Optics Communications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Tightly focusing vector circular airy beam through a hard aperture

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A R T I C L E I N F O

Article history:
Received 6 July 2014
Received in revised form
15 August 2014
Accepted 19 August 2014

Keywords:
Vector diffraction theory
High numerical aperture focusing features
Airy beams

A B S T R A C T

We investigate the tightly focusing property of radially polarized circular Airy beams through a hard aperture, and find that, in the longitudinal component of focal field, there are several spots arranging along the propagation axis. And the spot number is determined by the number of rings of input intensity pattern, as a result of the vectorial interference effect. When the aperture is fixed, the ring number can be controlled by tuning the initial radius of main ring of the input beam r_c. The intensity ratio between the middle and first/last spots varies with the decay factor of the input beam a. Taking advantage of these focusing properties, we can generate sphere- and cylinder-shape optical cages, 41λ-length optical needle, and 80λ-length optical dark channel.

1. Introduction

Since it was first proposed in 2010 [1], the circular Airy beam (CAB) has drawn significant interest due to its abruptly autofocusing property [1–5]. This kind of beam has a circularly symmetric initial amplitude [1], and can be created by using a 3/2 phase-only mask encoded onto a liquid crystal display [6,7]. When propagating in free space, it maintains a low intensity profile over several Rayleigh lengths until an abrupt focusing takes place right before a target, where the intensity is suddenly heightened by several orders of magnitude [1]. With the advantage of abruptly autofocusing property, the CAB has the ability to deliver high-energy pulses in transparent samples without damaging the material before the focus [8]. Therefore, it is an ideal candidate for biomedical treatment [9] and nonlinear optical applications [8]. The CAB also finds applications in optical manipulations, such as trapping and guiding micro particles [10,11], because this beam creates a great intensity gradient in the focal region comparing with the Gaussian beam. Unfortunately, the abruptly autofocusing property is very weak in the non-paraxial region [11]. Therefore, the CAB beam cannot be abruptly focused into a spot with a radius comparable to wavelength. As is well known, a sharp spot can be generated in the longitudinal component of focal field, when an input radially polarized beam is focused by a high-NA lens [12,13]. By designing the amplitude of input light beam, various intensity, phase, and polarization patterns can be created in the focal field to meet different applications [14–21]. Many kinds of input beams such as Gaussian [15], Bessel–Gaussian [16], and Laguerre–Gaussian beams [17] have already been studied and are demonstrated to have different focusing properties. Unlike previous works, in this paper, we investigate the CAB with a hard aperture under tightly focusing condition, and find that the focusing property of beam is unique. When a radially polarized CAB propagates through a hard aperture, then is focused by a high-NA lens, the intensity of the focal field will oscillate along longitudinal direction. And a chain of spots will appear in the longitudinal component of focal field along the propagation axis. The number of spots is the same as that of the rings in the input intensity pattern, which can be changed by tuning the initial radius of the main ring r_c. The first and last spots have maximum peak intensities, which will decrease when the decay factor of CAB, a, increases from 0 to 1. At the same time, the peak intensities of the spots near geometrical focus will increase, and the intensities at the gap between two adjacent spots become larger. When $a = 0.43$, the peak intensities of first/last spot is equal to that of middle one, and a super-long optical needle will be generated in the longitudinal focal field. In contrast, when $a = 1$ (the input beam has doughnut shape), the focal field will form a smooth Gaussian-shape profile along propagation axis [13]. According to the focusing property of the Airy beam, we generate sphere- and cylinder-shape optical cages, super-long optical needle and dark channel by properly designing the input parameters. The optical cage can be used as dark optical traps for atoms [22] and as an erase beam in the stimulated emission depletion microscopy [23], while the optical needle would find more applications in Raman spectroscopy [24], photolithography [25], and particle acceleration [26]. And the long optical dark channel is useful in optical guiding [27,28].

2. Theory and model

As is well known, when a radially polarized beam is focused by a high-NA lens, the radial and longitudinal components of the

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http://dx.doi.org/10.1016/j.optcom.2014.08.045
0030-4018/© 2014 Published by Elsevier B.V.

focal electric field can be written as [13,29]

$$E_r(r,z)=A\int_0^{\alpha}\cos^{1/2}\theta\,\sin 2\theta E_0(\theta)\exp(ikz\cos\theta)j_1(kr\sin\theta)d\theta, \tag{1a}$$

$$E_z(r,z)=2iA\int_0^{\alpha}\cos^{1/2}\theta\sin^2\theta E_0(\theta)\exp(ikz\cos\theta)j_0(kr\sin\theta)d\theta, \tag{1b}$$

where A is the normalized factor, $\alpha=71.8^\circ$ for a lens of NA=0.95 in free space, $j_0(x)$ and $j_1(x)$ denote zeroth- and first-order Bessel functions, and $E_0(\theta)=T(\theta)l_0(\theta)$ is the input field of a CAM through a hard aperture. The aperture is represented by:

$$T(\theta)=\begin{matrix}1 & 0\le\theta\le\theta_0\\ 0 & \text{other}\end{matrix} \tag{2}$$

where θ_0 is set to be equal to α below. The function $l_0(\theta)$ describes the amplitude distribution of a CAM, which is given by [1]:

$$l_0(\theta)=\text{airy}\frac{(r_c-\sin\theta)}{w}\exp\frac{a(r_c-\sin\theta)}{w}, \tag{3}$$

where r_c is the initial radius of the main ring, w is a scaling factor, and $a>0$ is the decay factor, which makes a restriction to the infinite Airy tail. One finds from Eqs. (1a) and (1b) that, the intensity distribution of the focal field varies with the input parameters of CAM.

3. Analyses and discussion

In the following, we will investigate the fundamental focusing property of a radially polarized CAB through a hard aperture. We set the decay factor $a=0.001$, which has a weak restriction to the tail of the CAB. However, we can use a hard aperture to cut the infinite Airy tail off. Since the size of the aperture is fixed, the number of rings in the input intensity pattern will change with the parameter r_c. When $w=0.02$ and r_c is chosen to be 0.67, 0.75, and 0.87, the ring number is equal to 11, 7, and 2, respectively, as shown in Fig. 1(a1–c1), where the coordinates $x_0=f\sin\theta\cos\phi$ and $y_0=f\sin\theta\sin\phi$. For simplicity, the focal length is set to be $f=1$ in the following. Due to the similarity of the properties between longitudinal and radial field components, we will only plot the intensity of longitudinal focal field. As demonstrated in Fig. 1 (a2–c2), there are several spots appearing in the intensity patterns of longitudinal focal field. And the spot number is exactly equal to the ring number of the input intensity pattern. The peak

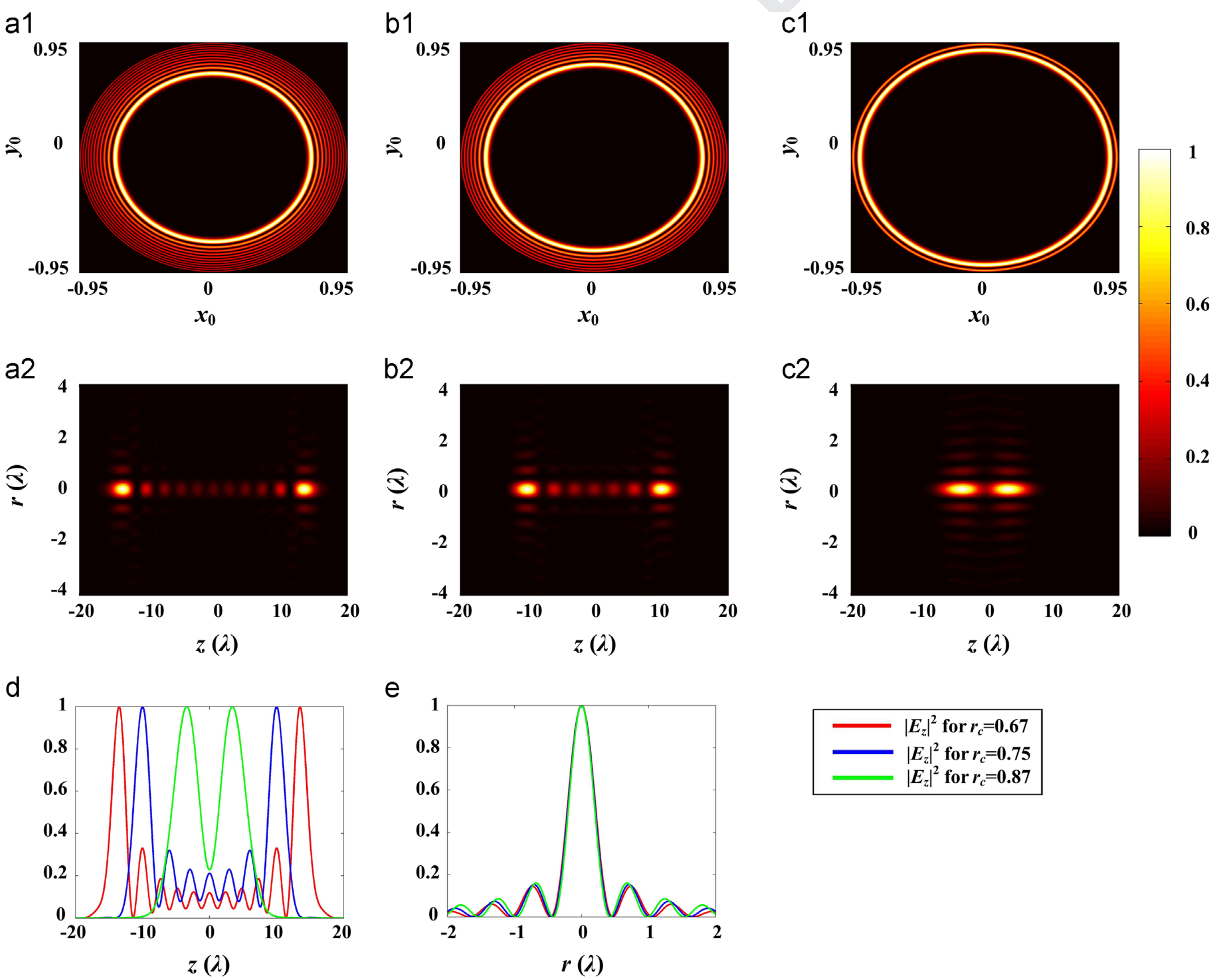

Fig. 1. The normalized intensity patterns of the input beams (a1–c1) and the longitudinal focal fields (a2–c2) for given input parameters $w=0.02$, $a=0.001$, and $r_c=0.67$, 0.75, and 0.87, respectively. For longitudinal component of focal field, the dependences of normalized intensity on z with $r=0$ fixed (d) and on r with fixed z at the first/last intensity peak (e), for given $r_c=0.67$ (red), 0.75 (blue), and 0.87 (green), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: W. Zhu, W. She, Optics Communications (2014), http://dx.doi.org/10.1016/j.optcom.2014.08.045