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Original research article

Intensity properties of anomalous hollow vortex beam propagating in biological tissues

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ABSTRACT

The propagation equations of an anomalous hollow vortex beam in biological tissues have been derived, and the intensity properties of anomalous hollow vortex beam propagating in biological tissues have been analyzed using the derived equations. The results show that the beam with smaller M propagating in biological tissues will firstly evolve into the flat-topped beam, and the beam with different M will all evolve into Gaussian beam at last.

1. Introduction

Recently, the propagation properties of dark hollow beams have been widely studied, and the models for the different dark hollow beams have been introduced. Chen et al. have studied the scintillation properties of dark hollow beams in a weak turbulent atmosphere [1]. Cai et al. have introduced the model of modified hollow Gaussian beam and studied its paraxial propagation properties [2]. Liu et al. have investigated the influences of uniaxial crystal on the properties of various dark hollow beams [3]. Wang et al. have studied the properties of partially coherent controllable dark hollow beams propagating through atmospheric turbulence [4]. Liu et al. have investigated the properties of partially coherent flat-topped vortex hollow beam propagating in random media [5–7]. Cai et al. have introduced a special model for an anomalous hollow beam and investigated its paraxial propagation properties [8]. Since then, the properties of anomalous hollow bema have been widely studied. Cai et al. have studied the propagation properties of anomalous hollow beams in turbulent atmosphere [9]. Liu et al. have investigated the properties of anomalous hollow beam in uniaxial crystals [10]. Wang et al. have investigated the properties of partially coherent anomalous hollow beams in uniaxial crystals [11]. Wang et al. have studied the fractional Fourier transform for an anomalous hollow beam [12]. Liu et al. have studied the properties of anomalous hollow beam in the far field [13]. Wang et al. have studied the nonparaxial properties for a partially coherent anomalous hollow beam [14]. Tian et al. have studied the characteristics of partially coherent anomalous elliptical hollow Gaussian beam propagating in atmospheric turbulence [15]. Wang et al. have introduced the model of radial phased-locked partially coherent anomalous hollow beam array and studied the properties of which propagating in turbulent atmosphere [16].

With the development of biomedical optics, the evolution properties of laser beams propagating in biological tissues have attracted much attentions. And the propagation properties of various laser beam in biological tissues have been widely studied [17–19]. While, the properties of anomalous hollow vortex beam propagating in biological tissues has not been reported in the past years. In this paper, we will study the propagation properties of anomalous hollow vortex beam in biological tissues.

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2. Propagation analysis

In the Cartesian coordinate system, the optical field of an anomalous hollow vortex beam at the source plane z = 0 can be defined as [20]:

$$E(\mathbf{r}_0, 0) = \left(-2 + \frac{8x_0^2}{w_{0x}^2} + \frac{8y_0^2}{w_{0y}^2}\right)\exp\left(-\frac{x_0^2}{w_{0x}^2} - \frac{y_0^2}{w_{0y}^2}\right)(x_0 + iy_0)^M \tag{1}$$

Where $\mathbf{r}_0 = (x_0, y_0)$ represents the vector at the source plane z = 0; w_{0x} and w_{0y} are the beam radius of the astigmatic beam in the x-axis and y-axis, respectively; M is the topological charge.

Based on the extended Huygens-Fresnel diffraction integral, and taking the z-axis as the propagation axis, the average intensity of anomalous hollow vortex beam propagation in biological tissue can be expressed as [17–19]

$$\begin{aligned}\langle I(\mathbf{r},z)\rangle = {} & \frac{k^2}{4\pi^2 z^2}\iiint\limits_{-\infty}^{+\infty}\!\!\int d\mathbf{r}_{10}d\mathbf{r}_{20}E(\mathbf{r}_{10}, 0)E^*(\mathbf{r}_{20}, 0)\\ & \times\exp\left[-\frac{ik}{2z}(\mathbf{r}\text{-}\mathbf{r}_{10})^2 + \frac{ik}{2z}(\mathbf{r}\text{-}\mathbf{r}_{20})^2\right]\\ & \times\langle\exp[\psi(\mathbf{r}_{10},\mathbf{r}) + \psi^*(\mathbf{r}_{20},\mathbf{r})]\rangle\end{aligned} \tag{2}$$

Where $k = 2\pi/\lambda$ denotes the wave number, λ denotes the wavelength; the asterisk denotes the complex conjugation; $\psi(\mathbf{r}_0, \mathbf{r}, z)$ is the random part of complex phase of a spherical wave propagating in biological tissues. The last term at the Eq. (2) can be expressed as:

$$\langle\exp[\psi(\mathbf{r}_{10},\mathbf{r}) + \psi^*(\mathbf{r}_{20},\mathbf{r})]\rangle = \exp\left[-\frac{(x_{10} - x_{20})^2 + (y_{10} - y_{20})^2}{\rho_0^2}\right] \tag{3}$$

with ρ_0 is the coherence length of a spherical wave propagating in biological tissues, and which can be written as:

$$|\rho_0(z)| = 0.22 \times (C_n^2 k^2 z)^{-1/2} \tag{4}$$

with

$$C_n^2 = \frac{\langle\delta n^2\rangle}{L_0(2 - \varsigma)} \tag{5}$$

where $\langle\delta n^2\rangle$ is the average variance of the refractive index; L_0 is the outer scale of the refractive index; ς represents the fractal dimension of biological tissues.

Submitting Eqs. (1) into (2), the average intensity of an anomalous hollow vortex beam propagating in biological tissues can be derived as

$$\begin{aligned}I(x, y, z) = {} & \frac{k^2}{4z^2}\frac{1}{\sqrt{a_x b_x a_y b_y}}\exp\left[-\frac{k^2}{4a_x z^2}x^2 - \frac{k^2}{4a_y z^2}y^2\right]\exp\left(\frac{c_x^2}{b_x} + \frac{c_y^2}{b_y}\right)\\ & \sum_{m=0}^{M}\frac{M!\,i^m}{m!\,(M-m)!}\sum_{n=0}^{M}\frac{M!\,(-i)^n}{n!\,(M-n)!}\\ & \left(4I_1 - \frac{16}{w_{0x}^2}I_2 - \frac{16}{w_{0y}^2}I_3 - \frac{16}{w_{0x}^2}I_4 - \frac{16}{w_{0y}^2}I_5 + \frac{64}{w_{0x}^4}I_6 + \frac{64}{w_{0x}^2 w_{0y}^2}I_7 + \frac{64}{w_{0x}^2 w_{0y}^2}I_8 + \frac{64}{w_{0y}^4}I_9\right)\end{aligned} \tag{6}$$

with

$$\begin{aligned}I_1 = {} & (M-m)!\left(\frac{1}{a_x}\right)^{M-m}\sum_{k=0}^{\left[\frac{M-m}{2}\right]}\frac{1}{k!\,(M-m-2k)!}\left(\frac{a_x}{4}\right)^k\sum_{l=0}^{M-m-2k}\frac{(M-m-2k)!}{l!\,(M-m-2k-l)!}\\ & \left(\frac{ik}{2z}x\right)^{M-m-2k-l}\left(\frac{1}{\rho_0^2}\right)^l 2^{-(M-n+l)}i^{M-n+l}\left(\frac{1}{b_x}\right)^{0.5(M-n+l)}H_{M-n+l}\left(-\frac{ic_x}{\sqrt{b_x}}\right)\\ & m!\left(\frac{1}{a_y}\right)^m\sum_{t=0}^{\left[\frac{m}{2}\right]}\frac{1}{t!\,(m-2t)!}\left(\frac{a_y}{4}\right)^t\sum_{l'=0}^{m-2t}\frac{(m-2t)!}{l'!\,(m-2t-l')!}\\ & \left(\frac{ik}{2z}y\right)^{m-2t-l'}\left(\frac{1}{\rho_0^2}\right)^{l'}2^{-(n+l')}i^{n+l'}\left(\frac{1}{b_y}\right)^{0.5(n+l')}H_n\left(-\frac{ic_y}{\sqrt{b_y}}\right)\end{aligned} \tag{7}$$