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Changeable focused field distribution of double-ring-shaped cylindrical vector beams

Liping Gong [a], Zhuqing Zhu [a,*], Xiaolei Wang [b], Yang Li [a], Ming Wang [a], Shouping Nie [a]

[a] Key Laboratory of Optoelectronic Technology of Jiangsu Province, School of Physical Science and Technology, Nanjing Normal University, Nanjing 210023, China
[b] Institute of Modern Optics, Nankai University, Key Laboratory of Optoelectronic Information Science & Technology, Ministry of Education, Tianjin 300071, China

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ABSTRACT

Based on vector diffraction theory, the focusing features of double-ring-shaped cylindrical vector (DCV) beams are studied in this paper. The intensity pattern in the vicinity of the focus can be tailored by appropriately adjusting the parameters of the ratio of the inner-to-outer ring radius and the polarization state of the incident DCV beams. It is shown that focused field with flattop or optical cage profile is easily obtained. Moreover, we also propose a new approach to generate a flattop focus with extended depth of focus and lower side-lobe levels by adding a diffractive optical element (DOE) which is cleverly loaded on the spatial light modulator (SLM). The results from this study would especially facilitate light manipulation of two types of particles with different refractive indices in only one optical-trap system.

1. Introduction

In recent years, more theories and experiments about focusing features of cylindrically vector (CV) beams have been reported [1–4]. It has been shown that radially polarized vector beams can generate a strong axial electric field component, and the azimuthally polarized beams can produce pure axial magnetic field component [5]. Owing to those unique properties, CV beams are widely applied in optical trapping [6], scanning optical microscopy [7], laser cutting of metals [8], determination of the orientation of single molecules [9,10] and particle acceleration [11,12]. For optical engineers and scientists, dynamic regulation of focal filed distribution is always one of the most important topics. To obtain smaller focal spot and diverse focused field distributions, it is often preferable to choose double-ring-shaped cylindrical vector (DCV) beams as the input beams which can be easily generated by a 4-f system with a spatial light modulator (SLM) and a common path interferometric arrangement [13]. Two types of tightly focused field of DCV beams, flattop light field and optical cage, have recently gained considerable research interest. By appropriately adjusting the rotation angle, K. Prabakaran et al. generated flat-topped focus shapes with high NA lens axicon and diffractive optical elements (DOEs) [14]. Similarly, K.B. Rajesh et al. generated a flattop light field by a modified high NA lens axicon with spherical aberration and the depth of focus was effectively extended [15,16]. Yuichi Kozawa et al. produced optical cage by changing the ratio of the pupil radius to the beams radius [17]. Bokor and Nándor generated the optical cage with uniform light intensity by changing the polarization of the inner and outer ring of the DCV beams [18]. Based on Bokor's work, Wang Xiling et al. proposed a new method to produce a controllable 3D optical cage [19]. The work listed above can only produce one of the two kinds of focal field at a time in the designed optical system. To obtain both of them, a diffractive optical element (DOE) and special optical elements are needed to be redesigned and manufactured, which are costly and time consuming [20]. However, two kinds of particles often need to be simultaneously manipulated in one optical-trap system [15,21,22]. In this paper a method that can alternatively generate focused field with flattop or optical cage profile by adjusting the polarization sate distribution and the radius radio of the inner and outer ring of DCV beams is proposed. Combining techniques in Ref. [13], a new approach using only a DOE loaded on the spatial light modulator (SLM) is also introduced to further increase the depth of focus of the flattop focal field and to inhibit its side lobe. Furthermore, the evolution of polarization through the focal region of optical cage is also studied in details, which may apply to trapping, manipulation, and orientation analysis.

2. Theoretical basis on tightly focused DCV beams with high NA lens

As described in Ref. [13], arbitrary vector beams with different polarization states can be obtained when an appropriate

* Corresponding author.
E-mail address: zhuqingzhu@gmail.com (Z. Zhu).

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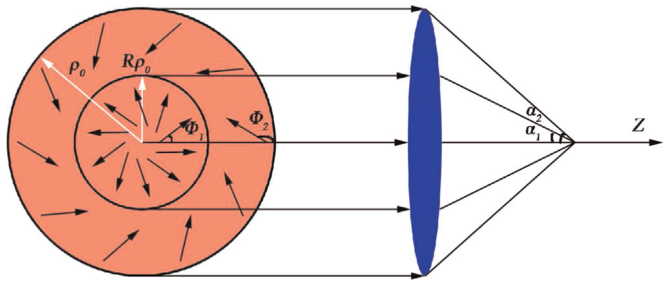

Fig. 1. The schematic diagram of the polarization of DCV beams and its convergence through a lens.

additional phase distribution δ is use, which δ can be a function of beam radius ρ and polarization angle ϕ and can be calculated from

$$\delta(\rho,\phi)=\begin{cases}\phi+\phi_1 & 0<\rho\le R\rho_0\\ \phi+\phi_2 & R\rho_0<\rho\le\rho_0\end{cases}$$

where ρ_0 is the radius of the input beam determined by the aperture of the objective lens. R is the ratio of the inner-to-outer ring radius. ϕ_1 and ϕ_2 denote the polarization angles with respect to the radial direction for the inner and out ring respectively.

Fig. 1 demonstrates an electric field of a DCV beam, in poplar coordinate, propagating in the z direction. The field is described as

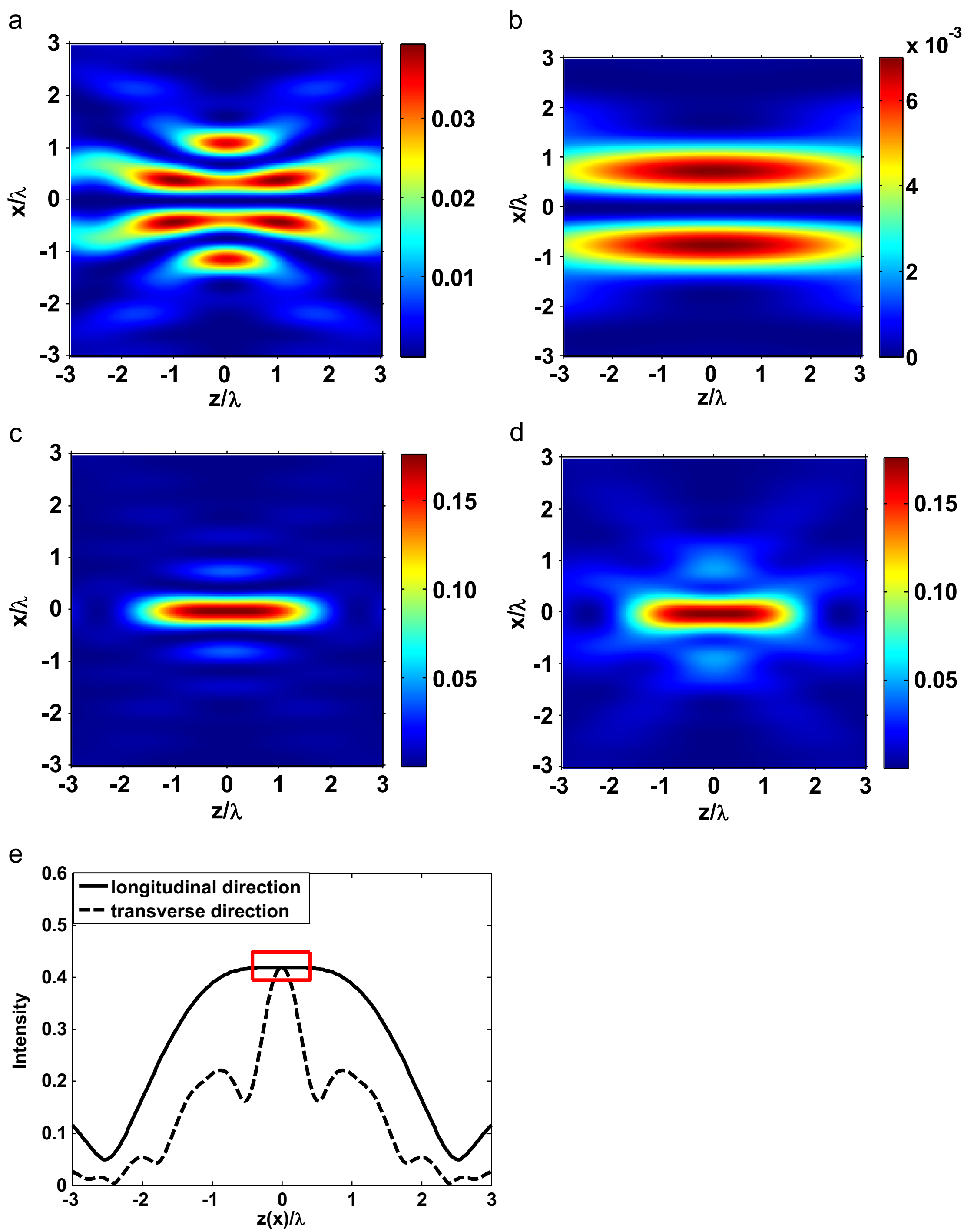

Fig. 2. Intensity patterns in the vicinity of the focus in the X–Z plane when $\phi_1=0.80\pi$, $\phi_2=0$, $R=0.58$. (a) The radial component; (b) the azimuthal component; (c) the axial component; (d) the total intensity distribution; (e) intensity profiles in the transverse and longitudinal direction. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)