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Propagation of Airy-related beams generated from flat-topped Gaussian beams through a chiral slab

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ABSTRACT

We derived the analytical expression for the propagation of Airy-related beams generated from flat-topped Gaussian beams through an ABCD optical system, and use it to study the propagation of this type of beams through a chiral slab. Several influence factors, such as the optical beams order N and the chiral parameter γ of the chiral medium, on the beam propagation properties both in near- and far-zones are discussed in detail. It is shown that the Airy tails of high order beams decay more quickly than those of low order beams in the chiral medium; the constructive interference effect between the LCP (left-circularly polarized) and RCP (right-circularly polarized) beams becomes more significant as the chiral parameter γ increases; the LCP and RCP beams are not separated in the near-zone, while the two beams are obviously separated in the far-zone, and accordingly the interference peaks decrease as the propagation distance increases in the chiral slab.

1. Introduction

Non-spreading or non-diffraction (also named diffraction-free) beams are by definition localized optical wave packets that remain invariant during propagation. Due to their novel features this intriguing class of wave packets have received sustained attention [1–9]. In 1979, Scholars Berry and Balazs made an important observation within the context of quantum mechanics: they theoretically demonstrated that the Schrödinger equation describing a free particle can exhibit a non-spreading Airy wave packet solution [1]. Bessel beams, initially predicted theoretically and demonstrated experimentally by Durnin et al. in 1987, is perhaps the best known example of diffraction-free wave [2]. In 2007, a finite-energy Airy beam is first introduced theoretically and demonstrated experimentally by extending Berry and Balazs's infinite-energy Airy model by Siviloglou and Christodoulides [3,4]. Owing to their non-diffraction properties, Airy beams have ability to reconstruct themselves during propagation even though parts of the beams are distorted or obstructed [5]. The Airy beams have been identified for unique features, such as weak diffraction, transverse acceleration [3,4], and self-healing [5]. And over very recent years, Airy beams have attracted a great deal of interest in applications such as optical clearing micro-particles [6], plasma physics [7], optical micro-manipulation [8,9] and other fields.

In general, the finite energy Airy beam can be generated from the fundamental Gaussian beam through a Fourier transformation provided that a cubic phase is imposed [4]. Meanwhile, many Airy-related beams have been proposed or generated by making some changes in the methods of generating Airy beams [10–16]. For example, using the partially coherent Gaussian beam as the incident beam, a broadband "white light" Airy beam can be generated, and its decay parameter depends on the spatial coherence of the incident beam [10]; by adding a special apodization mask in the light path, a reduced side-lobe Airy beam can be generated that has an effectively enhanced central lobe, and the side lobe is reduced compared with the common Airy beam [11].

It is known that chirality can lift the degeneracy of two circular polarizations [17]. When a linearly polarized beam is incident normally upon a chiral slab, it will be split into two circularly polarized beams (left-circularly polarized and right-circularly polarized beams) at the interface with different phase velocity propagating in the chiral slab. This circular birefringence of the chiral medium is of crucial importance in the fields of biochemistry, chemistry, and medicine. In this work, we investigate the propagation of Airy-related beam, which is generated from Airy transform from flat-topped Gaussian beams [18], through a chiral slab [19–25].

2. Propagation characteristics of the Airy-related beam through a chiral slab

Matrix optics is a powerful and analytical method to deal with the beam propagation problem. For a beam through a chiral slab,

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the corresponding transfer matrix of the optical system can be written as [26]

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

In Eq. (1), $n^{(L)} = n_0/(1+n_0k_0\gamma)$, $n^{(R)} = n_0/(1-n_0k_0\gamma)$ denote the refractive indices of the left-circularly polarized (LCP) and right-circularly polarized (RCP) beams, respectively. n_0 and γ represent the original refractive index and the chiral parameter of the chiral slab, respectively. $k_0 = 2\pi/\lambda_0$ is the wave number of the optical wave with λ_0 being the wavelength of the Airy-related beam in vacuum. Thus, the wave number of the left-circularly polarized and right-circularly polarized Airy-related beams in the chiral slab is $k^{(J)} = n^{(J)}k_0$, where $J = L,R$.

Here, we investigate the dynamics of one-dimensional (1D) Airy-related beam through a chiral slab. A symmetric 2D case can be obtained by replacing the coordinate x with y, and multiplying the two scalar fields together. The electric field profile of Airy-related beams generated from flat-topped Gaussian beams can be expressed as [18]

$$E_1(x_1; z=0) = 2\sqrt{\pi}A_0 \sum_{n=1}^{N} \frac{(-1)^{n-1}\sqrt{a_n}}{N} \binom{N}{n} \exp\left(\frac{2a_n^3}{3}\right) Ai\left(\frac{x_1}{\alpha} + a_n^2\right) \exp\left(\frac{a_n x_1}{\alpha}\right). \tag{2}$$

In Eq. (2), $Ai(\cdot)$ indicates the Airy function, x_1/α represents a dimensionless transverse coordinate, α denotes an arbitrary transverse scale, $a_n = w_0^2/(4n\alpha^2)$ represents the modulation parameter so as to ensure containment of the infinite Airy tail, A_0 is a constant related with the beam power, N denotes the order of the Airy-related beams, $\binom{N}{n}$ is a binomial coefficient, and w_0 is the waist size of fundamental Gaussian beam with $N=1$. It is clear from Eq. (2) that the Airy-related beams generated from flat-topped Gaussian beams can be considered as a finite sum of common finite energy Airy beams, and Eq. (2) becomes the common finite energy Airy beam when $N=1$.

To visualize the shape of Airy-related beams characterized by Eq. (2), a preliminary demonstration is shown in Fig. 1(a) for the flat-topped Gaussian beams, and (b) for the Airy-related beams generated from flat-topped Gaussian beams of different orders, respectively. All of the curves in Fig. 1 have been normalized to the peak intensity value. It is apparent from Fig. 1(a) that the irradiance profile becomes flat-topped when $N>1$, and the flat zone occupies a larger fraction of the beam profile when the value of N increases. And it is also clearly seen from Fig. 1(b) that the Airy-related beams generated from flat-topped Gaussian beams ($N>1$) possess profiles similar to those of the Airy beam generated from the fundamental Gaussian beam ($N=1$), and the Airy tails of higher order beams decay more quickly than that of lower order beams. Furthermore, the peak of the first lobe is a little shifted in the positive x-direction when the value of N increases, which can be inferred from the Airy function in Eq. (2). So the Airy-related beams can be modulated by varying the beam order N.

Within the framework of paraxial approximation, the propagation of a beam through the first order *ABCD* optical system is described by the generalized Huygens–Fresnel diffraction integral, which is known as Collins′ formula [27,26]

$$E^{(J)}(x;z) = \sqrt{\frac{ik_0}{2\pi B^{(J)}}} \int_{-\infty}^{\infty} \exp\left[-\frac{ik_0}{2B^{(J)}}(A^{(J)}x_1^2 - 2x_1x + D^{(J)}x^2)\right] E_1(x_1; z=0)dx_1 \tag{3}$$

In Eq. (3) the superscripts $J = L,R$ denote LCP and RCP, respectively. To calculate this integral, the Airy function can be written in terms of the integral representation [28]

$$Ai(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \exp\left(\frac{iu^3}{3} + ixu\right) du. \tag{4}$$

On substituting Eqs. (2) and (4) into Eq. (3), after tedious integral calculations, one obtains the expression of Airy-related beams′ field distribution in an arbitrary plane $z>0$:

$$\begin{aligned} E^{(J)}(x;z) = {} & \frac{2A_0}{\sqrt{A^{(J)}}} \sum_{n=1}^{N} \frac{(-1)^{n-1}\sqrt{\pi a_n}}{N} \binom{N}{n} \exp\left[-\frac{ik_0 C^{(J)} x^2}{2A^{(J)}}\right] \\ & \times Airy\left(\frac{x}{A^{(J)}\alpha} - \frac{B^{(J)2}}{4\alpha^4 k_0^2 A^{(J)2}} - \frac{iB^{(J)}a_n}{A^{(J)}k_0\alpha^2} + a_n^2\right) \\ & \times \exp\left[\frac{a_n x}{A^{(J)}\alpha} - \frac{a_n B^{(J)2}}{2A^{(J)2}k_0^2\alpha^4} + \frac{iB^{(J)3}}{8A^{(J)3}k_0^3\alpha^6}\right. \\ & \left. - \frac{ia_n^2 B^{(J)}}{A^{(J)}k_0\alpha^2} - \frac{iB^{(J)}x}{2A^{(J)2}k_0\alpha^3} + \frac{iB^{(J)}}{6\alpha^2 k_0 A^{(J)}} + \frac{2a_n^3}{3}\right]. \end{aligned} \tag{5}$$

In Eq. (5) $A^{(J)}$, $B^{(J)}$, $C^{(J)}$ and $D^{(J)}$ are elements of the optical transfer matrix for the LCP and RCP beams in the chiral slab, respectively. When the Airy-related beam propagates along the z-direction, the optical field is split into two components, e.g., the LCP and RCP beams. And the total field profile in the chiral slab is given by

$$E(x) = E^{(L)}(x) + E^{(R)}(x). \tag{6}$$

Thus, the total intensity of Airy-related beam in the plane $z>0$ can be expressed as

$$I = |E^{(L)}(x)|^2 + |E^{(R)}(x)|^2 + I_{int}, \tag{7}$$

with

$$I_{int} = E^{(L)}(x)E^{(R)*}(x) + E^{(R)}(x)E^{(L)*}(x), \tag{8}$$

where I_{int} denotes the interference term, and $*$ indicates the complex conjugation. By complex but straightforward deduction,

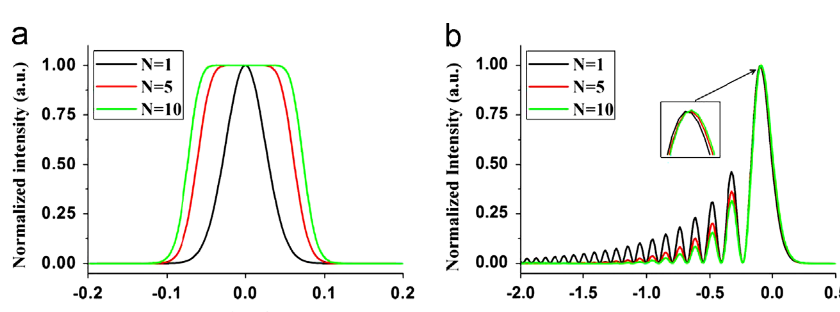

Fig. 1. The normalized intensity distribution of (a) flat-topped Gaussian beams and (b) Airy-related beams generated from flat-topped Gaussian beams of different orders N.