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Tight focusing of a radially polarized Laguerre–Bessel–Gaussian beam and its application to manipulation of two types of particles

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ABSTRACT

The intensity distributions near the focus for radially polarized Laguerre–Bessel–Gaussian beams by a high numerical aperture objective in the immersion liquid are computed based on the vector diffraction theory. We compare the focusing properties of the radially polarized Laguerre–Bessel–Gaussian beams with those of Laguerre–Gaussian and Bessel–Gaussian modes. Furthermore, the effects of the optimally designed concentric three-zone phase filters on the intensity profiles in the focal region are examined. We further analyze the radiation forces on Rayleigh particles produced by the highly focused radially polarized Laguerre–Bessel–Gaussian beams using the specially engineered three-zone phase filters.

1. Introduction

In an imaging system with a high numerical aperture (NA), polarization properties of the electromagnetic field are of particular importance. It has been demonstrated that, for a clear aperture, linear or circular polarization is superior to radial polarization in terms of spot size reduction. However, for a high NA objective, a radially polarized beam, when combined with annular aperture, produces a shaper spot size [1–3]. In addition, laser beams with radial polarization are also characterized by an intense longitudinal electric field at the focus when the beams are strongly focused. It is well known that a great number of attractive applications call for high transverse resolution with a strong longitudinal electric field component; for instance, high-density optical data storage [4,5], particle acceleration [6], Raman spectroscopy [7], high-resolution imaging [8], second-harmonic generation [9], material processing [10], and particle trapping [11,12].

In some applications, however, it is desirable to attain a small focal spot and also achieve a long depth of focus (DOF). For example, one would expect that the focus possesses high lateral resolution and a long DOF in optical data storage, which leads to a longer interaction between optical field and the object, as well as simpler alignment process and a better tolerance for beam focusing [13]. In view of the above requirements, some strategies have been proposed to produce a large needle of longitudinally polarized beam with a sub-wavelength transverse dimension such as binary optical phase filters [14–20], amplitude filters [21,22], complex filters [23,24] and high NA lens axicon [25]. Dorn et al. firstly experimentally validated that a radially polarized incident beam can be focused to a spot size significantly smaller than that for linear polarization by means of an annular aperture [1]. In theory, a needle of longitudinally polarized light with a sub-wavelength focal spot has been achieved by focusing a radially polarized Bessel–Gaussian (BG) beam with a high-NA objective and a five-zone phase element [14]. The research results of Zhang et al. manifested that the designed three-zone phase-only filter can not only increase the DOF of the solid immersion lens, but also effectively reduce the spreading of the focal spot and suppress the side-lobe intensity [18]. More recently, Zha et al. showed that the generation of longitudinally polarized beam can be achieved by tightly focusing a radially polarized BG beam with a high NA lens and a ternary optical element [24]. However, most of the explorations on the radially polarized beams are mainly concentrated on BG beam modes [14,21,24] or Laguerre–Gaussian (LG) beams with different modes [12,26,27]. Here, our goal is to obtain a small focal spot with a tunable axial extent regardless of input field profiles. Therefore, it is necessary to introduce new laser beams with radial polarization to improve the focusing performance. In 2000, Tovar proposed new

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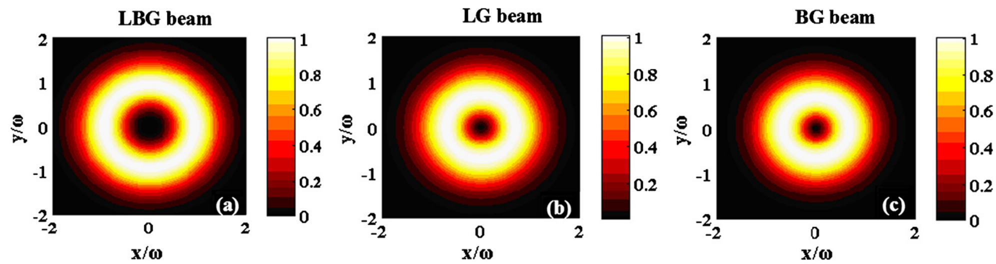

Fig. 1. Normalized intensity distribution of a radially polarized (a) LBG beam, (b) LG beam, and (c) BG beam with beam waist $\omega = 1$ mm. White and black colors represent the maximum and minimum intensity, respectively.

Laguerre–Bessel–Gaussian (LBG) beams as solutions of the paraxial wave equation in cylindrical coordinates [28]. The LBG beams can reduce to the BG modes and LG modes by properly tuning the initial parameters. Subsequently, the nonparaxial propagation properties of vectorial LBG beams were researched based on vectorial Rayleigh–Sommerfeld formulas [29]. However, to the best of our knowledge, the tightly focusing properties of the radially polarized LBG beams in the high NA condition have not been studied so far. Also, we find that the central dark area for the radially polarized LBG beam is larger than those for LG beams and BG beams, which implies that focusing properties of LBG beam are preferable over BG or LG beams with radial polarization. This is motivation of this paper.

In order to illustrate the superiority in trapping applications of the radially polarized LBG beams, the radiation forces on the Rayleigh particles produced by the highly focused radially polarized LBG beams are calculated. According to the Rayleigh scattering theory, the gradient force is proportional to the gradient of the square of the electric field whereas the absorption/scattering forces are proportional to the Poynting vector of the field. Calculation of the Poynting vector near the focus for a radially polarized beam demonstrated that there is without energy distribution on the beam axis [11,12]. This feature indicates the radial polarization field may reduce the scattering force and thus improve the axial trapping capacity compared with linear or circular polarization. Zhan showed this possibility for a metallic Rayleigh particle by using a single-ring-shaped radially polarized beam [11]. Since then the optical trapping of micrometer and nanometer-sized particles has been extensively investigated by virtue of the radially polarized beams [30–36]. Especially, Zhang et al. presented a tightly focused double-ring-shaped radially polarized beam can not only trap type A particles (particles with refractive indices larger than that of the ambient) but also trap type B particles (particles with refractive indices less than that of the ambient) by changing the truncation parameter [12]. Alternatively, Cai et al. demonstrated that the focused partially coherent beam can be used to trap a Rayleigh particle whose refractive index is larger or smaller than that of the ambient by varying its initial spatial coherence [37,38]. Here, we can also manipulate two types of particles with different refractive indices dependent of the additional three-zone phase filters with different radial positions of each ring, illuminated by the radially polarized LBG beams focused by a high NA objective in the immersion liquid.

The aim of our paper is to examine in detail the tightly focusing properties of the radially polarized LBG beams, as well as present the application in trapping particles with different refractive indices based on the Rayleigh scattering theory. The rest of the paper is organized as follows. In Section 2 the vector diffraction formulas of the radially polarized LBG beams are described. In Section 3 the numerical studies of the intensity distributions near the focus for the radially polarized LBG beams with direct focusing and additional phase modulations are presented. In Section 4 the radiation forces on the Rayleigh particles produced by the radially polarized LBG beams are studied. Finally, conclusions are given in Section 5.

2. Vector diffraction theory

In the focusing system with a high NA objective lens we investigated, the focusing beam of light is a radially polarized LBG beam. In the cylindrical coordinate system (r, ϕ, z), the pupil function $l_0(\theta)$ for a radially polarized LBG beam at the source plane $z = 0$ reads as [23,24]

$$l_0(\theta) = \frac{\beta^2 \sin\theta}{\sin^2\theta_{\max}} L_0^1\left(\frac{2\beta^2 \sin^2\theta}{\sin^2\theta_{\max}}\right) J_1\left(2\beta\frac{\sin\theta}{\sin\theta_{\max}}\right) \times \exp\left(-\frac{\beta^2\sin^2\theta}{\sin^2\theta_{\max}}\right), \quad (1)$$

with β, which is referred as the truncation parameter, is the ratio of the pupil radius to the incident beam waist in front of the focusing objective lens, $\theta_{\max} = \arcsin(\mathrm{NA}/n)$ represents the maximum value of the convergence angle θ, n is the refraction in the image plane, L_0^1 denotes the Laguerre polynomial with the radial and angular modes of 0 and 1, and J_1 is the Bessel function of the first kind of order one, respectively.

According to Eq. (1), it is apparent that the LBG beams consist of Laguerre polynomials, Bessel functions and Gaussian functions. Namely, by adjusting some parameters, LBG beams can degenerate to the LG beam modes and BG beam modes, respectively. Intensity distribution of the incident radially polarized LBG beams with beam waist $w = 1$ mm is revealed in Fig. 1(a). For comparison, Figs. 1(b) and (c) show the intensity distributions of the LG beams and BG beams on the x–y cross-section, respectively. Obviously, it can be seen from Fig. 1 that the central dark area for LBG beams is larger than those for LG beams and BG beams. Therefore, the incident field described by Fig. 1(a) includes more components with high frequency corresponding to Figs. 1(b) and (c). Namely, larger effective NA (effective NA $= \sin\theta$, θ is the bend angle of light rays) is provided for the radially polarized LBG beams [15]. This means that field oscillates more quickly to be possibly focused into a tighter spot for the radially polarized LBG beams.

By using the vector diffraction theory according to the Richards and Wolf approach [39,40] and Maxwell's equations [14], for a radially polarized LBG beam passes through a multi-belt phase filters and is subsequently focused by a high NA objective lens, the electric field $E(r, z)$ and magnetic field $H(r, z)$ near the focus can be written as

$$E_r(r,z) = A\int_0^{\alpha} \sin(2\theta)\cos^{1/2}(\theta) l_0(\theta) T(\theta) J_1(knr\sin\theta) e^{inkz\cos\theta} d\theta, \quad (2)$$