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Focusing properties of cylindrical vector vortex beams

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ABSTRACT

In this paper, following Richards and Wolf vectorial diffraction theory, the focusing properties of cylindrical vector vortex beams (CVVB) are investigated, and a diffractive optical element (DOE) is designed to spatially modulate the amplitude of the CVVB. Simulated results show that the CVVB focused by an objective also carry orbital angular momentum (OAM), and the optical fields near the focal region can be modulated by changing the topological charge of the CVVB. We numerically simulate the focus properties of radially and azimuthally polarized beams with topological charge equal to 0, 1, 2 and 10 respectively. As a result, a dark channel with a length about 20 λ can be obtained. These new properties have the potential applications such as particle acceleration, optical trapping and material processing.

1. Introduction

Cylindrical vector beams (CVB) [1] and optical vortex beams (OVB) [2] have many interesting features, especially when they are focused by a high numerical aperture (NA) objective [3,4]. Due to the extraordinarily axis symmetrical property of optical field distribution, the optical field at the focus of CVB possesses unique polarization properties [5–8]. For example, the longitudinal component of the focus from such CVB is much stronger than the transversal component, and the size of the longitudinal focus is much smaller than the transversal focus [5]. These new properties led to many potential applications, such as particle acceleration, optical trapping, surface plasma resonance (SPR), high-density optical data storage and material processing [9,10]. Recently, focusing CVB to a very tight spot was one of the most important topics for optical researches and applications, and it has attracted much attention [7–12]. OVB with phase singularity and a well-defined orbital angular momentum (OAM), also has many applications, such as optical tweezers, photo entanglement and optical communication [13–15]. In the past, much attention has been paid to CVB or OVB alone, while few researches have been done to integrate them together. In 2012, Chen et al. demonstrated the 4pi focusing system of radially polarized vortex beams with topological charge equal to 1 and 2, which was relatively bulky and complicated, and a dark channel is generated in the focus plane [16].

In this paper, the focus properties of cylindrical vector vortex beams (CVVB) are exploited according to the Richards and Wolf vectorial diffraction theory [16,17]. A diffractive optical element (DOE) is designed to spatially modulate the amplitude of the incident beams. The focus properties of radially polarized vortex beam (TMVB) and azimuthally polarized vortex beam (TEVB) with topological charge 0, 1, 2 and 10 are investigated respectively. Simulated results show that the focused optical fields carry OAM as well, with symmetric bright annular beam arrays near the paraxial focus. What is more, the optical fields near the focal region can be modulated by changing the topological charge of the incident CVVB, and the distance between the well-defined annular beam arrays and the dark channel is about 20 λ.

2. Theory

2.1. Geometry of the problem

Two types of CVB have been mostly studied: they are TM beam with radial polarization and TE beam with azimuthally polarization respectively. And the optical fields of these two beams can be described as [18]

$$\vec{E}(r,\varphi)=\begin{cases} l(r)\cdot\vec{e}_r \ \ (\mathrm{TM}) \\ l(r)\cdot\vec{e}_\varphi \ \ (\mathrm{TE}) \end{cases}, \tag{1}$$

where $l(r)$ is an amplitude factor which is assumed to vary radially while maintains cylindrical symmetry around the optical axis, $\vec{e}_r$ is the unit

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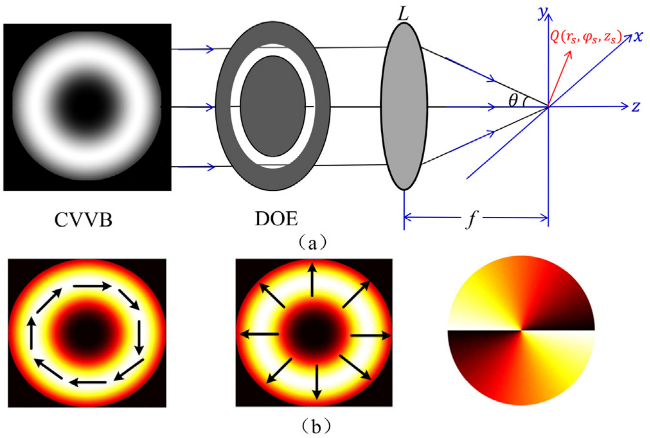

Fig. 1. (a) Geometry of the focusing system for CVVB. (b) Azimuthally and radially polarized beams with topological charge equal to 2.

vector in the radial direction, and $\vec{e}_{\varphi}$ is the unit vector in the azimuthal direction.

When the CVB with plane wave front, i.e. the topological charge is zero, passes through a spiral phase element (SPE) [1], such as spiral phase plate (SPP) or spatial light modulator (SLM), CVVB can be generated. And the output beam can be expressed as [19]

$$\vec{E}(r,\varphi) = \begin{cases} l(r) \cdot e^{im\varphi}\vec{e}_r & (TMVB) \\ l(r) \cdot e^{im\varphi}\vec{e}_{\varphi} & (TEVB) \end{cases}, \tag{2}$$

where m is the topological charge of CVVB, φ is the azimuth angle with respect to x-axis, and $l(r)$ is the amplitude factor.

As shown in Fig. 1(a), an incident CVVB passes through a diffractive optical element (DOE) which is used to control the transverse intensity profiles, then the beam is focused by a lens with a focal length of f, and the focal point is at point Q (r_s, φ_s, z_s) [16]. In our simulations, the transmission function of the designed DOE can be described as follow

$$P(\theta) = \begin{cases} 1 & \sin^{-1}(0.86) \le \theta \le \sin^{-1}(0.9) \\ 0 & \text{else} \end{cases}, \tag{3}$$

where θ represents the polar angle as shown in Fig. 1(a) [10]. Fig. 1(b) shows the profiles of TMVB and TEVB, and the phase distribution with topological charge of $m = 2$ respectively.

2.2. TMVB Illumination

For radially polarized TMVB illumination, the radial and longitudinal components of electric field near the focus can be expressed as follows [17]

$$E_r = \frac{-iA}{\pi} \iint e^{im\varphi} \cos^{1/2}\theta \sin\theta \cos\theta \cos(\varphi - \varphi_s) \cdot l(r) \cdot \mathrm{P}(\theta)\, e^{ik(z_s \cos\theta + r_s \sin\theta \cos(\varphi - \varphi_s))} d\varphi d\theta, \tag{4}$$

$$E_z = \frac{-iA}{\pi} \iint e^{im\varphi} \cdot \cos^{1/2}\theta \cdot \sin^2\theta \cdot P(\theta) \cdot l(r) \cdot e^{ik(z_s \cos\theta + r_s \sin\theta \cos(\varphi - \varphi_s))} d\varphi d\theta, \tag{5}$$

where $A = \pi f / \lambda_0$, which is relative to the focal length f and the wavelength λ_0, and $0 \le \theta \le \sin^{-1}(\mathrm{NA})$, where NA is the numerical aperture of the objective. As for radially polarized TMVB, the azimuthal component of the field is 0. As a result, the azimuthal component E_{φ}

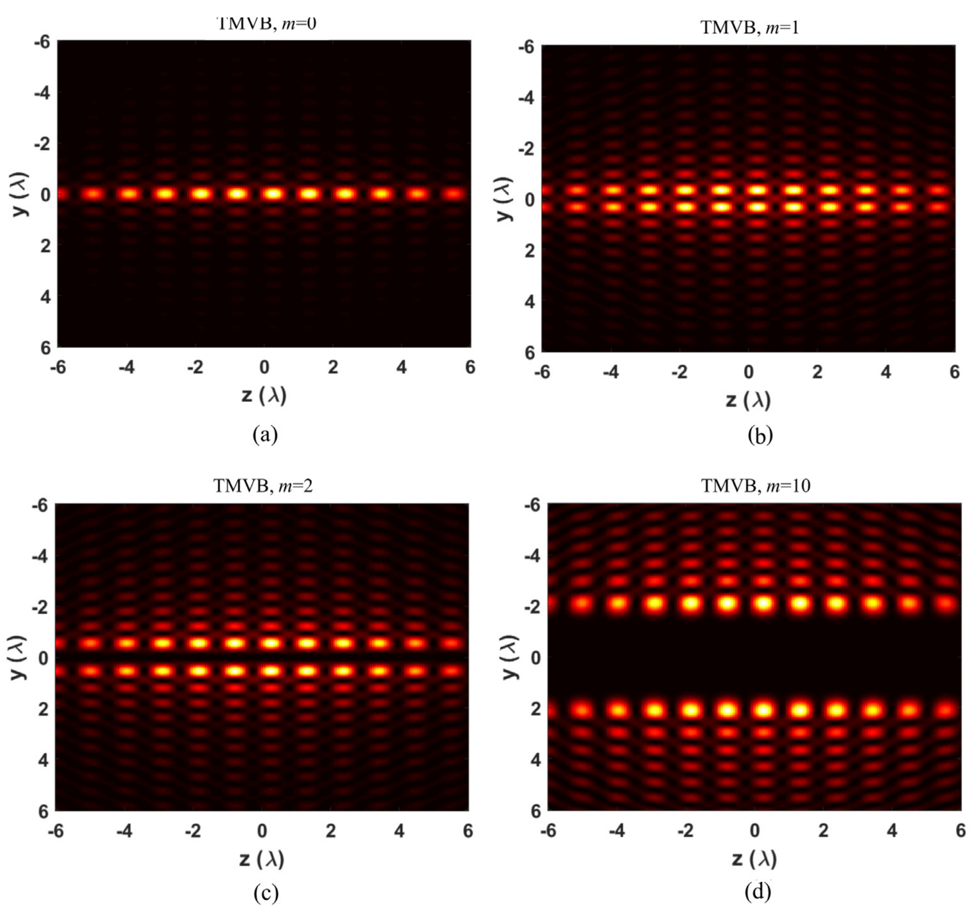

Fig. 2. Field intensity distributions of TMVB with topological charge of $m = 0, 1, 2,$ and 10 in y-z plane.