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Tunable optical gradient force of radially polarized Lorentz-Gauss vortex beam by sine-azimuthal variation wavefront

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A B S T R A C T

Tunable optical gradient force distributions of radially polarized Lorentz-Gauss vortex beam by sine-azimuthal variation wavefront were investigated by vector diffraction theory, which shows that many interesting force patterns may appear, including “x” shape optical trap, twines “C” shape optical trap, crescent shape optical trap, and overlapping optical gradient force traps. And whole force distributions are symmetric about two coordinate axes for case of even number value of phase parameter, while only symmetric about one coordinate axis for odd number value of phase parameter. Effect of charge number of the optical vortex on force pattern evolution is more remarkable for lower phase parameter than that for higher. Force pattern is very sensitive to phase parameter, therefore, force pattern may be used to act as one kind of measurement method of phase parameter.

1. Introduction

Optical tweezers have been become important tool in many domains [1,2], including particle manipulation [3,4], photon emission [5], force measurement [6,7], microscopy [8]. Usually, it is deemed that the forces exerted on the particles in light field include two kinds of forces, one is the gradient force, which is proportional to the intensity gradient; the other is the scattering force, which is proportional to the optical intensity [9], and the gradient force is important and necessary condition for constructing the optical tweezers. Optical radient force becomes one research topics point. Gao and co-workers investigated the optical gradient force in apodized optical system and force of hyperbolic-cosine-Gaussian beam with vortices [10,11]. Optical gradient force of cosh-Gaussian with sine-azimuthal and half-space phase modulation was also studied [12]. Recently, optical gradient force of linearly polarized sine-azimuthal Lorentz beam with one on-axis optical vortex was explored [13]. Wang et al. analytically studied dispersion properties and optical gradient forces of different-order transverse magnetic modes in two coupled hyperbolic metamaterial waveguides [14].

Lorentz-Gaussian beam has become one other optical branch and attracted much attention since it was introduced to describe the output beams from diode lasers [15–19]. Focusing properties of linearly polarized Lorentz-Gaussian beam with one on-axis optical vortex was investigated [17]. Recently, Zhou investigated the fractional Fourier transform of

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Lorentz-Gauss beams [20]. Focusing properties of Lorentz-Gaussian beam with trigonometric function modulation was also investigated by vector diffraction theory [21]. With the development of radially polarized beams, Sarawathi et al. investigated the tight focusing properties of radially polarized Lorentz-Gaussian beam [22].

In order to get insight into properties of Lorentz-Gauss beam more deeply, and extend its application domain, and to our best knowledge, there is no published files dealing with optical gradient force of radially polarized Lorentz-Gauss vortex beam, therefore, in this article, the tunable optical gradient force of radially polarized Lorentz-Gauss vortex beam by sine-azimuthal variation wavefront was investigated by considering full vector components in three orthogonal coordinate directions. Section 2 gives focusing principle of radially polarized Lorentz-Gaussian vortex beam sine-azimuthal variation wavefront modulation, and results and discussions were shown in Section 3. Conclusions were summarized in Section 4.

2. Focusing radially polarized Lorentz-Gaussian vortex beam with wavefront modulation

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 $\phi = -\pi\sin(n\varphi)$, n is phase parameter that indicates the sine phase change frequency on increasing azimuthal angle. According to variable and coordinate transformations [17–19,21], the focusing radially polarized Lorentz-Gaussian vortex beam with sine-azimuthal variation wavefront can be written as,

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

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. $\gamma_y = \gamma_0/r_p$ is called relative beam waist in x coordinate direction, and may also be called relative Lorentz parameter, r_p is the outer radius of optical aperture in focusing system. ω_0 and γ_0 are the $1/e$-width of the Gaussian distribution and the half width of the Lorentzian distribution, respectively. NA is the numerical aperture of the focusing system. $\vec{r}$ 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 with sine-azimuthal variation wavefront is [23–25],

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

where $\vec{e}_\rho$, $\vec{e}_\phi$, and $\vec{e}_z$ are the unit vectors in the radial, azimuthal, and propagating directions, respectively. 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 [23–25]

$$\begin{aligned} E_\rho(\rho,\phi,z) = {} & \frac{-iA}{\pi}\int_0^\alpha\int_0^{2\pi}\sqrt{\cos\theta}\cdot\sin\theta\cos\theta\cos(\varphi-\phi) \\ & \cdot\exp\left[-\frac{\cos^2(\varphi)\cdot\sin^2\left(\theta\right)}{NA^2\cdot w_x^2}\right] \\ & \cdot\frac{1}{1+\frac{\sin^2(\varphi)\cdot\sin^2(\theta)}{NA^2\cdot\gamma_y^2}}\cdot\exp\left[-i\pi\sin(n\varphi)\right] \\ & \cdot\exp(im\varphi)\cdot\exp\left\{ik\left[z\cos\theta+\rho\sin\theta\cos(\varphi-\phi)\right]\right\}d\varphi d\theta \end{aligned} \tag{3}$$

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

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