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Intensity and polarization properties of elliptically polarized vortex beams in turbulent atmosphere

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ABSTRACT

Based on the extended Huygens–Fresnel principle, the propagation of elliptically polarized vortex beams in a turbulent atmosphere is investigated. The analytical expressions for the average intensity and degree of polarization of the elliptically polarized vortex beams are derived in a turbulent atmosphere, respectively. The influences of polarization ellipticity, topological charge, beam width, and structure constant of the atmospheric turbulence on average intensity and degree of polarization are numerically demonstrated and analyzed in detail.

1. Introduction

In recent years, there has been an increasing interest in vector vortex beams which admit spatially variant states of polarization. The well-known cylindrical vector beams [1,2] and circularly polarized vortex beams [3] are two extreme cases of the vector vortex beams. Attention has been drawn to these polarized modes, in particular due to their ability to produce strong longitudinal field components and smaller waist sizes upon focusing by high numerical aperture objectives [1,4–8]. According to the higher-order Poincare sphere representation of state of polarization for vector vortex beams, elliptically polarized (EP) vortex beam is a generalized case of the vector vortex beam [9]. The tightly focusing properties of the EP vortex beam have also been studied [10]. Generation method of arbitrary vector vortex beams has been presented through the interference of two circular beams with opposite topological charge [11], or by diffracting a Gaussian laser beam from a spatial light modulator consisting of a high-resolution reflective nematic liquid crystal display [12].

On the other hand, the propagation of various kinds of vector vortex beams in a turbulent atmosphere has been widely investigated due to its considerable importance in optical communication and remote sensing. It is demonstrated that the behavior of the vector vortex beams in turbulent atmosphere is closely related to initial beam parameters and polarization properties [13–19]. Several papers have been published on the propagation properties of various kinds of vector beams, such as radially (azimuthally) polarized vortex beam and other generalized cylindrical vector beams in turbulent atmosphere with analytical expression [13–17]. Meanwhile, numerical results of propagation properties of the vector beams are also derived by Cheng et al. [18,19]. However, to the best of our knowledge, the intensity and polarization properties of EP vortex beam, which is a generalized case of the vector vortex beam, have not been studied so far.

In this paper, the propagation properties including the average intensity and degree of polarization of EP vortex beams in a turbulent atmosphere are explored. The influences of polarization ellipticity, topological charge, beam width, and structure constant of the atmospheric turbulence on average intensity and degree of polarization are illustrated by numerical examples.

2. Theoretical model

In cylindrical coordinates, the vectorial electric field of an EP vortex beam at the source plane $z=0$ can be expressed as [12,20]

$$\mathbf{E}(r,\varphi,z=0)=\begin{bmatrix}E_x\\E_y\end{bmatrix}=E_0\left(\frac{r}{w_0}\right)^m\exp\left(-\frac{r^2}{w_0^2}\right)\begin{bmatrix}\cos(m\varphi+\varphi_0)\cos\beta-i\sin(m\varphi+\varphi_0)\sin\beta\\\sin(m\varphi+\varphi_0)\cos\beta+i\cos(m\varphi+\varphi_0)\sin\beta\end{bmatrix},\quad(1)$$

where r and φ are the radial and azimuthal coordinates, respectively, E_0 is a constant,w_0 denotes the waist width of Gaussian beam, m is the topological charge, β is the ellipticity and φ_0 represents the direction of the polarization ellipse when $\varphi=0$, as shown in Fig. 1.

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Fig. 2 shows the polarization states distribution of some examples of vector vortex beams. The EP vortex beams with arbitrary positive topological charge are shown in Fig. 2(a). The classic cases of vector vortex beams can be degenerated from Eq. (1). For $m=1$ and $\beta=0$, Eq. (1) denotes the well-known radially and azimuthally polarized vortex beam if φ_0 takes 0 and $\pi/2$, respectively. In the case of $\beta=\pi/4$, it reduces to the circularly polarized vortex beam. The polarization states distribution of them are orderly illustrated in Fig. 2(b)–(d).

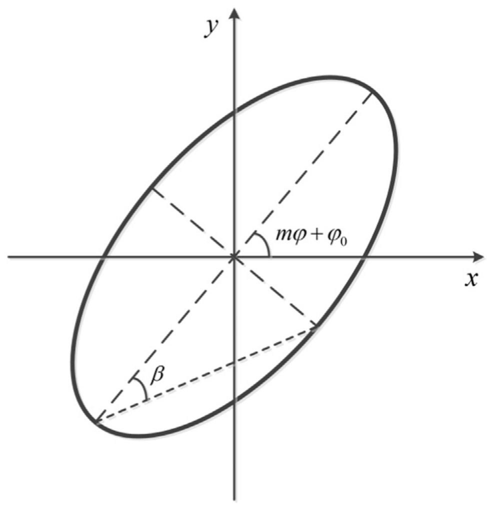

Fig. 1. The polarization ellipse of elliptically polarized vortex beams. m is the topological charge, β is the ellipticity and φ_0 represents the direction of the polarization ellipse when azimuthal coordinates $\varphi=0$.

For an EP vortex beam, the beam coherence-polarization (BCP) matrix that indicates the polarization and the intensity properties in the z=constant plane can be defined as follows [21–23]:

$$\Gamma(\mathbf{r}_1,\mathbf{r}_2,z)=\begin{pmatrix}\Gamma_{xx}(\mathbf{r}_1,\mathbf{r}_2,z) & \Gamma_{xy}(\mathbf{r}_1,\mathbf{r}_2,z)\\ \Gamma_{yx}(\mathbf{r}_1,\mathbf{r}_2,z) & \Gamma_{yy}(\mathbf{r}_1,\mathbf{r}_2,z)\end{pmatrix}, \tag{2}$$

where

$$\Gamma_{\alpha\beta}(\mathbf{r}_1,\mathbf{r}_2,z)=\left\langle E_\alpha(\mathbf{r}_1,z)E^*_\beta(\mathbf{r}_2,z)\right\rangle,\ (\alpha,\beta=x,y), \tag{3}$$

$\mathbf{r}_1=(r_1,\ \varphi_1)$ and $\mathbf{r}_2=(r_2,\ \varphi_2)$ are the position vectors at the z=constant plane.

By substituting Eq. (1) into Eq. (2), the element of BCP matrix for an EP vortex beam at the source plane ($z=0$) plane can be given by

$$\Gamma_{xx}(\mathbf{r}_1,\mathbf{r}_2,0)=E_0^2\left(\frac{r_1r_2}{w_0^2}\right)^m\exp\left(-\frac{r_1^2+r_2^2}{w_0^2}\right)\times\begin{bmatrix}\cos(m\varphi_1+\varphi_0)\cos(m\varphi_2+\varphi_0)\cos^2\beta\\ +i\cos(m\varphi_1+\varphi_0)\sin(m\varphi_2+\varphi_0)\sin\beta\cos\beta\\ -i\sin(m\varphi_1+\varphi_0)\cos(m\varphi_2+\varphi_0)\sin\beta\cos\beta\\ +\sin(m\varphi_1+\varphi_0)\sin(m\varphi_2+\varphi_0)\sin^2\beta\end{bmatrix} \tag{4}$$

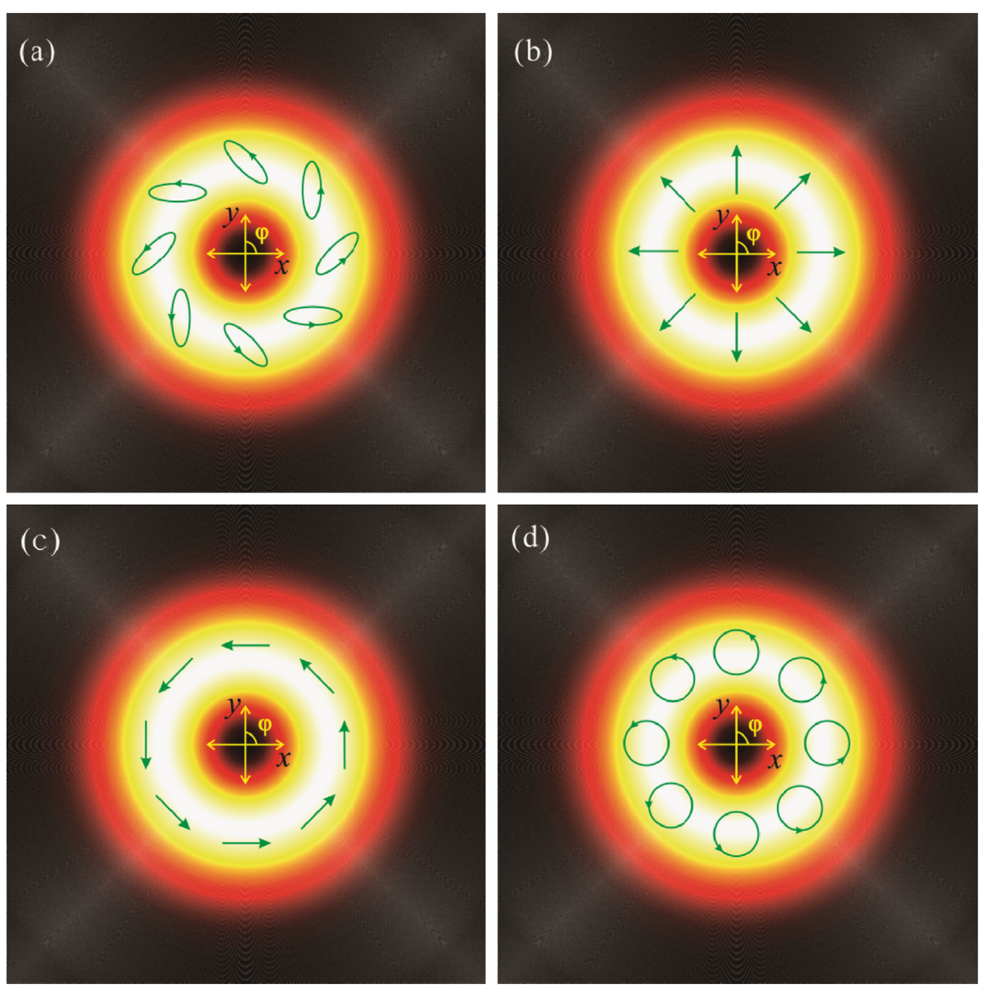

Fig. 2. The polarization states distribution of some examples of vector vortex beams: (a) elliptically polarized vortex beam; (b) radially polarized vortex beam; (c) azimuthally polarized vortex beam; (d) circularly polarized vortex beam.