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Multi-focus of modulated polarized Airy beam

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ABSTRACT

The focusing performance of a modulated polarized Airy beam is explored by using the Richards and Wolf vectorial diffraction model in a high numerical aperture system. The multiple foca appeared on the focal plane or along the optical axis when a complex amplitude modulating function was introduced. Two focusing spots with long-focal-depth were additionally observed due to the Airy beam and complex amplitude modulation. The distance between the focuses were changed from 1.15λ to 3.56λ with FWHM of 0.9λ for one-dimensional linear polarized incident beam and from 1.15λ to 3.64λ for two-dimensional beam. The multiple focusing spots are expected to apply in the field of optical trapping and particle acceleration.

1. Introduction

Since the accelerating Airy beam was experimentally observed in 2007 [1], the propagation characteristics and their applications [2–7] such as diffraction-free, self-bending, [2] self-healing [3,5], light sheet microscopy [6] and self-accelerating electron beams [7], were widely explored. Recently, many researchers have considered the Airy-like beam such as circular Airy beam, symmetric Airy beam [8] and other transverse shaped beam [9]. Many researches focused on the self-acceleration and the applications of Airy beams [10,11], but few researches described the energy distribution near the focal area [12]. Meanwhile, for the focusing polarized beam, recent researches are the circularly symmetric beams with various modulation such as Bessel-Gaussian (BG) beam, Laguerre-Gaussian (LG) beam [13–16], hypergeometric Gauss modes of type-II (HyGG-II) beam [17] and circular Airy beam [18] with quasi-cosine modulation [13] and multi-rings phase modulation [19]. Non-symmetrically polarized beams, which will show different focusing performance in a high NA focusing system, are seldom investigated. Therefore, we research the focusing performance of one- and two-dimensional (1D and 2D) polarized Airy beams in a focusing system with high numerical aperture (NA) in this paper. In order to obtain accurate results, the Richards–Wolf's formula is applied. The focusing performance near the focus will be analyzed for different parameters.

In Section 2, expressions of 1D and 2D Airy beam are introduced. In Section 3, the Richards–Wolf's formula is described for a high NA focusing system. Numerical results of the polarized Airy beam focused by high NA focusing system are given in Section 4. Analysis and discussion are also provided in this section. In Section 5, conclusions are given.

2. One- and two-dimensional Airy beam

Airy wave packets were predicted by Berry and Balazs within the context of quantum mechanics [20]. However, Airy wave packet was firstly observed in 2007 due to the infinite energy of an Airy beam. Siviloglou et al. achieved a new kind of finite energy Airy beam by using the exponentially decaying amplitude truncated method. It has been proved that these finite energy Airy beams almost have same lateral profile and non-diffraction propagation characteristics of an ideal Airy wave packets. The feature of self-bending, self-healing and diffraction-free has been demonstrated [21]. The finite energy 1D Airy beam can be expressed as [21]

$$\Phi(s,\xi) = Ai\left(s - \left(\frac{\xi}{2}\right)^2 + ia\xi\right) \times \exp\left(as - \left(\frac{a\xi^2}{2}\right) - i\left(\frac{\xi^3}{12}\right) + i\left(\frac{a^2\xi}{2}\right) + i\left(\frac{s\xi}{2}\right)\right), \quad (1)$$

where $s = x/x_0$, $\xi = z/kx_0^2$, and $k = 2\pi n/\lambda_0$. s is the normalized transverse coordinate and a is the attenuation factor. x_0 is the transverse scale that is used to describe the transverse size of the beam [22]. ξ is the normalized propagation distance and k is the wavenumber of the optical wave. The initial intensity distribution ($\xi = 0$) of the 1D Airy beam is shown in Fig. 1(a) (the intensity scale bar in the following intensity distribution figure is the same with this one). The initial envelope of 2D Airy beam is given by $\Phi(x,y) = Ai(x/x_0)Ai(y/y_0)\exp[a(x/x_0) + a(y/y_0)]$, as shown in Fig. 1(b). 1D and

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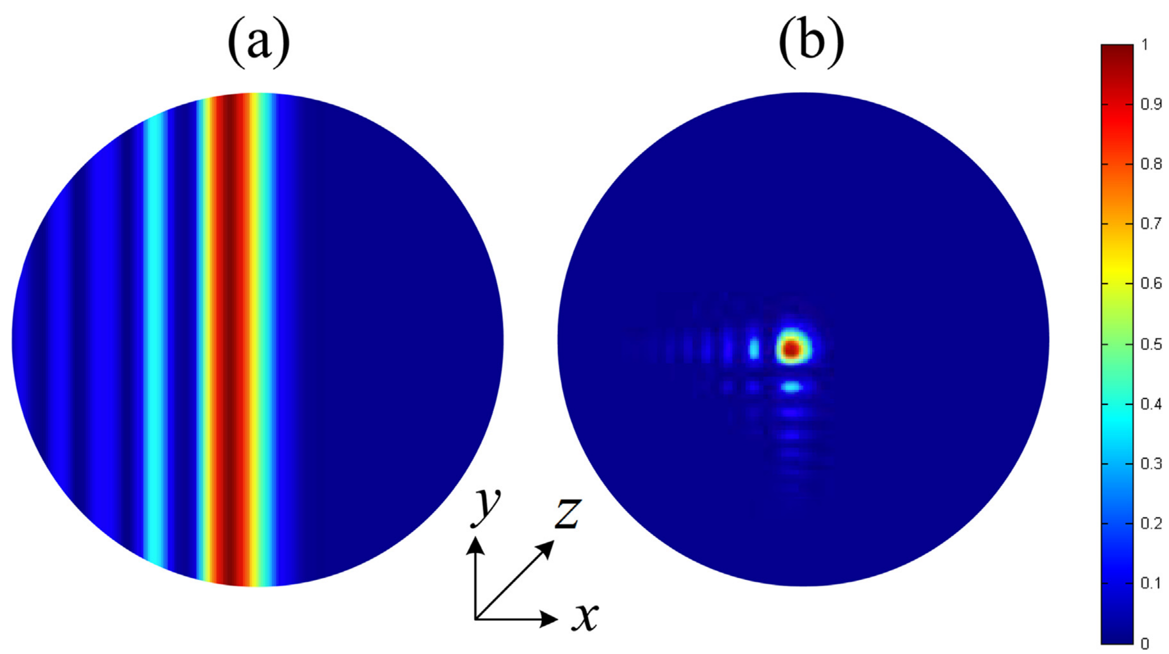

Fig. 1. Amplitude distribution of Airy beam on the input pupil. (a) 1D beam and (b) 2D beam (a=0.1 and x_0=0.1).

2D Airy beams have the same self-bending transposition features [21].

Compared with other diffraction-free beam such as Bessel-Gauss beam and Mathieu beam [23], it is worth noting that 1D Airy beam only has symmetry on y-direction and 2D Airy beam lacks parity symmetry. Due to the complex intensity distribution, their focusing fields exhibit multifocal characteristics on the focal plane and along optical axis in a high NA focusing system when amplitude modulated function is introduced.

3. Vector representation of a high NA focusing system

In a high NA aplanatic focusing optical system, the vector electric field near the focus in a homogeneous dielectric medium can be considered from Richards and Wolf's theory [24]

$$E(\rho,\varphi,z) = -\mathrm{i}A\int_0^{\alpha}\int_0^{2\pi} B(\theta,\phi)P(\theta,\phi)\cos^{\frac{1}{2}}\theta \\ \exp\{ik[\rho\sin\theta\cos(\phi-\varphi)+z\cos\theta]\}\sin\theta \mathrm{d}\theta \mathrm{d}\phi, \tag{2}$$

where (ρ, φ, z) are the cylindrical coordinates in the focal region. (θ, ϕ) are the spherical angular coordinates of the input pupil of the focusing system. $B(\theta, \phi)$ is the transmission function. $P(\theta, \phi)$ is the polarization matrix. $n\sin\alpha$=NA, and n is the refractive index of the media. NA is chosen as 0.99 in this paper. A is constant coefficient. $k=2\pi/\lambda$ is the wavenumber and λ is the wavelength.

Polarization matrix $P(\theta, \phi)$ depends on the polarization of the incident Airy beam. For certain kinds of polarization distribution, the polarization matrix can be written as the following [25]:

- Linear x-polarization

$$P(\theta,\phi) = \begin{bmatrix} 1+\cos^2\phi(\cos\theta-1) \\ \sin\phi\cos\phi(\cos\theta-1) \\ -\cos\phi\sin\theta \end{bmatrix}. \tag{3}$$

- Circular polarization ("+" for left-handed polarization and "−" for right)

$$P(\theta,\phi) = \begin{bmatrix} [1+\cos^2\phi(\cos\theta-1)] \pm i[\sin\phi\cos\theta(\cos\theta-1)] \\ [\sin\phi\cos\phi(\cos\theta-1)] \pm i[1+\sin^2\phi(\cos\theta-1)] \\ -\sin\theta(\cos\phi \pm i\sin\phi) \end{bmatrix}. \tag{4}$$

- Radial polarization

$$P(\theta,\phi) = \begin{bmatrix} \cos\phi\cos\theta \\ \sin\phi\cos\theta \\ -\sin\theta \end{bmatrix}. \tag{5}$$

- Azimuthal polarization

$$P(\theta,\phi) = \begin{bmatrix} \sin\phi \\ -\cos\phi \\ 0 \end{bmatrix}. \tag{6}$$

4. Numerical results and discussions

In previous contents, the vector representation of the focusing field near the focus has been given. The vector method is employed to explore the focusing performance of a high NA focusing system with the transmission function $B(\theta, \phi)$ illuminated by the finite energy 1D and 2D Airy function. Variables x_0 and y_0 are normalized by the input pupil R. The relation between (x, y) and (θ, ϕ) in a aplanatic focusing system described by sine rule can be written as

$$x = \beta\sin\theta\cos\phi/\sin\alpha \quad \text{and} \quad y = \beta\sin\theta\sin\phi/\sin\alpha, \tag{7}$$

where β is a parameter acting as a unit. Therefore, 1D and 2D Airy beams in spherical coordinate can be rewritten as

$$B(\theta,\phi) = \mathrm{Ai}\left(\frac{\beta\sin\theta\cos\phi}{x_0\sin\alpha}\right)\exp\left(a\frac{\beta\sin\theta\cos\phi}{x_0\sin\alpha}\right), \tag{8}$$

$$B(\theta,\phi) = \mathrm{Ai}\left(\frac{\beta\sin\theta\cos\phi}{x_0\sin\alpha}\right)\exp\left(a\frac{\beta\sin\theta\cos\phi}{x_0\sin\alpha}\right) \\ \times \mathrm{Ai}\left(\frac{\beta\sin\theta\sin\phi}{x_0\sin\alpha}\right)\exp\left(a\frac{\beta\sin\theta\sin\phi}{x_0\sin\alpha}\right). \tag{9}$$