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Tight focusing of radially polarized circular Airy vortex beams

Musheng Chen [a,b], Sujuan Huang [a,*], Wei Shao [a]

[a] School of Communication and Information Engineering, Key Laboratory of Special Fiber Optics and Optical Access Networks, Shanghai University, Shanghai, 200072, China

[b] School of Physical and Information Engineering, Quanzhou Normal University, Fujian, 362000, China

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ABSTRACT

Tight focusing properties of radially polarized circular Airy vortex beams (CAVB) are studied numerically. The light field expressions for the focused fields are derived based on vectorial Debye theory. We also study the relationship between focal profiles, such as light intensity distribution, radius of focal spot and focal length, and the parameters of CAVB. Numerical results demonstrate that we can generate a radially polarized CAVB with super-long focal length, super-strong longitudinal intensity or subwavelength focused spot at the focal plane by properly choosing the parameters of incident light and high numerical aperture (*NA*) lens. These results have potential applications for optical trapping, optical storage and particle acceleration.

1. Introduction

The study of circular Airy beams (CAB) has attracted great attentions attribute to its self-accelerating, non-diffracting, and self-healing property. Without any lenses, the CAB has a wavefront's energy abruptly auto-focused in the focal field. Furthermore, the maximum intensity of focal point can be enhanced about two orders of magnitude compared with that in the initial plane [1–3]. Due to the self-accelerating property, the CAB has the ability to deliver high energy to transparent samples without scathing the material before the focus and produce a greater gradient force on the particle [4,5]. However, the intensity distribution of CAB at the focal point is not hollow, which makes CAB extremely hard for trapping the micro particle whose refractive index is lower than the surrounding medium. Moreover, the CAB does not carry the orbital angular momentum, which is shown that it cannot be used to transport and rotate small particles [6–8]. As for particle trapping, dark spot intensity distribution along the optical axis also can trap the particle in three dimensional space. The combination of CAB and a vortex optical field can significantly expand their applications for biomedical treatment, optical trapping, optical micromanipulation of particles and electron capture [9].

In order to meet the requirements of particle trapping, CAVB should be focused by a high numerical aperture lens because it cannot be abruptly focused into a subwavelength focused spot [10]. Comparing linearly, circularly and elliptically polarized vortex beams, radially polarized vortex beams focused by a high NA lens have new features, which are very beneficial for optical trapping and particle acceleration. When the radially polarized beams are focused by a high *NA* lens, the size of focal spot is much smaller than linear or circularly polarized beams, and even beyond the Rayleigh diffraction limitation. Besides, the intensity of longitudinal component will become much stronger than radial component [11–15].

The tight focusing properties of different kinds of radially polarized vortex beams, such as Laguerre Gaussian vortex beams and Bessel Gaussian vortex beams, have been discussed both theoretically and experimentally [16–19]. More recently, Zhu et al. numerically studied the high *NA* focusing properties of CAB [10]. To the best of our knowledge, the study the tight focusing of the radially polarized CAVB has not been reported until now. Numerical results show that the intensity of longitudinal component, size of focal spot and focal length in the focal region are dependent not only on the NA value, but also on the parameters of incident beam. By adjusting the parameters of incident light and NA value, we can obtain the radially polarized CAVB with super-long focal length, super-strong longitudinal intensity or subwavelength focused spot at the focal plane.

2. Tight focusing theory of radially polarized CAVB

In this paper, vectorial Debye theory is used to analyze the tight focusing of radially polarized CAVB. The electric field distribution of CAVB at $z = 0$ can be represented by:

$$u(r, \varphi, z = 0) = Ai\left(\frac{r_c - r}{w}\right) \exp\left(a\frac{r_c - r}{w}\right) r^l e^{il\varphi}, \qquad (1)$$

* Corresponding author.
E-mail address: sjhuang@shu.edu.cn (S. Huang).

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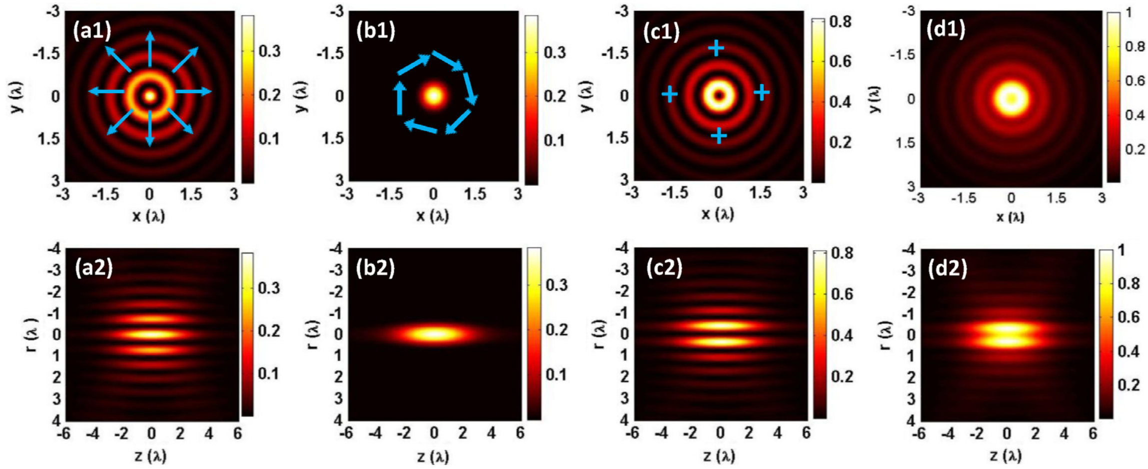

Fig. 1. Tight focusing behaviors of radially polarized CAVB in the focal plane under the conditions of $a = 0.05$, $r_c = 1$ mm, $l = 1$, $\lambda = 633$ nm, $w = 0.08$ mm, $NA = 0.85$, $f = 1$ mm. Top panels (a1–d1) and bottom panels (a2–d2) are the radial, azimuthal, longitudinal components and total intensity patterns in x–y and r–z plane, respectively.

where $Ai(.)$ denotes the Airy function, r is the radial coordinate around the optical axis, φ is azimuthal angle, r_c is the radius of the primary ring, a is decay factor, w is the scaling factor, l is the topological charge [1,2]. These parameters greatly affect the tight focusing properties of CAVB. Generally, the commercial objectives are often designed to obey the sine condition $r = f \cdot \sin\theta$. Thus the pupil plane polarization function $p(\theta)$ can be written as:

$$p(\theta) = Ai\left(\frac{r_c - f\sin\theta}{w}\right)\exp\left(a\frac{r_c - f\sin\theta}{w}\right)(f\sin\theta)^l e^{il\varphi}, \tag{2}$$

where f is the focal length of the objective, $\sin\theta$ is the *NA* angle [10].

According to the vectorial Debye theory, when a radially polarized vortex beams is focused by a high *NA* objective, the phase singularity leads to polarization transformation [20–22]. The amplitudes of radial, azimuthal and longitudinal electrical field components at the focal plane can be expressed as [23,24]:

$$\begin{bmatrix} E_r \\ E_\varphi \\ E_z \end{bmatrix} = ikf\int_0^\alpha p(\theta)\sqrt{\cos\theta}\sin\theta e^{ikz\cos\theta}\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} d\theta, \tag{3}$$

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \frac{i^l e^{il\varphi}}{2}\begin{bmatrix} i\left[J_{l+1}(kr\sin\theta) - J_{l-1}(kr\sin\theta)\right]\cos\theta \\ \left[J_{l+1}(kr\sin\theta) + J_{l-1}(kr\sin\theta)\right]\cos\theta \\ -2J_l(kr\sin\theta)\sin\theta \end{bmatrix}, \tag{4}$$

where J_l is the lth order Bessel function of the first kind, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength in free space, $\alpha = \arcsin(NA)$ is the maximum ray angle passing through the objective, Q is the corresponding polarization types. The intensity of the radial component I_r, longitudinal component I_z and the total component I_t of the tightly focused beams at the focal plane can be given as:

$$I_r = \left|E_r(r,\phi,z)\right|^2, \tag{5}$$

$$I_z(r,\phi,z) = \left|E_z(r,\phi,z)\right|^2, \tag{6}$$

$$I_t(r,\varphi,z) = \left|E_r(r,\varphi,z)\right|^2 + \left|E_\varphi(r,\varphi,z)\right|^2 + \left|E_z(r,\varphi,z)\right|^2. \tag{7}$$

3. Numerical results and analysis

In this paper, we use the ratio of maximum longitudinal intensity to maximum radial intensity I_z/I_r, radius of peak intensity and focal depth to further reveal the tight focusing properties of radially polarized CAVB. Radius of peak intensity is the size from the center of the focal hole to its maximum intensity. Focal length is the full width at half maximum along the z direction.

3.1. Numerical results

In the following, we analyze tight focusing properties of radially polarized circular Airy vortex beam through numerically evaluation of the integrals given above. It is worthy note that all length measurements are normalized to the wavelength. We set Eqs. (2)–(4) with $a = 0.05$, $r_c = 1$ mm, $w = 0.08$ mm, $\lambda = 633$ nm, $NA = 0.85$, $f = 1$ mm. Figs. 1 and 2 show the focal structure generated by tightly focused radially polarized CAVB for $l = 1$ and $l = 2$ respectively, where the electric field vectors are indicated by arrows and plus sign. From Figs. 1 and 2, it is observed that there are several circular spots appearing in the intensity patterns of radial and longitudinal focal field. As shown in Fig. 1, the longitudinal component has a hollow shape intensity and the total intensity of focal field is nonzero on the optical axis when $l = 1$, which indicate that the vortex properties of focal field are lost [12,25]. FWHM of the focal spot is about 0.58λ, which beyond the Rayleigh diffraction limitation ($0.61\lambda/NA = 0.72\lambda$), and the focal length is 5.47λ. The unique subwavelength focal spot result from the complex interaction of phase structure and polarization direction of the incident beam during interference in space [20]. Fig. 2 shows that the focal intensity distribution for $l = 2$ is a confined focal hole and the total intensity is zero near the focal plane. The radius of peak intensity at the focal plane is about 0.56λ, and the focal length is 5.72λ. The intensity distribution in the focal plane also can be analyzed by the Bessel function of Eqs. (3) and (4). Only when $l = \pm 1$, the total intensity on the optical axis will be nonzero on the optical axis. However, for $l > 1$, the total intensity on the optical axis is zero due to destructive interference. As shown in Fig. 3, the maximum intensity of the longitudinal component considerably exceed the strength of the radial and azimuthal components. The total intensity and focal spot size in the focal field are dominantly determined by the longitudinal component, which are quite different from the phenomenon of the linearly or circular polarized vortex beam [26].

3.2. Analysis

3.2.1. The tight focusing properties of CAVB with different topological charge

To illustrate the dependence of the tight focusing properties of radially polarized CAVB on topological charge l, we gradually increase l from 0 to 10 and remain the same for other parameters as in Fig. 2. Fig. 4 shows the focusing properties of CAVB for different l. As shown in Fig. 4(b), the radius of peak intensity increases with the increase of l. As a result, more lights are focused through outer edge of the lens, which will contribute more to the intensity of longitudinal component in the focal field and increase the value of I_z/I_r, as shown in Fig. 4(a). Moreover, with the increase of l, constructive interference of