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Experimental investigation on the polarization evolution characteristics of arbitrary cylindrical vector beams in uniaxial crystals orthogonal to the optical axis

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ABSTRACT

The propagation properties of a variety of laser beams in uniaxial crystals are extensively investigated by numerical simulations. However, the related experimental demonstrations are sporadic up to now. Herein, we report an experimental investigation of the polarization characteristics of arbitrary cylindrical vector beams (i.e., radially polarized beam, azimuthally polarized beam, high-order vector beam, and fractional vector beam) passing through a rutile crystal whose optical axis is orthogonal to the beam axis. It is shown that the polarization modulation of the uniaxial crystal results in the polarization evolution of cylindrical vector beams from the localized linear polarization to hybrid polarization with $2m$-fold rotational symmetry (where m is the topological charge), which agrees well the theoretical result. The polarization modulation using the uniaxial crystal has the applications in the generation of complex vector beams and the material characterization.

1. Introduction

As an intrinsic and fundamental vectorial nature of light, polarization plays a significant role in focusing properties, propagation behaviors, and light–matter interactions [1]. Recently, manipulating polarization of light field has drawn considerable attention due to the fact that cylindrical vector beams with spatially variant state of polarization (SoP) have peculiar properties [2] and extensive applications in optical trapping [3], optical machining [4], nonlinear optical microscopy [5], etc. Researchers have experimentally generated a variety of cylindrical vector beams with the localized linear polarization, such as radially polarized beam (RPB) [6], azimuthally polarized beam (APB) [7], high-order vector beam (HVB) [8], fractional vector beam (FVB) [9], radial-variant vector beam [10], and spatial-variant linearly polarized vector beam [11]. At the same time, the propagation properties of cylindrical vector beams through an *ABCD* optical system [12], in free space [13–15], in turbulent atmosphere [16,17], in isotropic [18,19] and anisotropic [20] nonlinear optical media have been investigated, respectively.

Besides in free space, in turbulent atmosphere, and in a nonlinear optical medium, cylindrical vector beams also propagate in anisotropic media, such as uniaxial crystal, which is treated by solving Maxwell's equations. In fact, many optical elements based on anisotropic materials (e.g., polarizer and compensator) are involved in the propagation of laser beams in uniaxial crystals [1]. Based on plane-wave angular spectrum representation of the electromagnetic field, Ciattoni et al. [21–23] have developed the paraxial schemes for describing a cylindrically symmetric beam propagation in uniaxial crystals along and orthogonal to the optical axis, respectively. Using the existing theory, researchers have extensively investigated the propagation properties of a variety of cylindrical vector beams in uniaxial crystals [24–29]. For instance, Cincotti et al. [24] evaluated the expressions of radially and azimuthally polarized vortices propagating along the optical axis of a uniaxial anisotropic crystal, using a vectorial cylindrical angular spectrum representation. Guo et al. [25] derived the analytical formulae for the elements of the cross-spectral density matrix of radially polarized partially coherent beams propagating through uniaxial crystals orthogonal to the optical axis. Li et al. [26,27] reported the propagation properties of cylindrically polarized vector beams in uniaxial crystals along and orthogonal to the optical axis, respectively. Zhou et al. [28] analyzed the nonparaxial propagation of a cylindrical vector Laguerre-Gaussian

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beam in a uniaxial crystal orthogonal to the optical axis. Lian et al. [29] presented the polarization rotation of hybridly polarized beams in a uniaxial crystal orthogonal to the optical axis.

With the aid of numerical simulations, many investigations of the above-mentioned vector beams propagating in uniaxial crystals have revealed the intensity distributions, degrees of polarization, and effective beam widths of the beams after the propagation [25–27]. However, the report on the anisotropy of the uniaxial crystal changing the SoP is sporadic [29], though it may have important technological applications. On the other hand, the size of the cylindrical vector beams paraxial propagating in uniaxial crystals is conventionally assumed to be tens of micrometers in the theoretical analysis [25–27]. Experimentally, direct generation of cylindrical vector beams with the size of tens-of-micrometers is difficult in general. Moreover, a light beam with small size will be diffracted inevitably as it paraxial propagates both in crystal and in free space. That is why an experimental report on the beam propagation in uniaxial crystals is seldom in the literature up to now [29,30].

In this work, we report an experimental investigation on the polarization evolution characteristics of an arbitrary cylindrical vector beam passing through a uniaxial crystal whose optical axis is orthogonal to the beam axis. By measuring the Stokes parameters, we visualize the SoP distributions of four types of cylindrical vector beams (i.e., RPB, APB, HVB, and FVB) without and with the rutile crystal. We demonstrate that the polarization modulation of the uniaxial crystal results in the polarization evolution of cylindrical vector beams from the localized linear polarization to hybrid polarization with $2m$-fold rotational symmetry. Besides, we briefly discuss the applications of this polarization modulation using the uniaxial crystal.

2. Experiment

The electric field distribution of the cylindrical vector beam can be expressed as [8]

$$\vec{E}(r,\varphi) = A(r)[\cos(m\varphi+\varphi_0)\vec{e}_x + \sin(m\varphi+\varphi_0)\vec{e}_y]. \quad (1)$$

Here r and φ are the polar radius and azimuthal angle in the polar coordinate system, respectively. $A(r)$ stands for the axially symmetric amplitude distribution of the vector beam, m is the topological charge, and φ_0 is the initial phase. $\vec{e}_x$ and $\vec{e}_y$ are the unit vectors in the Cartesian coordinate system. Interestingly, two extreme cases of vector beams describing by Eq. (1) are the RPB and APB when $m = 1$ with $\varphi_0 = 0$ and $\pi/2$, respectively.

To generate cylindrical vector beams with localized linear polarization, we adopt a universal approach in a common path interferometer with the aid of a $4f$ system, based on the combination of a pair of orthogonal circularly polarized base vectors with opposite topological charges on the Poincaré sphere [8,31,32]. The experimental arrangement is shown in Fig. 1. A collimated laser beam with linear polarization at a wavelength of 532 nm illuminates a computer-controlled holographic grating [e.g., Fig. 1(b)] on a transmissive phase-only spatial light modulator (SLM), in which the additional phase is modeled as $\delta(\varphi) = m\varphi + \varphi_0$. Subsequently, the diffracted lights with ±1th orders are converted into the left-handed (LH) and right-handed (RH) circularly polarized beams by a pair of orthogonal $\lambda/4$ wave plates, respectively. Finally, the ±1 orders are recombined by lens (L2) in its rear focus plane where a Ronchi phase grating (G) is placed. We experimentally generated the localized linearly-polarized vector beams with the radius of $\omega \sim 1.0$ mm.

The generated vector beam is focused by a thin lens (L3) with a focal length of $f = 500$ mm, whose front focal plane is located at the grating. The resulting beam waist at the focal plane is $\omega_0 \simeq 85$ μm, and its corresponding Rayleigh range z_0 is estimated to be 43 mm. The uniaxial crystal (rutile TiO_2 single crystal ⟨100⟩ orientation, 10×10×5.0 mm^3 in size, $n_o = 2.616$, $n_e = 2.903$) is placed at the focal region of the converging lens (L3). In the Cartesian coordinate system, as shown in Fig. 1(c), the optical axis of the uniaxial crystal is parallel to the x axis

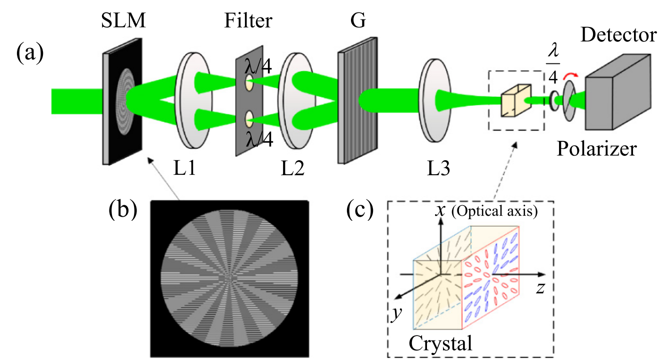

Fig. 1. (a) Experimental arrangement for measuring the Stokes parameters of arbitrary cylindrical vector beams passing through a uniaxial crystal whose optical axis is orthogonal to the optical axis. (b) An example of the designed holographic grating for $m = 2$ and $\varphi_0 = 0$ displays on the SLM. (c) Cylindrical vector beam propagates along the z axis through a uniaxial crystal, whereas the optical axis of the crystal coincides with the x axis. L1–L3, lens; G, Ronchi phase grating.

and the z axis is the propagation axis of the beam. Hence, a vector beam propagates in a uniaxial crystal whose optical axis is orthogonal to the beam axis. The transmitted beam is observed along the beam's propagation direction. Note that the condition of $z_0 \gg L$ (where $L = 5$ mm is the thickness of the crystal) is satisfied and the center of the uniaxial crystal is located at the focal plane of L3, a problematic assumption that the cylindrical vector beam propagates in the crystal without the change of the beam size is valid. That is, it is reasonably regarded that the parallel beam normally incidents onto the crystal. On the other hand, under the paraxial approximation, the focused cylindrical vector beam has localized linear polarization, and its field distribution preserves the initial polarization at any propagation position in free space [33]. These facts allow us to directly characterize the SoP distribution of the cylindrical vector beam at the far-field observational plane with and without the rutile crystal at the focal region of L3, because the variation of SoP only originates from the uniaxial crystal. Based on the quarter-wave retarder polarizer method [1], we use a quarter wave plate, the linear polarizer, and a detector (Beamview, Coherent Inc.) to measure the Stokes parameters of the cylindrical vector beam with and without the rutile crystal.

Using the measured Stokes parameters of S_1, S_2, and S_3, we can compute the orientation angle α and the ellipticity angle β of the localized polarization ellipse on the transverse plane by

$$\alpha = \frac{1}{2}\arctan(S_2/S_1), \quad (2)$$

$$\beta = \frac{1}{2}\arcsin(S_3/S_0). \quad (3)$$

With the known parameters of α and β, the SoP distribution of the cylindrical vector beam with and without the uniaxial crystal can be visualized by plotting the polarization ellipse for equally spaced points on the transverse plane. Besides, the ellipticity of the localized polarization ellipse is $\chi = \tan\beta$. Specially, one gets $\chi = 0$ for the linear polarization, $\chi = -1$ for the LH circular polarization, and $\chi = 1$ for the RH circular polarization.

3. Results and discussions

In principle, adopting the experimental arrangement shown in Fig. 1, an arbitrary cylindrical vector beam can be generated by changing the parameters of m and φ_0. As examples, we generate four types of cylindrical vector beams, namely, RPB ($m = 1$, $\varphi_0 = 0$), APB ($m = 1$, $\varphi_0 = \pi/2$), HVB ($m = 2$, $\varphi_0 = 0$), and FVB ($m = 1.5$, $\varphi_0 = 0$). Importantly, we investigate the polarization evolution characteristics of the cylindrical