Optik 154 (2018) 133–138

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Tight focusing properties of anomalous vortex beams

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ARTICLE INFO

Article history:
Received 24 June 2017
Accepted 3 October 2017

Keywords:
Singular optics
Diffraction theory
Laser beam characterization

ABSTRACT

Tight focusing properties of an anomalous vortex beam (AVB) passing through a high numerical aperture (NA) lens system are investigated, based on vector Debye integral. The numerical examples show that intensity distribution for the AVBs in focal region depend on the beam parameters including the topological charge m, the order of the AVBs n. Furthermore, the phase distribution and the intensity distribution at the different propagation distance z are discussed in detail. Our results will be useful to find the potential applications of AVBs.

1. Introduction

Vortex is a general phenomenon in wave fields, in which the flow rotates around the dark center [1]. In an optical vortex, its central light intensity is zero and the phase is undetermined [2]. In 1992, Allen et al. identified that vortex beams with a phase term of $\exp(il\varphi)$ carry an orbital angular momentum of $l\hbar$ per photon, where l is the topological charge, φ is the azimuthal angle and $\hbar$ is Planck's constant [3]. The properties of vortex beams have attracted the strong interest of many researchers [4–6], and so far, vortex beams have found important applications in free-space information transfer and communications [7] and optical manipulation [8], etc. In 2013, a new type of vortex beam called anomalous vortex beam(AVB) has been proposed both theoretically and experimentally, the AVB will eventually become an elegant Laguerre-Gaussian beam in the far field (or in the focal plane) in free space [9]. Recently, the characteristic of AVBs through paraxial optical systems [10,11] and in strongly nonlocal nonlinear media [12] has been discussed.

On the other hand, the focusing properties of the beams focused by a high NA lens system have attracted much attention due to their potential applications in high density optical data storage [13], material processing [14] and particle trapping, etc. [15,16]. Therefore, in recent years, the tight focusing properties of vortex beams have been studied extensively [17–23], such as, the degree of polarization has been discussed by considering the distribution of the spectral densities of the three electric field components in the focusing region [17], and the electric fields have been calculated in the study of azimuthally and radially polarized beams focused by a high NA lens system [19], besides, the tight properties of an asymmetric Bessel beam and Gaussian beam are studied in detail as well [21,22].

However, up to now, to our knowledge, the tight focusing properties of AVBs passing through a high NA lens system have not been studied yet. The purpose of this letter is to investigate the tight focusing properties of AVBs, and which will be important to the applications of AVBs in some fields.

In Section 2, the theoretical electric fields for AVBs passing through a high NA lens system are derived. In Section 3, some numerical simulation results are presented and discussed. The Section 4 is a summary of the paper.

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https://doi.org/10.1016/j.ijleo.2017.10.013

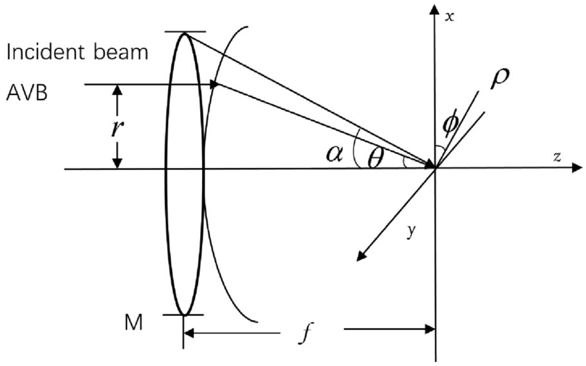

Fig. 1. Schematic diagram of the tight focusing system.

2. Theory

The electric field of the AVB at z = 0 is defined as follows

$$E_{n,m}(r,\varphi) = E_0\left(\frac{r}{w_0}\right)^{2n+|m|} \exp\left(-\frac{r^2}{{w_0}^2}\right) \exp(-im\varphi). \tag{1}$$

where E_0 is a constant, n is the beam order of the AVB, m is the topological charge, and w_0 is beam waist size of the fundamental Gaussian beam ($m = n = 0$), r and φ are radial and azimuthal coordinates, respectively. According to the vector Debye integral, for a linearly polarized incident beam along x axis, the electric field in the vicinity of the focal region of a high NA lens system can be expressed as [24–26].

$$E(\rho,\phi,z) = \frac{i}{\lambda}\int_0^{2\pi}\int_0^{\alpha} E(\theta,\varphi) \times T(\theta) \times \begin{bmatrix} [\cos\theta + \sin^2\varphi(1-\cos\theta)]\vec{e_x} \\ [\cos\varphi\,\sin\varphi(\cos\theta - 1)]\vec{e_y} \\ (\cos\varphi\,\sin\theta)\vec{e_z} \end{bmatrix} \times \exp[-ik\rho\,\sin\theta\,\cos(\varphi-\phi)] \exp(-ikz\,\cos\theta) \sin\theta\, d\theta\, d\varphi \tag{2}$$

where $T(\theta)$ is the apodization function (for an aplanatic lens $T(\theta) = \cos^{\frac{1}{2}}\theta$ [18]), $E(\theta, \varphi)$ is the pupil apodization function at the entrance pupil, θ is the angle of convergence. The schematic diagram of the tight focusing system is shown in Fig. 1. As shown in Fig. 1, λ is wavelength of the incident beam; $k(k = \frac{2\pi}{\lambda})$ is the wavenumber; f is the focal length of the high numerical aperture objective; The parameters ρ, ϕ, z are the cylindrical coordinates of an observation; $\vec{e_x}$, $\vec{e_y}$, $\vec{e_z}$ are the unit vectors along the x, y, z directions, respectively. α is given by numerical aperture value $\sin\alpha$.

Under the sine condition, we get $r = f\sin\theta$, so that the pupil apodization function of the AVB can be written as

$$E_{n,m}(\theta,\varphi) = E_0\left(\frac{f\,\sin\theta}{w_0}\right)^{2n+|m|} \exp\left(-\frac{f^2\sin^2\theta}{{w_0}^2}\right) \exp(-im\varphi), \tag{3}$$

According to Eqs. (1)–(3), after some simplification, the x, y, and z components of the electrical field in the vicinity of the focus can be simplified as

$$\begin{aligned} E_x(\rho,\phi,z) = ik\int_0^{\alpha} A\left(\theta\right) \{&(-1)^m \frac{1+\cos\,\theta}{2} i^m J_m(k\rho\,\sin\,\theta) \exp(-im\phi) \\ &-(-1)^{m+2}\frac{1-\cos\,\theta}{4} i^{m+2} J_{m+2}(k\rho\,\sin\,\theta) \exp[-i(m+2)\phi] \\ &-(-1)^{m-2}\frac{1-\cos\,\theta}{4} i^{m-2} J_{m-2}\left(k\rho\,\sin\,\theta\right) \exp[-i(m-2)\phi]\} d\theta, \end{aligned} \tag{4a}$$

$$\begin{aligned} E_y(\rho,\phi,z) = -\frac{k}{4}\int_0^{\alpha} A\left(\theta\right)(\cos\,\theta - 1)\{&(-1)^{m+2} i^{m+2} J_{m+2}\left(k\rho\,\sin\theta\right) \exp[-i(m+2)\phi] \\ &-(-1)^{m-2} i^{m-2} J_{m-2}\left(k\rho\,\sin\theta\right)\, \exp[-i(m-2)\phi]\} d\theta, \end{aligned} \tag{4b}$$