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Focal pattern evolution of radially polarized Lorentz-Gaussian vortex beam

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ABSTRACT

Focusing properties of linearly radially Lorentz-Gaussian vortex beams was investigated, in which all three orthogonal field components were considered in research. The focal pattern distorts considerably and regularly on increasing charge number for certain parameters, and there are two intensity peaks locating weak intensity ring along one coordinate direction. Distance between two intensity peaks increases on increasing charge number, which may be used to measure charge number. The effect of beam parameters on focal pattern evolution was also studied, which shows that effect of Gauss parameter is more considerably than that of Lorentz parameter. The focal pattern evolution direction can be changed by increasing Gauss parameter, which may results in novel intensity distributions.

1. Introduction

Since Lorentz-Gaussian beams were introduced to describe the output beams from diode lasers [1–3], these kinds of beams have attracted much attention [4–7]. Experimental results of far field of diode lasers show that the field distribution in the directions normal and parallel to the junction plane agree well with Lorentzian and Gaussian functions, respectively [8]. Zhou investigated the fractional Fourier transform of Lorentz-Gauss beams [9]. Wang and co-workers studied the propagation of Lorentz-Gauss beams in crystal and fractional Fourier transform optical systems [10]. In addition, elegant super Lorentz-Gauss beams were also proposed [11]. Recently, focusing properties of Lorentz-Gaussian beam with trigonometric function modulation was investigated by vector diffraction theory [12]. Optical vortex was also introduced in Lorentz-Gaussian beams to construct Lorentz-Gaussian vortex beams. Focusing properties of linearly polarized Lorentz-Gaussian beam with one on-axis optical vortex was investigated [6]. Torre has gotten insight into the Wigner distribution function of a Lorentz-Gauss vortex beam [13].

On the other hand, radially polarized beams have becomes one research topics for many year for their focusing characteristics [14–17]. Radially polarized beams can be used in many domains, including super-resolution [18], particle manipulation [19], ultrafast phenomena sensing [20]. Recently, Berguiga and co-workers proposed time-lapse scanning surface plasmon microscopy of living adherent cells with a radially polarized beam [21], and new generation methods was also carried out [22]. Radially polarized properties search has extended to terahertz domain [23]. Sarawathi and co-workers investigated

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the tight focusing properties of radially polarized Lorentz-Gaussian beam [24], in which the focusing of radially polarized Lorentz-Gaussian beam was investigated without considering optical component in azimuthally coordinate direction. In order to understanding properties of radially polarized Lorentz-Gaussian vortex beam deeply, the focal pattern evolution of radially polarized Lorentz-Gaussian vortex beam was investigated by considering full vector components in three orthogonal coordinate directions. Section two gives focusing principle of radially polarized Lorentz-Gaussian vortex beam, and results and discussions were shown in section 3. Conclusions were summarized in section 4.

2. Principle of focusing radially polarized Lorentz-Gaussian vortex beam

The radially polarized Lorentz-Gaussian vortex beam is one kind of vector beam whose polarization vector is all along radial direct direction, the amplitude distribution of the electric field in the directions parallel and normal to the junction are the Loreatzian and Gaussian functions, and wavefront contains one on-axis optical vortex. According to variable and coordinate system transformations [1–9], the radially polarized Lorentz-Gaussian vortex beam can be written in the focusing optical system,

$$E_0\left(\theta,\phi\right) = \exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot\frac{1}{1+\frac{\sin^2(\phi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp\left(im\phi\right)\vec{r} \tag{1}$$

Where m is the charge number of the optical vortex, and $w_x=\omega_0/r_p$ is called relative beam waist in y coordinate direction and also called as relative Gauss parameter. NA is the numerical aperture of the focusing system. $\gamma_y=\gamma_0/r_p$ is called relative beam waist in x coordinate direction, and can be called relative Lorentz parameter, r_p is the outer radius of optical aperture in focusing system, and ω_0 and γ_0 are the $1/e$-width of the Gaussian distribution and the half width of the Lorentzian distribution, respectively. Here $\vec{r}$ is vector unit of the radial coordinate, and ϕ is the azimuthal angle.

According to vector diffraction theory, the electric field in focal region of radially polarized Lorentz-Gaussian vortex beam is [25,26],

$$\vec{E}\left(\rho,\phi,z\right) = E_\rho\vec{e}_\rho + E_\phi\vec{e}_\phi + E_z\vec{e}_z \tag{2}$$

where $\vec{e}_\rho$, $\vec{e}_\phi$, and $\vec{e}_z$ are the unit vectors in the radial, azimuthal, and propagating directions, respectively. To indicate the position in image space, cylindrical coordinates (ρ,ϕ,z) with origin $\rho=z=0$ located at the paraxial focus position are employed. E_ρ, E_ϕ, and E_z are amplitudes of the three orthogonal components and can be expressed as [26,27]

$$E_\rho\left(\rho,\phi,z\right)=\frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot E_0\left(\theta,\phi\right)\cdot\sin\theta\cos\theta\cos\left(\phi-\phi\right)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos\left(\phi-\phi\right)\right]\right\}\mathrm{d}\phi\mathrm{d}\theta \tag{3}$$

$$E_\phi\left(\rho,\phi,z\right)=\frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot E_0\left(\theta,\phi\right)\cdot\sin\theta\cos\theta\sin\left(\phi-\phi\right)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos\left(\phi-\phi\right)\right]\right\}\mathrm{d}\phi\mathrm{d}\theta \tag{4}$$

$$E_Z\left(\rho,\phi,z\right)=\frac{iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot E_0\left(\theta,\phi\right)\cdot\sin^2\theta\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos\left(\phi-\phi\right)\right]\right\}\mathrm{d}\phi\mathrm{d}\theta \tag{5}$$

where θ denotes the tangential angle with respect to the z axis, A is one constant, and ϕ is the azimuthal angle with respect to the x axis. k is wave number. By substituting the Eq. (1) into Eqs. (3)–(5), optical field distribution in three orthogonal components can be obtained as,

$$E_\rho\left(\rho,\phi,z\right)=\frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin\theta\cos\theta\cos\left(\phi-\phi\right)\cdot\exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot\frac{1}{-}$$
$$1+\frac{\sin^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot\gamma_y^2}\cdot\exp\left(im\phi\right)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos\left(\phi-\phi\right)\right]\right\}\mathrm{d}\phi\mathrm{d}\theta \tag{6}$$

$$E_\phi\left(\rho,\phi,z\right)=\frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin\theta\cos\theta\sin\left(\phi-\phi\right)\cdot\exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot\frac{1}{1+\frac{\sin^2(\phi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp$$
$$\left(im\phi\right)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos\left(\phi-\phi\right)\right]\right\}\mathrm{d}\phi\mathrm{d}\theta \tag{7}$$

$$E_Z\left(\rho,\phi,z\right)=\frac{iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin^2\theta\cdot\exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot\frac{1}{1+\frac{\sin^2(\phi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp$$