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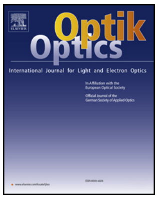

Original research article

Average intensity of anomalous hollow beam with orbital angular momentum in atmospheric turbulence

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ABSTRACT

The propagation equation of average intensity of anomalous hollow beam (AHB) with optical angular momentum (OAM) in atmospheric turbulence has been derived, and the influences of constant of refraction index structure of atmospheric turbulence and the parameters of AHB with OAM on the average intensity and spreading properties are analyzed. It is found that AHB with OAM propagating in atmospheric turbulence can almost the dark hollow center as the propagation distance increases, and the AHB with OAM propagating in free space can keep its dark hollow center, and the beam propagating in stronger atmospheric turbulence will lose its initial dark hollow beam profiles more rapidly. This obtained results are useful to the practical application in free space optical communication using the AHB with OAM.

1. Introduction

With the development of free space optical communication, the propagation properties of laser beam in random media have attracted the attentions of researchers. In the past years, the properties of laser beams propagating in atmospheric turbulence have been widely studied. Chen et al. have investigated the scintillation properties of dark hollow beams propagation in turbulent atmosphere [1]. Wang et al. have investigate the propagation of partially coherent controllable dark hollow beams in turbulent atmosphere [2]. Wang and Zhao have investigated the propagation properties of a radial phased-locked partially coherent anomalous hollow beam array in turbulent atmosphere [3]. Liu et al. have illustrated the properties of partially coherent flat-topped vortex hollow beam in turbulent atmosphere [4]. And liu et al. have also studied the influence atmosphere turbulence on the partially coherent four-petal Gaussian vortex beams [5]. Wang et al. have review the propagation properties of partially coherent beam in turbulent atmosphere [6]. In the studies of influence of optical system and atmosphere on the properties of beam, Liu et al. have investigated the properties of partially coherent flat-topped vortex hollow beam [7] and four-petal Gaussian beams [8]. In the studied of partially coherent pulsed beam in atmospheric turbulence, Liu et al. have studied the spectrally partially coherent Gaussian Schell-model pulsed beams propagating in atmospheric turbulence [9], and Banakh and Gerasimova have studied the pulsed Laguerrian beams in a turbulent atmosphere [10]. Wang and Korotkova have investigated the properties of Circularly symmetric cusped random beams propagating in atmospheric turbulence [11]. In the studies of vortex propagating in atmospheric turbulence, Liu et al. have investigated the propagation properties of four-petal Gaussian vortex beam [12] and flat-topped vortex hollow beams propagating in atmospheric turbulence [13], Qu et al. have investigated the average intensity and polarization properties of elliptically polarized

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vortex beams propagating in atmospheric turbulence [14], Zhi et al. have investigated the properties of ring Airy Gaussian beams with optical vortices through anisotropic non-Kolmogorov turbulence [15]. However, to the best of our knowledge, the average intensity of anomalous hollow beam (AHB) with optical angular momentum (OAM) in atmospheric turbulence has not been reported. In this paper, the average intensity of the AHB with OAM propagating in atmospheric turbulence has been investigated.

2. Propagation of AHB with OAM in atmospheric turbulence

In the Cartesian coordinate system, the optical field of an AHB with OAM at the source plane z = 0 can be defined as [16]:

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

where 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.

Taking the z-axis as the propagation axis, within the approximation of paraxial propagation, the average intensity of beam propagation in atmospheric turbulence can be written by the extended Huygens-Fresnel diffraction integral [1–15]

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

Where $\mathbf{r} = (x,y)$ and $\mathbf{r}_0 = (x_0,y_0)$ are the position vectors at the source plane and receive plane, respectively; $k = 2\pi/\lambda$ is the wave number with λ being the wavelength; the asterisk denotes the complex conjugation; $\psi(\mathbf{r}_0, \mathbf{r}, z)$ is the solution to the Rytov method that represents the random part of the complex phase;

And

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

with $\rho_0 = (0.545C_n^2k^2z)^{-3/5}$ is the spherical-wave lateral coherence radius due to turbulence, and C_n^2 is the constant of refraction index structure of atmospheric turbulence.

On submitting Eq. (1) into Eq. (2), and considering the following equation [17]

$$(x_0 + iy_0)^M = \sum_{l=0}^{M} \frac{M!i^l}{l!(M-l)!}x_0^{M-l}y_0^l \tag{4}$$

$$\int_{-\infty}^{+\infty} x^n \exp(-px^2 + 2qx)dx = n!\exp\left(\frac{q^2}{p}\right)\left(\frac{q}{p}\right)^n\sqrt{\frac{\pi}{p}}\sum_{k=0}^{\left[\frac{n}{2}\right]}\frac{1}{k!(n-2k)!}\left(\frac{p}{4q^2}\right)^k \tag{5}$$

$$H_{2d}(x) = \sum_{l=0}^{d}\frac{(-1)^l(2d)!}{l!(2d-2l)!}(2x)^{2d-2l} \tag{6}$$

The average intensity of an AHB with OAM propagating in atmospheric turbulence can be obtained as

$$\begin{gathered}I(x, y, z) = \frac{k^2}{4\pi^2z^2}\sum\nolimits_{m=0}^{M}\frac{M!\,i^m}{m!\,(M-m)!}\sum\nolimits_{n=0}^{M}\frac{M!\,(-i)^n}{n!\,(M-n)!}\\ \left(4I_1 - \frac{16}{w_{0x}^2}I_2 - \frac{16}{w_{0y}^2}I_3 - \frac{16}{w_{0x}^2}I_4 - \frac{16}{w_{0y}^2}I_5 + \frac{64}{w_{0x}^4}I_6 + \frac{64}{w_{0x}^2w_{0y}^2}I_7 + \frac{64}{w_{0x}^2w_{0y}^2}I_8 + \frac{64}{w_{0y}^4}I_9\right)\end{gathered} \tag{7}$$

with

$$\begin{aligned}I_1 = {} & \sqrt{\frac{\pi}{a_x}}(M-m)!\left(\frac{1}{a_x}\right)^{M-m}\exp\left[\frac{1}{a_x}\left(\frac{ik}{2z}x\right)^2\right]\sum\nolimits_{k=0}^{\left[\frac{M-m}{2}\right]}\frac{1}{k!\,(M-m-2k)!}\left(\frac{a_x}{4}\right)^k\\ & \sum\nolimits_{l=0}^{M-m-2k}\frac{(M-m-2k)!}{l!\,(M-m-2k-l)!}\left(\frac{ik}{2z}x\right)^{M-m-2k-l}\left(\frac{1}{\rho_0^2}\right)^l\sqrt{\frac{\pi}{b_x}}2^{-(M-n+l)}i^{M-n+l}\\ & \exp\left(\frac{c_x^2}{b_x}\right)\left(\frac{1}{b_x}\right)^{0.5(M-n+l)}H_{M-n+l}\left(-\frac{ic_x}{\sqrt{b_x}}\right)\sqrt{\frac{\pi}{a_y}}m!\left(\frac{1}{a_y}\right)^m\exp\left[\frac{1}{a_y}\left(\frac{ik}{2z}y\right)^2\right]\\ & \sum\nolimits_{t=0}^{\left[\frac{m}{2}\right]}\frac{1}{t!\,(m-2t)!}\left(\frac{a_y}{4}\right)^t\sum\nolimits_{l'=0}^{m-2t}\frac{(m-2t)!}{l'!\,(m-2t-l')!}\left(\frac{ik}{2z}y\right)^{m-2t-l'}\left(\frac{1}{\rho_0^2}\right)^{l'}\\ & \sqrt{\frac{\pi}{b_y}}2^{-(n+l')}i^{n+l'}\exp\left(\frac{c_y^2}{b_y}\right)\left(\frac{1}{b_y}\right)^{0.5(n+l')}H_n\left(-\frac{ic_y}{\sqrt{b_y}}\right)\end{aligned} \tag{8}$$