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Propagation of a vortex Airy beam in chiral medium

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ABSTRACT

The analytical expression for the propagation of a vortex Airy beam through ABCD optical systems is derived. As an example, the propagation of the beam in chiral medium is discussed. It is shown that the vortex will destroy the center lobe of the Airy beam at a critical position which is different for the left circularly polarized (LCP) and the right circularly polarized (RCP) vortex Airy beam. The intensity distribution exhibits novel features due to the existence of the vortex. In addition, the intensity distributions of the LCP beam and the RCP beam are more sensitive to the chirality parameter in far-zone than that in near-zone. The transverse shift of the center lobe of a vortex Airy beam during propagation is affected by the chiral parameter.

1. Introduction

Since the finite-energy Airy beam was introduced and generated experimentally in 2007 [1,2], it has attracted considerable attention due to its unique properties, such as slow diffraction [1,3], transverse acceleration (self-bend) and self-healing [4,5]. Based on the intriguing properties of the Airy beam, a lot of work has been done to investigate the underlying characteristics and the applications of the Airy beam both theoretically and experimentally, such as surface Airy plasmons [6], Airy beam laser [7], the reflection and refraction of an Airy beam at a dielectric interface [8], evanescent Airy beam [9], and the generation of electron Airy beam [10]. In addition, the propagation of an Airy beam through various media including the turbulence atmosphere [11], water [12], transparent particles [13], and uniaxial crystal [14] has been studied.

On the other hand, optical vortex has been the subject of many investigations, and there are many methods to produce optical vortex experimentally [15–17]. The optical vortex has been applied in optical communication, optical micromanipulation and other fields due to its interesting characteristics, such as phase singularity, autofocusing properties and vector structure [18–21]. Recently, the propagation dynamic of the vortex incorporated in various background beams, such as the fundamental Gaussian beams and the partially coherent beams, has been reported [22,23]. Similarly, the propagation of an optical vortex superimposed on Airy beams has been a highlight [24–28]. For example, Mazilu et al. studied the accelerating vortex nested in Airy beams by imposing a spiral phase plate on a cubic phase pattern [24]. Dai et al. investigated the propagation dynamic of vortex Airy beams by a phase spatial light modulator [25,26]. Chen et al. analyzed the features of a vortex Airy beam using Wigner distribution function and the collapse dynamic of a vortex Airy beam in a Kerr medium [27,28].

In this paper we will analyze the propagation of the Airy beam with unit-charged vortex through chiral medium. Chiral medium has many dramatically different characteristics compared with ordinary medium [29–31]. For example, when a linearly polarized beam is incident upon a slab of chiral medium, it will be split into two components, i.e., the left circularly polarized beam (LCP) and the right circularly polarized beam (RCP) inside the surface. And the two waves have different phase velocities in chiral medium. There have been substantial interests about the propagation of light waves through chiral medium [32,33]. However, to the best of our knowledge, the propagation of the vortex Airy beam in chiral medium has not been reported.

The propagation of a vortex Airy beam through an optical ABCD system is analyzed first, followed by the case for the propagation of such beams through chiral medium. Then we investigate the influence of the vortex on the propagation of the Airy beam in chiral medium. We also study the intensity distributions of the field in near and far-zone under different chirality parameters.

2. Analytical expression for the vortex Airy beam through an optical ABCD system or a chiral medium

The scalar field of an exponentially apertured Airy beam in the plane $(z=0)$ can be expressed as follows [1,2,5]:

$$u(x,y,z=0)=Ai\left(\frac{x}{x_0}\right)\exp\left(\frac{ax}{x_0}\right)Ai\left(\frac{y}{y_0}\right)\exp\left(\frac{ay}{y_0}\right), \tag{1}$$

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where Ai is the Airy function, x_0 (y_0) denotes the arbitrary transverse scale in x (y) direction, and a represents the exponential truncation factor which determines the propagation distance.

The field distribution of the Airy beam superimposed by a l-order optical vortex in the initial plane can be expressed as follows [25,27]:

$$u(x,y,z=0)=Ai\left(\frac{x}{x_0}\right)Ai\left(\frac{y}{y_0}\right)\exp\left(\frac{ax}{x_0}+\frac{ay}{y_0}\right)[(x-x_d)+i(y-y_d)]^l, \quad (2)$$

where x_d and y_d denote the original locations of the vortex; l is the topological charge of the vortex. For simplicity, we choose the unit topological charge. The paraxial propagation of the vortex Airy beam through an optical ABCD system can be determined by Huygens–Fresnel integral in the form [34]:

$$u(x,y,z)=\frac{ik_0}{2\pi B}\iint u(x_1,y_1,z=0)\times\exp\left\{-\frac{ik_0}{2B}[A(x_1^2+y_1^2)-2(xx_1+yy_1)+D(x_1^2+y_1^2)]\right\}dx_1dy_1. \quad (3)$$

The fundamental integral definition of the Airy function is [35]

$$Ai(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\exp\left(-\frac{iz^3}{3}-izx\right)dz. \quad (4)$$

On substituting Eqs. (2) and (4) into Eq. (3), we can obtain the field distribution of the vortex Airy beam after it propagates a distance z, with the form of

$$u(x,y,z)=\frac{B}{k_0A^2}\exp[P(x,y,z)](q_1+q_2+q_3), \quad (5)$$

where

$$P(x,y,z)=\frac{a}{A}\left(\frac{x-2x_m}{x_0}+\frac{y-2y_m}{y_0}\right)+\left(\frac{-ik_0D}{2B}+\frac{ik_0}{2AB}\right)(x^2+y^2)+i\left[\frac{B^3}{12A^3k_0^3}\left(\frac{1}{x_0^6}+\frac{1}{y_0^6}\right)-\frac{a^2B}{2Ak_0}\left(\frac{1}{x_0^2}+\frac{1}{y_0^2}\right)-\frac{B}{2A^2k_0}\left(\frac{x}{x_0^3}+\frac{y}{y_0^3}\right)\right], \quad (6)$$

$$q_1=\frac{k_0}{B}Ai\left(\frac{x-x_m}{Ax_0}-\frac{iaB}{Ak_0x_0^2}\right)Ai\left(\frac{y-y_m}{Ay_0}-\frac{iaB}{Ak_0y_0^2}\right)[x-Ax_d-2x_m+i(y-Ay_d-2y_m)], \quad (7a)$$

$$q_2=\frac{-i}{x_0}\left[Ai'\left(\frac{x-x_m}{Ax_0}-\frac{iaB}{Ak_0x_0^2}\right)+aAi\left(\frac{x-x_m}{Ax_0}-\frac{iaB}{Ak_0x_0^2}\right)\right]Ai\left(\frac{y-y_m}{Ay_0}-\frac{iaB}{Ak_0y_0^2}\right), \quad (7b)$$

$$q_3=\frac{1}{y_0}\left[Ai'\left(\frac{y-y_m}{Ay_0}-\frac{iaB}{Ak_0y_0^2}\right)+aAi\left(\frac{y-y_m}{Ay_0}-\frac{iaB}{Ak_0y_0^2}\right)\right]Ai\left(\frac{x-x_m}{Ax_0}-\frac{iaB}{Ak_0x_0^2}\right), \quad (7c)$$

where Ai' represents the derivative of the Airy function, $x_m=(B^2/4Ak_0^2x_0^3)$ and $y_m=(B^2/4Ak_0^2y_0^3)$ are defined as the general transverse motions of the Airy beam in x and y directions, respectively.

According to Eqs. (7a)–(7c), we can see that the component of q_1 denotes the conventional Airy beam imposed with an optical vortex.

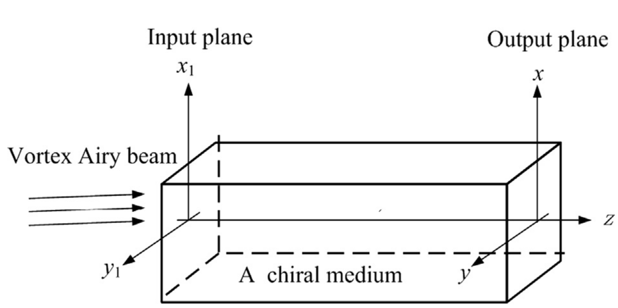

Fig. 1. Geometry of a vortex Airy beam passing through a chiral medium.

And the location of the vortex is at the point $(Ax_d+2x_m,\ Ay_d+2y_m)$. Obviously, the vortex follows a parabolic trajectory as the Airy beam does. Suppose that $A=1$, in this case its transverse acceleration is faster than the center lobe of the Airy beam, which is consistent with the phenomenon observed experimentally [24]. In addition, it is clear that the vortex will superimpose completely on the center lobe of the Airy beam when the locations of the vortex and the center lobe of the Airy beam satisfy the following relation:

$$x_m=2x_m+Ax_d,\quad y_m=2y_m+Ax_d. \quad (8)$$

q_2 denotes the profile of the Airy beam with y component described by the Airy function and x component described by the combination of Airy function and its derivative. q_3 is similar to q_2 only with the coordinates x and y exchanged, besides a $\pi/2$ skewing exists between them.

Eq. (5) is the general expression of the field distribution of a vortex Airy beam passing through an optical ABCD system. Now we consider a special case, i.e. the propagation of a vortex Airy beam through a chiral medium (see Fig. 1). The ABCD matrix of the propagation system in the chiral medium can be expressed as [32,33]

$$\begin{bmatrix}A^{(L)} & B^{(L)}\\ C^{(L)} & D^{(L)}\end{bmatrix}=\begin{bmatrix}1 & z/n^{(L)}\\ 0 & 1\end{bmatrix},\ \text{and}\ \begin{bmatrix}A^{(R)} & B^{(R)}\\ C^{(R)} & D^{(R)}\end{bmatrix}=\begin{bmatrix}1 & z/n^{(R)}\\ 0 & 1\end{bmatrix}, \quad (9)$$

where $n^{(L)}=n_0/(1+n_0k_0\gamma)$ and $n^{(R)}=n_0/(1-n_0k_0\gamma)$ represent the refractive indices of the LCP beam and the RCP beam respectively. γ is the chiral parameter; $k_0=2\pi/\lambda$ is the wave number of incident wave in vacuum. It is clear that the ABCD matrix is different for LCP beam and RCP beam. On substituting Eq. (9) into Eq. (5), we can obtain the analytical expression of the LCP and RCP vortex Airy beams at any output plane in the chiral medium. In the following, the corresponding propagation properties of the LCP and RCP beams are presented separately.

Based on the Eqs. (8) and (9), we can obtain this special propagation distance where the vortex superimposes on the center lobe of the Airy beam, and it is expressed as follows:

$$z_0^{(J)}=2n^{(J)}k_0x_0\sqrt{x_0x_d}\quad (x_0=y_0, J=L,R). \quad (10)$$

It is shown that $z_0^{(J)}$ is different for the LCP vortex Airy beam and the RCP vortex Airy beam and is related to the chiral parameter γ.

3. Numerical calculation and analysis

We assume that $a=0.05$, $\lambda=632.8$ nm,$x_0=0.15$ mm, $y_0=0.15$ mm, $\gamma=0.16/k_0$, and $x_d=y_d=-0.3$ mm. Through further calculation the special distance can be obtained as $z_0^{(L)}=1280.9$ mm and $z_0^{(R)}=3645.5$ mm.

Fig. 2(a) shows the intensity distribution of the LCP vortex Airy beam at $z_0^{(L)}=1280.9$ mm. A doughnut-shaped center lobe can be observed because the vortex completely superimposes on the center lobe of the Airy beam. Fig. 2(b)–(d) describes the intensity distributions of the three individual components q_1, q_2 and q_3 respectively. From Fig. 2(b)–(d), it is found that the location of the vortex is determined only by the termq_1, which is agreed with the theoretical analysis.

The intensity distribution of the LCP vortex Airy beam located at four different propagation distances is depicted in Fig. 3(a)–(d). It can be seen that the center lobe moves along the parabolic trajectory. At the critical position, the center lobe is distorted due to the superimposition of the Airy beam and the vortex. But with the propagation distance increasing the center lobe is reconstructed due to its self-healing property. Fig. 3(e)–(h) shows the corresponding phase distribution. A clear forking shape is observed during propagation, which proves the revival of the vortex after a long distance. It is in good agreement with the result