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Propagation of an Airy-Gaussian-Vortex beam in a chiral medium

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ABSTRACT

Based on the Huygens diffraction integral, the analytical expressions of electric field distribution of the Airy-Gaussian-Vortex (AiGV) beam in a chiral medium are derived, and its propagation properties are investigated. With increasing the value of chiral parameter γ, the parabolic deflection of the LCP light increases and the RCP light decreases respectively. For the first-order AiGV beam with only one positive or negative optical vortex (OV), a half-moon-shaped intensity profile can be observed because of overlap of the OV and the Airy main lobe, and then the main lobe will be reconstructed and the vortex could be recovered after the overlap position. The intensity distribution of AiGV beam, the deflection trajectories of central positions of Airy beam and OV under different competing parameters between Gaussian and Airy terms have been studied. Furthermore, for the second-order counterrotating AiGV beam with positive and negative vortexes, it could be considered the superposition of two first-order AiGV beams with respective positive and negative vortexes. Two vortexes can regenerate during propagation and the intensity distribution the AiGV beam in the far zone can be controlled by adjusting the coordinates of two vortexes.

1. Introduction

In 1979, Berry and Balazs found the accelerating Airy-pocket solution of the Schrödinger equation within the context of quantum mechanics [1], and Airy beam with the properties of diffraction-free, self-bending and self-healing was first predicted theoretically and demonstrated experimentally by Siviloglou and Christodoulides in 2007 [2–4]. For several years, Airy beam has attracted significant attentions in applications such as optical cleaning of microparticles [5,6], generating versatile linear bullets [7], curved plasma channel generation [8,9] and vacuum electron acceleration [10]. As we all known, the initial Airy beam with infinite energy is not realizable in practice, but Siviloglou's research [3] shows the method of Gaussian beams with cubic phase through a Fourier transformation can be used to generate Airy beam easily.

In order to describe the propagation of the Airy beam in a more realistic way, the Airy-Gaussian (AiG) beam as a generalized form of the Airy beam has been introduced [11], which carries finite power and hold the diffraction-free properties within limited propagation distance and can be understood as an finite energy Airy beam passes through the Gaussian aperture. Recently, the propagation of AiG beam in strongly nonlocal nonlinear media [12], in Kerr medium [13], in a quadratic medium [14], in uniaxial crystals [15], in a chiral medium [16] and through slabs of right-handed materials and left-handed materials [17] have been presented. What's more, the Airy-Gaussian-Vortex (AiGV) beam could be obtained from the AiG beam multiplied vortex factor and exhibits some intriguing properties such as intensity singularities and phase singularities [18]. In this year, the AiGV beam propagating in the uniaxial crystals [19], in linear and nonlinear media [20] and in gradient-index medium [21] have been studied.

Compared with ordinary medium, chiral medium has a wide variety features, especially optical properties [22–24]. When a linearly polarized light is incident upon a slab of chiral medium, it can be split into left hand circular polarized (LCP) light and right hand circular polarized (RCP) light [25,26]. Meanwhile, the two waves have different phase velocity inside the chiral medium [27] due to the different refractive index and absorption coefficient for LCP light and RCP light, which is termed as circular birefringence (CB). X Y Liu and D M Zhao studied the propagation of Airy beam with one positive vortex in chiral medium [28].

In this paper, the propagation dynamics of an AiGV beam with positive and negative vortexes are investigated theoretically and numerically in a chiral medium. We deduce the analytical expressions of the electric field distribution of the finite energy AiGV beams based on the Huygens diffraction integral. For the first-order AiGV beam with only one positive or negative optical vortex (OV), the intensity and phase distributions are calculated numerically in initial plane and in different propagation distance. We find the centers of Airy beam and OV are completely superposed on an overlap position. We plot the parabolic trajectory of the AiGV beam propagating in the chiral

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medium to compare the characters between LCP and RCP lights with different chiral parameters. Then the trajectory of the central intensity of the Airy beam and OV with different chiral parameters has been studied. What is more, we have analyzed the influence of competing factor on AiGV beam. For the second-order counterrotating AiGV beam with positive and negative vortexes, it could be considered the superposition of two first-order AiGV beams with respective positive and negative vortexes. We find that the coordinates of the positive and negative vortexes have a great influence on the AiGV beam, which can be used to control the beam profile and the peak region when the competing factor is defined. Finally, we summarize the characteristics of the AiGV beam propagating in the chiral medium.

2. Analytical expression of the AiGV beam through an ABCD optical system

The two-dimensional AiGV beam has been considered and the electric field distribution of the finite energy AiGV beam in the initial plane (z_0=0) can be expressed as [19,20]

$$E_0(x_0, y_0, 0) = A_0 Ai\left(\frac{x_0}{w_1}\right)\exp\left(\frac{ax_0}{w_1}\right)Ai\left(\frac{y_0}{w_2}\right)\exp\left(\frac{ay_0}{w_2}\right)\exp\left(-\frac{x_0^2+y_0^2}{w_0^2}\right)\times \left(\frac{x_0-x_1}{w_1}+i\frac{y_0-y_1}{w_2}\right)^m\left(\frac{x_0-x_2}{w_1}-i\frac{y_0-y_2}{w_2}\right)^n, \quad (1)$$

where A_0 represents the constant amplitude of the AiGV beam, a represents an exponential truncation factor ranging from 0 to 1 so as to ensure containment of the infinite Airy tail [3], w_0 is the waist size and w_1, w_2 represent arbitrary transverse scales in the x and y directions. Then we set up w_1=w_2=$\chi_0 w_0$, χ_0 is a competing factor controlling the beam to tend to Airy-vortex (AiV) beam with a small value or Gaussian-Vortex (GV) beam with a large value. $((x_0-x_1)/w_1+i(y_0-y_1)/w_2)^m$ is the positive vortex factor and $((x_0\text{-}x_2)/w_1\text{-}i(y_0\text{-}y_2)/w_2)^n$ is the negative one, m and n represent the orders of the vortex, respectively, x_1, x_2 and y_1, y_2 are the positions of the center of the positive and negative vortexes. $Ai(\bullet)$ represents the Airy function and can be expressed as [30]

$$Ai(x) = \frac{1}{2\pi}\int \exp[i(\frac{t^3}{3}+xt)]dt, \quad (2)$$

Then the ABCD matrix of the propagation system in the chiral medium can be expressed as [25]

$$\begin{pmatrix} A^{(L)} & B^{(L)} \\ C^{(L)} & D^{(L)} \end{pmatrix} = \begin{pmatrix} 1 & z/n^{(L)} \\ 0 & 1 \end{pmatrix}, \; and \begin{pmatrix} A^{(R)} & B^{(R)} \\ C^{(R)} & D^{(R)} \end{pmatrix} = \begin{pmatrix} 1 & z/n^{(R)} \\ 0 & 1 \end{pmatrix}, \quad (3)$$

where $n^{(L)}$=$n_0/(1+n_0k_0\gamma)$ and $n^{(R)}$=$n_0/(1-n_0k_0\gamma)$ denote the refractive indices of the LCP and RCP components, respectively, n_0 is the original refractive indices in the chiral medium, k_0 is the wave number of the incident beams in vacuum and γ denotes the chiral parameter.

Now we consider the paraxial propagation of the AiGV beam through the optical ABCD system with the Huygens diffraction integral [31]

$$E(x, y, z) = \frac{i}{\lambda B}\iint E_0(x_0, y_0, 0)\exp\left\{-\frac{ik_0}{2B}[A(x_0^2+y_0^2) - 2(x_0x+y_0y) + D(x^2+y^2)]\right\}dx_0dy_0, \quad (4)$$

where A, B and D are elements of the transfer matrix as shown in Eq. (3). For the chiral medium as shown in Eq. (3), A=D=1. Substituting Eqs. (1) and (2) into Eq. (4), we can obtain the analytical electric filed distribution of an AiGV beam.

Usually, we cannot get the integral (4) for any orders of m and n. In the paper, we first discuss the case of m=1, n=0, i.e., the first-order AiGV with positive vortex. Because the case of m=0, n=1 (the first-order AiGV with negative vortex) show the same propagation properties as the case of m=1, n=0 except the opposite phase distributions, we only present the former in the following text. Moreover, we study the situation of the positive and negative vortexes existed simultaneously (m=1, n=1, the second-order counterrotating AiGV). However, the integral transformation of AiGV beam in the chiral medium with the vortex order lager than 1 (such as m=2, n=0) is quite complicated and the solution is hard to achieve. Meanwhile, H T Dai et al. [29] have demonstrated experimentally that OV with higher orders has no obvious effect on the transverse deflection velocity of an OV, thus we will not analyze the situation with higher vortex order.

The analytical electric filed distribution of an AiGV beam at the output plane are as follows with m=1, n=0 and m=1, n=1, respectively [21]

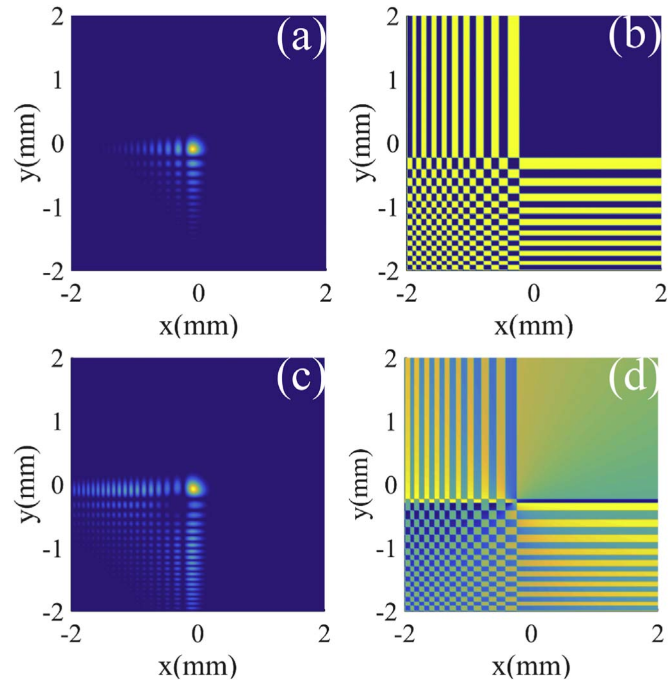

Fig. 1. Numerical simulation of the transverse intensity and phase distributions at the initial plane z=0. (a), (b) Denote intensity and phase of the AiG beam. (c), (d) Denote intensity and phase of the AiGV beam.

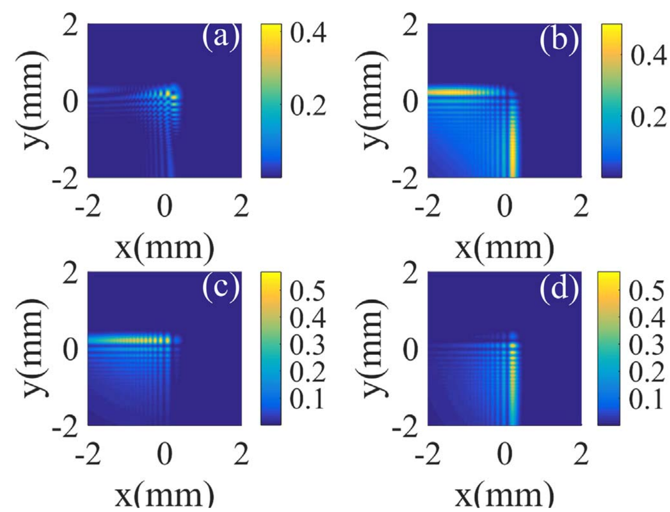

Fig. 2. Numerical simulation of the intensity distribution of the LCP AiGV beam propagating in the chiral medium with γ=0.16/k_O in the distance z_s=697 mm. (a) Represents the LCP AiGV beam. (b), (c) and (d) represent the components of P_1, P_2 and P_3, respectively.