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Focusing properties of radially polarized helico-conical Lorentz-Gauss beam

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A B S T R A C T

Helico-conical wavefront modulation affects focusing properties and plays an important role in many optical systems. Radially polarized Lorentz-Gauss beams were modulated with helico-conical wavefront and their focusing properties were investigated by vector diffraction theory. Results show that focusing properties may be alerted considerably by helico-conical parameters, and some novel focal patterns appear. The focal patterns turn on spiral inteinsity curves, and the effect of numerical aperture is weaker than that of helico-conical parameters. Some optical gradient force distributions are also calculated to show that focusing radially polarized helico-conical Lorentz-Gauss beam may find wide applications in optical manipulation.

1. Introduction

Lorentz-Gaussian beam has become one other optical branch and attracted much attention [1–4], and vector properties of vector beams were also introduced in Lorentz-Gaussian beam. In the field of optics, scientists are constantly trying them best to dig more secrets. On the other hand, helico-conical optical beams have also attracted much attention, and show many novel propagating and focusing characteristics [5–7]. Mysterious veil, the relevant features of the radially polarized helico-conical Lorentz-Gauss beam in the focus area, are gradually to be uncovered. Such beams are most often referred to as optical vortices with a striking trait which is the vanishing field at the singularity location resulting in a doughnut or ring-shaped intensity cross-section [8]. So, they have a broaden application in varies of fields, such as optical micro manipulation, optical information transmission, biological medicine and so on, which makes different researches of radially polarized helicon-conical Lorentz-Gauss beam a hot spot.

In order to get insight into properties of Lorentz-Gauss beam more deeply, and extend its application domain. To our best knowledge, there is no published files focusing on radially polarized helico-conical Lorentz-Gauss beam [8,9]. In this article, radially polarized Lorentz-Gauss beams were modulated with helico-conical wavefront and their focusing properties were investigated by vector diffraction theory. The method of numerical calculation is proposed to analyze the impact of the different values of charge number m, eccentric parameter K and NA on the focus characteristics of the radially polarized helicon-conical Lorentz-Gauss beam and we will make detailed analysis to them.

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2. Focusing radially polarized helico-conical lorentz-Gauss beam

The wavefront of radially polarized Lorentz-Gaussian vortex beam is modulated with sine-azimuthal variation wavefront in this article, and the wavefront is in form of,

$$\psi(r,\phi) = m\phi\left(K - r/r_0\right) == \exp\left[im\phi\left(K - \frac{\sin\theta}{NA}\right)\right] \tag{1}$$

Where m, the charge number of the optical vortex, is an integer that determines the number of 2π-phase shifts that occur across one revolution of the azimuthal angle, ϕ. K is a constant that takes a value of 1. r_0 is a normalization factor of the radial coordinate, r. According to variables and coordinate transformations, the focusing radially polarized Helico-conical Lorentz-Gaussian beam can be determined as [8–11],

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

As mentioned by Eq. (2), $w_x = \omega_0/r_p$ is called relative beam waist in y coordinate direction and also called as relative Gauss parameter. $\gamma_y = \gamma_0/r_p$ is addressed as the relative beam waist in x coordinate direction, which is also named as the relative Lorentz parameter, r_p is the outer radius of optical aperture in focusing system. The $1/e$-width of the Gaussian distribution and the half width of the Lorentzian distribution are defined as ω_0 and γ_0 respectively. NA is the numerical aperture of the focusing system and $\vec{r}$ is vector unit of the radial coordinate.

According to vector diffraction theory, the electric field in focal region of radially polarized Lorentz-Gaussian vortex beam with sine-azimuthal variation wavefront is [12–14],

$$\vec{E}(\rho,\varphi,z) = E_\rho\vec{e}_\rho + E_\varphi\vec{e}_\varphi + E_z\vec{e}_z \tag{3}$$

Where $\vec{e}_\rho$, $\vec{e}_\varphi$, and $\vec{e}_z$ are the unit vectors in the radial, azimuthal, and propagating directions, respectively. 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 [13–15]

$$E_\rho(\rho,\varphi,z) = \frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin\theta\cos\theta\cos(\phi-\varphi)\cdot\exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot \frac{1}{1+\frac{\sin^2(\phi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp\left[-i\pi\sin(n\phi)\right]\cdot\exp(im\phi)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos(\phi-\varphi)\right]\right\}d\phi d\theta \tag{4}$$

$$E_\varphi(\rho,\varphi,z) = \frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin\theta\cos\theta\sin(\phi-\varphi)\cdot\exp\left[-\frac{\cos^2(\phi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right]\cdot \frac{1}{1+\frac{\sin^2(\phi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp\left[-i\pi\sin(n\phi)\right]\cdot\exp(im\phi)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos(\phi-\varphi)\right]\right\}d\phi d\theta \tag{5}$$

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

Where θ denotes the tangential angle with respect to the z axis, A is a constant, and ϕ is the azimuthal angle in regard to the x axis. k is wave number. The optical intensity in focal region is proportional to the modulus square of Eq. (3).

The gradient force corresponding to the focal intensity distribution can be expressed as [15,16],

$$F_{grad} = \frac{n_b^2 r^3}{2}\cdot\left(\frac{T^2-1}{T^2+2}\right)\nabla\left|\vec{E}(\rho,\psi,z)\right|^2 \tag{7}$$

where r is the radius of particles, n_b is the refraction index of the surrounding medium. And parameter T, the relative index of refraction, equals to the ratio of the refraction index of the particle n_p to the refraction index of the surrounding medium n_b. Gradient force F_{grad} points in the direction of the gradient of the light intensity if the diffractive index of particles is bigger than that of surrounding medium, i.e. $n_p > n_b$. Optical gradient force pattern can be investigated by means of Eq. (7).