed-form solution of the paraxial wave equation [1,4] in experiment, the Lorentz–Gauss beam can be realized by certain double heterojunction lasers [5,6]. The characteristics and applications of Lorentz–Gauss beams have been investigated [7–11]. Since then, the Lorentz–Gauss beams have been studied extensively. The vectorial structures of Lorentz–Gauss beams have been examined in the far field [12]. The analytical propagation expressions of Lorentz–Gauss beams beyond the paraxial approximation have been derived [9,13]. The fractional Fourier transform has been applied to treat the propagation of the Lorentz–Gauss beam [14]. The focal shift of a Lorentz–Gauss beam focused by an aperture-lens system has been numerically investigated [8]. Based on the second-order moments, the beam propagation factors of Lorentz–Gauss beams have been investigated [15]. The average intensity and spreading of a Lorentz–Gauss beam in turbulent atmosphere and propagation of a partially coherent Lorentz–Gauss beam through a paraxial ABCD optical system were also investigated [16]. The propagation of Lorentz–Gauss beams in uniaxial crystals orthogonal to the optical axis and through an apertured fractional Fourier transform optical system were also studied [17,18]. In addition, Radiation force of highly focused Lorentz–Gauss beams on a Rayleigh particle was also investigated theoretically [19]. In 1986, Ashkin et al. reported that optical trapping of dielectric particles by a single-beam gradient force trap was demonstrated for the first time [20]. Since then, this new technology has found wide applications in manipulating various particles such as micro-sized dielectric particles, neutral atoms, cells, DNA molecules, and living biological cells [21–26]. The conventional optical traps or tweezers are constructed mainly by fundamental Gaussian beams. However, many researches have demonstrated that other beams are also useful in trapping particles. The trapping characteristics of different beams, such as Laguerre Gaussian beams [27], hollow Gaussian beams [28], Bessel Gaussian beams [29], cylindrical vector beams [30], Gaussian Schell model beams [31] and flat-topped Gaussian beams [32] have been studied. It has been found that the radiation forces produced by a laser beam are mainly related to its beam characteristics such as beam profile and polarization. However, to the best of our knowledge, the focusing of radially polarized Lorentz–Gauss beams containing optical vortex has not been studied so far. In order to get deep insight into the properties of Lorentz–Gauss beams and extend their applications,

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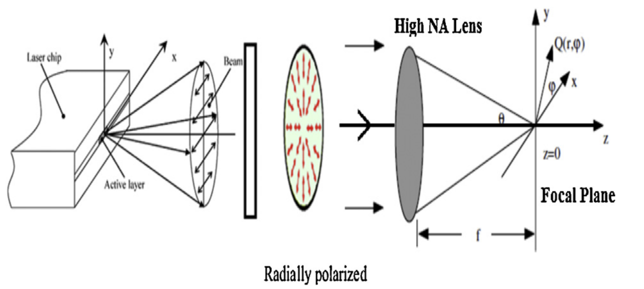

Fig. 1. The sketch of the optical system, in which the Lorentz–Gauss beam is highly focused by the lens.

focusing properties of radially polarized Lorentz–Gaussian beam with one on-axis optical vortex was investigated by vector diffraction theory.

2. Theory

A schematic diagram of the suggested method is shown in Fig. 1. The incident radially polarized Lorentz–Gaussian beam is focused through a high NA lens system. The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method [33] 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. [34], 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

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

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

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

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

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. Here $P(\theta) = \exp(im\varphi)$ for a plane radially polarized vortex beam and for the Lorentz–Gaussian beam, the electric field distribution can be written as [35]

$$P(\theta) = \exp\frac{[-\cos^2(\varphi) \times \sin 2(\theta)]}{NA^2W^2} \times \frac{1}{1+(\sin 2(\varphi)\sin^2(\theta)/NA^2\gamma^2} \exp(im\varphi) \tag{4}$$

Here γ is called relative beam waist, and can be called relative Lorentz parameter. m is the charge number of the optical vortex and W is called relative beam waist.

3. Results

We perform the integration of Eq. (1) numerically using parameters $\lambda = 1$, and NA = 0.95. Here, for simplicity, we assume that the

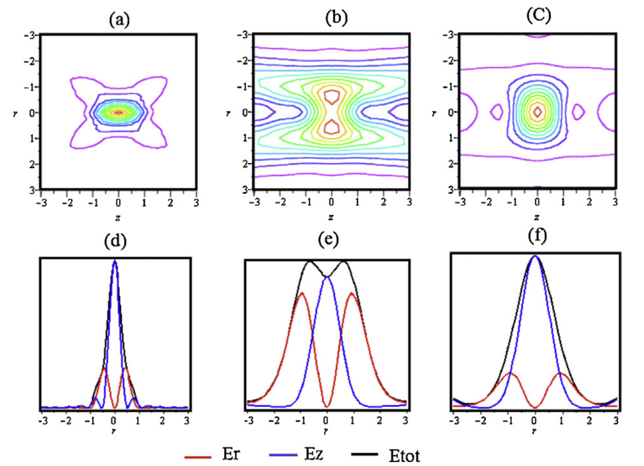

Fig. 2. (a and d) Plane radially polarized beam, (b and e) radially polarized Lorentz–Gaussian beam for NA = 0.95, W = 0.3, γ = 0.3, (c and f) radially polarized Lorentz–Gaussian beam for W = 0.3, γ = 1.2, and m = 0.

refractive index n = 1. For all calculation in the length unit is normalized to λ and the energy density is normalized to unity. Fig. 2 illustrates the evolution of three-dimensional light intensity distribution of high NA lens for the incident plane radially polarized vortex beam and radially polarized Lorentz–Gaussian beam based on Eq. (1). It is observed from Fig. 2(a), the generated focal segments for m = 0 of a plane radially polarized beam is a focal spot having FWHM of 0.6λ and focal depth of 1.4λ. The 2D intensity profile calculated at the focus shown in Fig. 2(d) revels that the longitudinal component of the intensity profile is dominating the radial component. Hence the generated spot is a longitudinally polarized one. Next we consider the tight focusing properties of radially polarized Lorentz–Gaussian beam, with beam parameter W = 0.3, γ = 0.3. Fig. 2(b) shows the focal segment generated by the tight focused Lorentz–Gaussian beam of above mention beam parameters. It is observed from the Fig. 2(b), the focal segment of the generated focal spot extended radially with a bumpy structure of total intensity profile at the focus as shown in Fig. 2(e). It also observed, the radial and longitudinal components are almost equal in intensity and the FWHM of the generated focal spot is 2λ. Fig. 2(c and f) shows the focal segment generated by the Lorentz–Gaussian beam with beam parameter W = 0.3, γ = 1.2. It is observed that the generated focal segments is a focal spot with FWHM 1.74λ and focal depth of 1.32λ. The 2D intensity profile calculated at the focus, shows that the radial component is only 10% of the longitudinal component. Thus for the topological charge m = 0, the plane radially polarized beam and the radially polarized Lorentz–Gaussian beam with beam parameter (W = 0.3, γ = 0.3) shows similar behavior under the tight focusing condition except the fact that the focal spot generated by the Lorentz beam of above mentioned parameter is little bigger when compared to the plane radially polarized beam. However the Lorentz–Gaussian beam with parameter (W = 0.3, γ = 1.2) shows completely different behavior due to the large radial component.

It is observed for the plane radially polarized vortex beam of topological charge m = 1, the generated focal segment appears to broaden radially and is shown in Fig. 3(a). The component intensity calculated at the focus reveals that the radial and longitudinal is almost equal and is shown in Fig. 3(d). Next we consider the tight focusing properties of radially polarized Lorentz–Gaussian beam of same topological charge with beam parameter W = 0.3, γ = 0.3. Fig. 3(b) shows the focal segment generated by the tight focused Lorentz–Gaussian beam of above mentioned beam parameters. It is observed from Fig. 2, the generated focal structure is a focal spot of FWHM 1.46λ having large focal depth 7λ. The calculated 2D profile shown in Fig. 3(e) revels the radial component is dominating and