Research Article

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Effect of Primary Spherical Aberration on Tightly Focused Linearly Polarized Lorentz Gaussian Beam

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ABSTRACT

In this paper attention is provided to the effects of primary spherical aberration on the linearly polarized Lorentz–Gauss beam with one on-axis optical vortex investigated by vector diffraction theory. It is observed that by properly choosing the Lorential parameter charge one can obtain many novel focal patterns suitable for optical tweezers, laser printing and material process. However, it is observed that the focusing objective with spherical aberration generates structural modification and positional shift of the generated focal structure.

Keywords: Annularobstruction; Lorentz gauss beams.

1. INTRODUCTION

Many areas in optical sciences make use of a tightly focused light beam such as confocal microscopy (Wilson, 1990) and optical data storage (Ichiliura *et al.* 1997). A highly concentrated and well-matched field is also a necessary requirement for coupling to small quantum systems (Van Enk and Kimble, 2000) and applying light forces to microscopic particles (MaiaNeto and Nussenzveig, 2000). In the regime of strong focusing, the widely used scalar theories are inadequate to describe the focal field. Since for many applications an exact knowledge of the structure of the focal field is required, an vectorial focusing theory approach is required. 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 as a closed-form solution of the paraxial wave equation (Gawhary and Severini, 2006; Bandres and Gutiérrez-Vega, 2007); in experiment, the Lorentz-Gauss beam can be realized by certain double hetero junction lasers (Dumke, 1975; Naqwi and Durst, 1990). Due to the high angular spread, Lorentz–Gauss beams have been proposed to describe the radiation emitted by a single mode diode laser (Naqwi and Durst, 1990; Yang, 2008). Lorentz beams and Gaussian beams are the two extreme cases of Lorentz–Gauss beams. The symmetry properties (Gawhary, 2006), the focal shift (Zhou, 2008), the beam propagation factor (Zhou, 2009), and the Wigner distribution function of Lorentz-Gauss beams (Zhou and Chen, 2012) have been investigated.

The characteristics and applications of Lorentz Gauss Beams have been investigated (Torre *et al.* 2008; Zhou, 2008; 2009; 2010; Zhou and Chu, 2010). The virtual source for generation of the rotational symmetric Lorentz–Gauss beam has been identified, and the closed form expressions including integral and differential representations have been derived (Sun *et al.* 2012). If the radiation emitted by a single mode diode laser goes through spiral phase plate, it becomes a Lorentz-Gauss vortex beam. The wave-front phase of a Lorentz-Gauss vortex beam can be modulated the spiral phase plate. The advantage of a Lorentz-Gauss vortex beam over the Loretnz-Gauss beam is that it has a twisted phase front and zero intensity in the center region of the beam profile. Owing to carrying the orbital angular momentum, a Lorentz-Gauss vortex beam has potential applications in the fields of optical micromanipulation, nonlinear optics, quantum information processing, etc., (He *et al.* 1995; Curtis *et al.* 2002; Gibson *et al.* 2004). Focusing properties of linearly polarized Lorentz-Gauss beam with one on-axis optical vortex was investigated by vector diffraction theory (Rui *et al.* 2013). Results show that the focal pattern can be altered considerably by charge number of the optical vortex and the beam parameters. In recent years many papers devoted to studying the effect of different aberrations on high aperture optical systems. The influence of spherical aberration and defocus was investigated (Visser and Wiersma, 1991; 1992). It was found that the axial intensity distribution becomes essentially asymmetrical relative to the focal plane. Several papers (Braat, 2003; 2005) have been devoted to the analysis and development of the Nijboer-Zernike theory. However, to the best of our knowledge, the tight focusing properties of linearly polarized Lorentz-Gauss beam containing optical vortex in presence of primary spherical aberration are evaluated by using a vector Diffraction theory. In this paper we present the results of intensity distribution of linearly polarized Lorentz-Gauss beam with and without vortex beam.

2. THEORY

In the focusing systems, the incident beam is Lorentz-Gauss beam, whose geometric parameters and coordinate system the amplitude distributions of the electric field in the directions parallel and normal to the junction are the Lorentzian and Gaussian functions, respectively (Naqwi and Durst, 1990; Zhou, 2009). Therefore, the electric field distribution can be rewritten as,

$$E_0(\theta,\varphi) = \exp\frac{\left[-\cos^2(\varphi)\times\sin 2(\theta)\right]}{NA^2\omega_x{}^2} \times \frac{1}{1+\dfrac{\sin 2(\varphi)\sin^2(\theta)}{NA^2\omega_\gamma{}^2}}\exp(im\varphi) \rightarrow (1)$$

It is assumed that the incident Lorentz-Gauss beam is linearly polarized along the x axis. According to vector diffraction theory, the electric field in focal region can be written in the follow form (Gu, 2000; Ganic *et al*. 2003).

$$E(\rho,\psi,z) = \frac{1}{\lambda}\iint_\Omega\left\{\left[\cos\theta+\sin 2\psi(1-\cos\theta\right]\times\cos\varphi\sin\varphi(\cos\theta-1)y+\cos\varphi\sin\theta z\right\}$$
$$\times\exp\frac{\left[-\cos^2(\varphi)\times\sin 2(\theta)\right]}{NA^2\omega_x{}^2}\times\frac{1}{1+\dfrac{\sin 2(\varphi)\sin^2(\theta)}{NA^2\gamma_\gamma{}^2}}\exp(im\varphi)$$
$$\times A_1\times\exp\left[-ik\rho\sin\theta\cos(\varphi-\psi)\right]\exp(-ikz\cos\theta)\sin\theta d\theta d\varphi\rightarrow(2)$$

Where φ∈[0, 2π) , θ∈[0, arcsin(NA)]. Vectors **x**, **y**, and **z** are the unit vectors in the x, y, and z directions, respectively. It is clear that the incident beams is depolarized and has three components (E_i, E_j and E_k) in **x**, **y**, and **z** directions, respectively. The variables ρ, ψ and z are the cylindrical coordinates of an observation point in focal region. The wave aberration function, which denotes the deviation of the actual wavefront from the ideal wavefront in the presence of primary spherical aberration and defocusing, can be written as

$$A_{sph}(\theta) = \exp\left[ikA_s\left(\frac{\sin\theta}{\sin\alpha}\right)^4 + A_d\left(\frac{\sin\theta}{\sin\alpha}\right)^2\right]\rightarrow(3)$$

Where $A_s$and A_d are, respectively, the spherical aberration and the defocusing coefficient in units of wavelength. The presence of coma can be expressed as Kant, (1993).

3. RESULTS & DISCUSSION

It is observed from fig. 1, that for an obstructed case, the presence of *SA* shifted and elongated, the focal spot in the axial direction away from the aperture. For w_x=0.3 and wy=0.3, the FWHM of the generated focal spot is 0.623λ and focal depth s 1.4λ for *As*= 0. However increasing the *As* to 0.5λ,1.0λ and 1.5λ ,the axial focal shift of 0.7λ ,1.8λ and 2.5λ is observed with focal depth of around 1.8λ is achieved, thus increasing the SA coefficient elongation of the focal spot in the axial direction along with position of maximum intensity.

Fig. 2 is same as in fig. 1 but for w_x=0.3,w_y=1.2, which is the most ideal case of the Lorentz beam generated by heterojunction diode laser. It is observed as in the previous case the presence of *SA* generated focal shift and elongation of focal spot in the axial direction. FWHM of focal spot is measured as 0.526λ DOF as 1.2λ for *As=0*.Howeverfocal shift of 1λ,1.8λ and 2.5λ is observed with focal depth of around 1.2λ for *As* to 0.5λ,1.0λ and 1.5λ respectively.

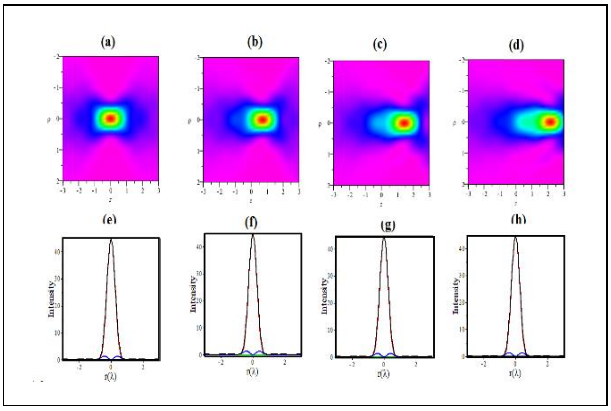

Fig. 1: (a-d) linearly polarized Lorentz-Gaussian beam with primary spherical aberration for NA = 0.95, w_x= 0.3, w_y= 0.3, n = 0. Corresponding to A_s =0λ,0.5λ,1λ and 1.5λ respectively. Fig. (e-h) are corresponding intensity calculated in the radial axis

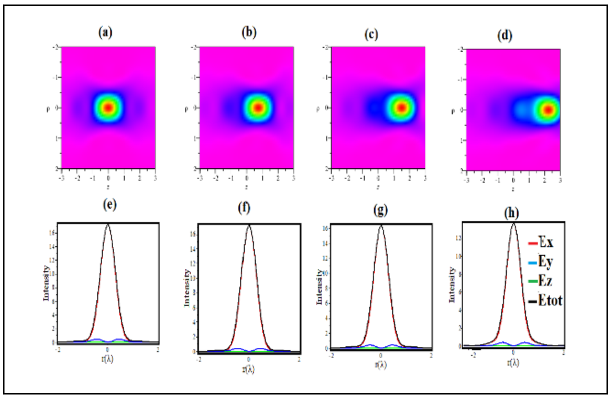

Fig. 2: (a-d) Llinearly polarized Lorentz-Gaussian beam with primary spherical aberration for NA = 0.95, w_x= 0.3, w_y= 1.2, n = 0. Corresponding to A_s =0λ,0.5λ,1λ and 1.5λ respectively. Fig.(e-h) are corresponding intensity calculated in the radial axis

In order to reduce the focal spot we introduced annular obstruction with δ=0.5 to the aperture and corresponding plots are show in fig.3. It is noted that the FWHM of the focal spot is 0.428λ and focal depth around 1.96λ is observed for As=0.However positional shift of 1.1λ,2λ and 3λ is observed for *As* to 0.5λ,1.0λ and 1.5λ. thus introduction of annular obstruction generated the focal spot it does not elongates the focal spot in the axial direction as if in the previous case.

Fig. 4 shows same as fig.3 but for δ=0.75. It is noted that increasing the annular obstruction further increases the focal depth and focal shift. It is noted that for As=0, the FWHM of focal spot 0.625λ and focal depth 3.256λ. it is also noted increasing the *As* to 0.5λ,1.0λ and 1.5λ results in focal shift 1λ,2.2λ and 3.1λ respectively.

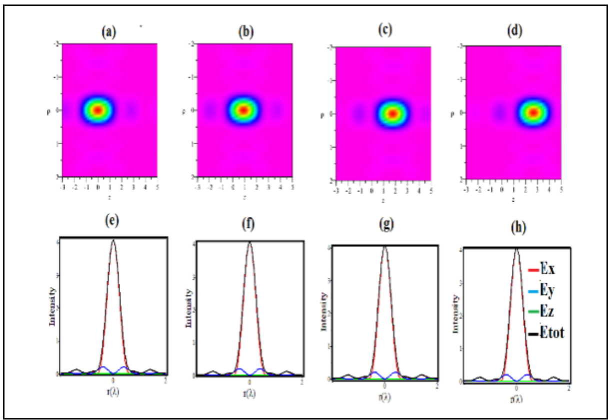

Fig. 3: (a-d) Linearly polarized Lorentz-Gaussian beam with primary spherical aberration for NA = 0.95, w_x= 0.3, w_y= 1.2, using annular obstruction δ=0.5, n = 0. Corresponding to A_s =0λ,0.5λ,1λ and 1.5λ respectively. Fig.(e-h) are corresponding intensity calculated in the radial axis

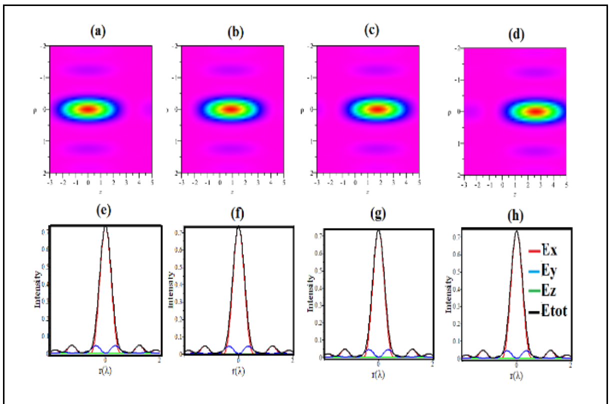

Fig. 4: (a-d) Linearly polarized Lorentz–Gaussian beam with primary spherical aberration for NA = 0.95, w_x= 0.3, w_y= 1.2, using annular obstruction δ=0.75, n = 0. Corresponding to A_s =0λ, 0.5λ,1λ and 1.5λrespectively. Fig.(e-h) are corresponding intensity calculated in the radial axis

4. CONCLUSION

Effect of primary spherical aberration on the tight focusing properties of a linearly polarized Lorentz-Gauss beam containing one optical vortex was investigated numerically by the vector diffraction theory. It is noted that under the obstruction condition, the presence of SA generated the focal shift along with elongation of focal spot in the axial direction .However introducing the annular obstruction with δ=0.5 and δ=0.75 shows the reduction of focal spot and improvement of focal depth which again suffers focal shifting corresponding to increasing of spherical aberration coefficient .However elongation of focal spot in the axial direction is not observed for the obstruction case. The authors expects such that study is important in practical applications such as optical tweezers, laser printing and material processing.

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