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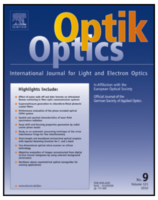

Full length article

Twist phase-induced characteristic changes of a radially polarized partially coherent beam in a uniaxial crystal

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ABSTRACT

We derived analytical formula for the cross-spectral density matrix of a radially polarized partially coherent twist (RPPCT) beam in a uniaxial crystal orthogonal to the optical axis with the help of the extended Huygens-Fresnel integral formula and unified theory of coherence and polarization. Furthermore, we explore the evolution properties of a RPPCT beam in a uniaxial crystal. It is found that the RPPCT beam becomes an anisotropic RPPCT beam and the beam is rotating with beam propagation in uniaxial crystal. Its evolution properties change with twist factor and the ratio of extraordinary index to ordinary refractive index. The twist factor affects their rotation orientation angles, and the ratio of extraordinary index to ordinary refractive index has an effect on their twisted levels.

1. Introduction

According to polarization properties, a light beam can be classified as a uniformly or non-uniformly polarized beam. As a typical non-uniformly polarized beam, the radially polarized coherent (RPC) beam has axially symmetric polarization. It can provide a strong longitudinal electric field component with a non-propagating component and a smaller spot size than the diffraction limit for uniformly polarized beam when focused by a high numerical aperture (NA) objective [1–3]. Due to its unique tightly focusing properties and potential applications [4]. The RPC beam has been widely used in data storage [5], high-resolution microscopy [6,7] and nano-particle manipulation [8,9]. Since 2003, direct detection and characterization of this sharp longitudinal field by experimental demonstration was reported [10], various schemes have been proposed to produce a radially polarized partially coherent (RPPC) beam [11,12]. Experimental generation of a RPPC beam can be found in Ref. [13]. Propagation properties of a RPPC beam in free space, atmospheric and oceanic turbulence have been studied widely [14–16]. It is realized that a focus beam spot with a doughnut, fat-top or Gaussian profile can be obtained by varying the initial special coherence of a partially coherent radially or azimuthally polarized beam [17]. Theoretical and experimental studies of the spectral changes of a polychromatic radially polarized partially coherent beam were reported[18]. The focal properties of a radially polarized partially coherent vortex beam through a high numerical objective were also revealed [19].

However, previous researches on beams did not consider the beam's initial phase distribution. A twist phase differs from the customary quadratic phase factor in many aspects. It exists only in partially coherent beams [20], and has an intrinsic chiral or handedness property. Thus, a beam with twist phase has orbital angular momentum, and it induces the rotation of the beam spot on propagation [21]. The recent results showed that orbital angular momentum of electromagnetic Gaussian Schell-Model (EGSM) beam with twist phase closely depends on its twist factors and degree of polarization in the source

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plane [22]. In 1994, experimental observation of the twist Gaussian Schell-Model (TGSM) beam was reported [23]. From then on, paraxial propagation of TGSM beam through free space, paraxial optical systems and turbulent atmosphere have been studied in detail. It was found that a TGSM beam has advantage over the Gaussian Schell-Model beam without twist phase for reducing the negative influence of turbulent atmosphere [24]. The spectral shifts and spectral switches of a partially coherent beam with twist phase was investigated [25], the results showed that the twist factor affected the spectral shifts and spectral switches. Ghost imaging with a TGSM beam was studied [26], and results presented that, as the absolute value of the twist factor increased, the ghost image disappeared gradually, but its visibility increased. The evolution properties of a TGSM beam in a uniaxial crystal was revealed [27], the result illustrated that the uniaxial crystal offers an effective way for modulating the properties of a TGSM beam. One may use uniaxial crystal to determine whether a TGSM beam carried twist phase or not. Also some researchers suggested that a TGSM beam can be expanded as a series of partially coherent modified Bessel-Gaussian beams [28]. This provides a new view of partially coherent beams with twist phase and a powerful model in the study of partially coherent twisting beams [29]

Recently, studies of vectorial partially coherent beam with twist phase were reported and some interesting results were obtained [27,30]. As a natural extension of a coherent vector beam, the radially polarized partially coherent twist (RPPCT) beam was introduced and propagation properties of this beam in free space were studied [31]. To the best of our knowledge, the propagation of a RPPCT beam through a uniaxial crystal has not yet been reported up until now. A beam with twist phase has wide application as mentioned above, and a RPPCT beam propagating in a uniaxial crystal is different from that in free space [32], so it is important to investigate the propagation of a RPPCT beam in a uniaxial crystal. In the reminder of this paper, our aim is to investigate the evolution properties of a RPPCT beam propagating in a uniaxial crystal. Some interesting and useful results are founded.

2. Analytical paraxial propagation formula for the cross-spectral density matrix of a RPPCT beam propagating in a uniaxial crystal

We assume that a vectorial electromagnetic RPPCT beam is generated in the plane $z = 0$ and propagates into the half-space $z > 0$, where a uniaxial crystals exists. The beam propagates along the positive z direction, which is orthogonal to the optical axis. The RPPCT beam is given by [13–16]

$$E(x_0, y_0, 0) = A_{x0}\frac{x_0}{w_{x0}}\exp(-\frac{{r_0}^2}{{w_{x0}}^2})\exp(i\beta_x)\vec{e}_x + A_{y0}\frac{y_0}{w_{y0}}\exp(-\frac{{r_0}^2}{{w_{y0}}^2})\exp(i\beta_y)\vec{e}_y, \tag{1}$$

where $A_{\alpha 0}$ and $w_{\alpha 0}(\alpha = x, y)$ are the characteristic amplitude and beam size of the RPPCT beam in the source plane, respectively. The transverse position vector in the source is expressed as $\vec{r}_0$, and ${r_0}^2 = {x_0}^2 + {y_0}^2$. $\vec{e}_x$,$\vec{e}_y$represent the unit vector along the x and y axies, respectively. β_i is an arbitrary phase. Based on the unified theory of coherence and polarization, the second-order coherence properties of the RPPCT beam in the space- frequency domain can be described by the 2×2 cross-spectral density (CSD) matrix [33], whose elements in the source plane are defined as

$$\leftrightarrow W(\vec{r}_1, \vec{r}_2, z) = \left[W_{\alpha\beta}(\vec{r}_{01}, \vec{r}_{02}, z)\right] = \left[\langle E_\alpha{}^*(\vec{r}_{01}, z)E_\beta{}^*(\vec{r}_{02}, z)\rangle\right], \left(\alpha, \beta = x, y\right) \tag{2}$$

where $E_\alpha(\vec{r}_1, z)$and $E_\beta(\vec{r}_2, z)$ denote the α and β components of an electric field at two arbitrary points $(\vec{r}_1, z)$and$(\vec{r}_2, z)$, separately. The angular brackets represent the ensemble average, and the asterisk is the complex conjugate. Considering the twist phase distribution of a RPPCT beam and the realizability condition of a RPPCT beam [11–13], we also define the elements of the CSD matrix of a RPPCT beam in the initial plane z = 0 as follows:

$$\begin{aligned} W_{\alpha\beta}(\vec{r}_{10}, \vec{r}_{20}, 0) &= A_{\alpha 0}A_{\beta 0}B_{\alpha\beta}\frac{\alpha_{10}\beta_{10}}{w_0^2}\exp\left(-\frac{x_{10}^2 + x_{20}^2 + y_{10}^2 + y_{20}^2}{w_0^2}\right) \\ &\times \exp\left[-\frac{(x_{10} - x_{20})^2 + (y_{10} - y_{20})^2}{2\delta_0^2}\right] \times \exp\left[-ik\mu x_{10}y_{20} + ik\mu x_{20}y_{10}\right], \left(\alpha, \beta = x, y\right) \end{aligned} \tag{3}$$

where $k = 2\pi/\lambda$ denotes wave number with wave length λ,$B_{\alpha\beta} = |B_{\alpha\beta}|\exp(i\phi)$ is the correlation coefficient between the E_x and $E_y$electric field components and satisfy the relation$B_{\alpha\beta} = B^*_{\beta\alpha}$. we suppose that parameter $w_{\alpha 0} = w_{\beta 0} = w_0, A_{\alpha 0} = A_{\beta 0} = 1$, δ_0 present transverse coherent length, μ is a scalar real-valued twist factor on the input plane, limited by$|\mu| \le 1/k\delta_0^2$owing to the non-negativity requirement on the CSD of the beam. With the help of paraxial approximation, the propagation of the elements of the CSD matrix of a RPPCT beam propagating in a uniaxial crystal orthogonal to the optical axis can be treated by the following formulae [32,33]

$$\begin{aligned} W_{xx}(x_1, y_1, x_2, y_2, z) &= \frac{k^2 n_0^2}{4\pi^2 z^2}\iint\iint W_{xx}(x_{10}, y_{10}, x_{20}, y_{20}, 0)dx_{10}dy_{10}dx_{20}dy_{20} \\ &\exp\left\{\frac{k}{2izn_e}\left[n_0^2(x_1 - x_{10})^2 + n_e^2\left((y_1 - y_{10})^2\right)\right] - \frac{k}{2izn_e}\left[n_0^2(x_2 - x_{20})^2 + n_e^2\left((y_2 - y_{20})^2\right)\right]\right\}, \end{aligned} \tag{4}$$