Acceleration control of Airy beams with optically induced refractive-index gradient

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We demonstrate both experimentally and theoretically controlled acceleration of one- and two-dimensional Airy beams in optically induced refractive-index potentials. Enhancement as well as reduction of beam acceleration are realized by changing the index gradient, while the beam shape is maintained during propagation through the linear optical potential. Our results of active acceleration manipulation in graded media are pertinent to Airy-type beam propagation in various environments. © 2011 Optical Society of America

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Free-space self-accelerating Airy beams [1,2] have attracted a great deal of research interests due to potential applications of their peculiar features [3–5]. Both linear and nonlinear generation and control of Airy beams have been reported [6–12], mostly in free space or uniform media. However, in many environments, the refractive media are intrinsically complex and nonuniform. For instance, the atmosphere can be taken as one type of layered refractive-index media. In optics and photonics, graded index variation appears all the time. It is thus desirable to study the propagation of Airy beams in nonuniform or periodic media. Just as a time-varying spatially uniform force or a linear potential can be utilized to control the acceleration of temporal Airy wave packets [13], a spatially varying uniform force or linear optical potential can have a pronounced effect on self-bending Airy beams. Such a feature could be used for routing plasmonic Airy beams, as proposed recently [14,15].

In this Letter, we demonstrate both theoretically and experimentally active control of self-accelerating Airy beams with an optically induced graded index structure. By proper design of the refractive-index gradient, enhancement, reduction, and complete suppression of the Airy beam acceleration are realized. Our method brings about another possibility for linear control of the Airy beams in inhomogeneous media, independent of the amplitude or the phase modulation of the input Airy beams.

The theoretical model for linear propagation of one-dimensional (1D) Airy beams in graded index media ($\Delta n = \delta_n x$ with δ_n being a constant) is described by the following paraxial wave equation:

$$i\frac{\partial\varphi}{\partial z} + \frac{1}{2k}\nabla_\perp^2\varphi = -\frac{k}{n}\Delta n\varphi, \qquad (1)$$

where φ is the slowly varying envelope of the wave function, k is the wavenumber in the medium, $n = 2.3$ is the refractive index of the uniform medium, and $\Delta n \ll n$ indicates the graded index change. By taking a truncated Airy beam as the initial condition $\varphi(x,0) = \mathrm{Ai}(x/x_0)\exp(ax)$ (where Ai denotes the Airy function, x_0 is an arbitrary transverse scale, and a is the truncation factor), the beam evolution can be expressed as

$$\begin{aligned}\phi(x,z) = \mathrm{Ai}&\left[\left(x - \frac{z^2}{4k^2x_0^3} - \frac{\delta_n z^2}{2n}\right)/x_0 + i\frac{az}{kx_0}\right]\\ &\cdot\exp\left[ax - \frac{a}{2}\left(\frac{1}{k^2x_0^3} + \frac{\delta_n}{n}\right)z^2\right.\\ &-\frac{i}{12}\left(\frac{1}{k^3x_0^6} + \frac{2k\delta_n^2}{n^2} + \frac{3\delta_n}{nkx_0^3}\right)z^3 + \frac{ia^2}{2k}z\\ &\left.+ i\left(\frac{1}{2kx_0^3} + \frac{k\delta_n}{n}\right)zx\right]. \qquad (2)\end{aligned}$$

From Eq. (2), it can be seen that the trajectory of the Airy beam in linear potential remains as parabola but with a modified acceleration factor $1/2k^2x_0^3 + \delta_n/n$ determined only by the wavelength and the index distribution of the medium. When $\delta_n > 0$, the Airy beam accelerates faster, as illustrated in Fig. 1(b), whereas $\delta_n < 0$ leads to reduced acceleration [Fig. 1(c)]. Interestingly, the Airy beam acceleration can be completely compensated if we set the gradient of index at $\delta_n = \delta_{nc} = -n/2k^2x_0^3$ as shown in Fig. 1(d). The relationship between the acceleration factor and δ_n is plotted in Fig. 1(e).

For a two-dimensional (2D) Airy beam $\varphi(x,y,0) = \mathrm{Ai}(x/x_0)\mathrm{Ai}(y/y_0)\exp(a_x x + a_y y)$, we set the angle between the gradient direction and the x axis to be θ, and then the index potential is governed by $\Delta n = \delta_n(x\cos\theta + y\sin\theta)$. Equation (1) can be reduced into two 1D equations by the method of separation of

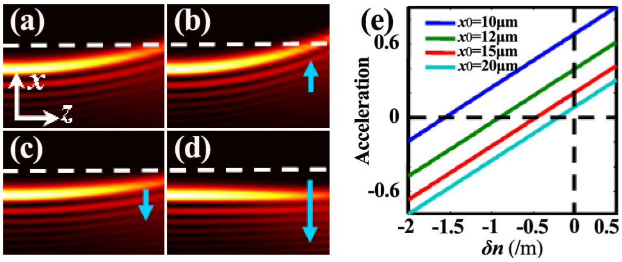

Fig. 1. (Color online) Theoretical results of 1D Airy beams propagating in a medium with different index gradients δ_n. (a) Normal propagation at $\delta_n = 0$. (b) Enhanced and (c) reduced acceleration at $\delta_n > 0$ and $\delta_n < 0$, respectively; (d) no acceleration at $\delta_n = \delta_{nc}$. (e) Plot of acceleration as a function of δ_n under different x_0. The white dashed lines mark the position of the central lobe at the output in (a), and the arrows illustrate the index gradient.

variables. The acceleration factor along the x and y axes can then be found from the equations as $1/2k^2x_0^3 + \delta_n \cos\theta/n$ and $1/2k^2y_0^3 + \delta_n \sin\theta/n$, respectively. It is clear that the accelerations in the two orthogonal directions are determined both by the magnitude and direction of the index gradient. Under the appropriate conditions, the transverse bending of the Airy beam can be eliminated by the index gradient, as for the 1D case. Furthermore, acceleration control and lateral shift of the Airy beam along particular directions can be done by rotating the beam itself or the graded index medium.

Our experimental setup is shown in Fig. 2, where a linear transverse refractive-index gradient is induced in a biased photorefractive (SBN) crystal by white-light illumination with intensity I_m from a direction orthogonal to beam propagation. The index change $\Delta n = \gamma I_m/(1 + I_m)$ depends on I_m and the bias field (here $\gamma = 6.8 \times 10^{-4}$ when the bias field is 4.0 kV/cm). The intensity I_m is transversely nonuniform but invariant along the z direction as shown in Figs. 2(b) and 2(c)], thus creating a graded index potential throughout the otherwise uniform crystal.

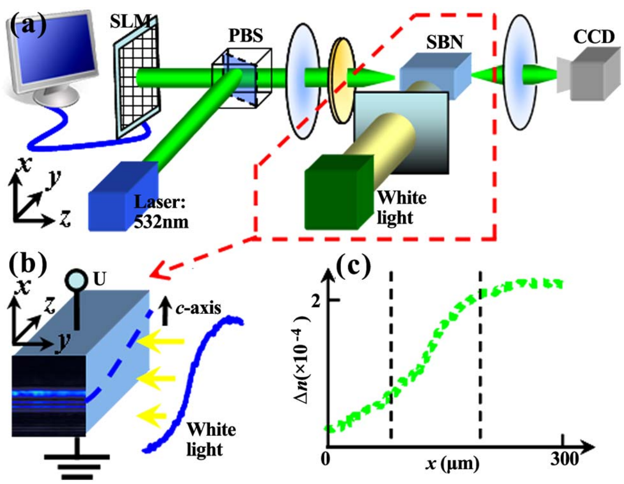

Fig. 2. (Color online) (a), (b) Schematic of the experimental setup. A biased SBN crystal is illuminated by nonuniform white light from x–z plane, while the Airy beam is launched along the z direction. (c) Plot of induced refractive-index change along the x direction where two vertical dashed lines define the graded index area for beam control.

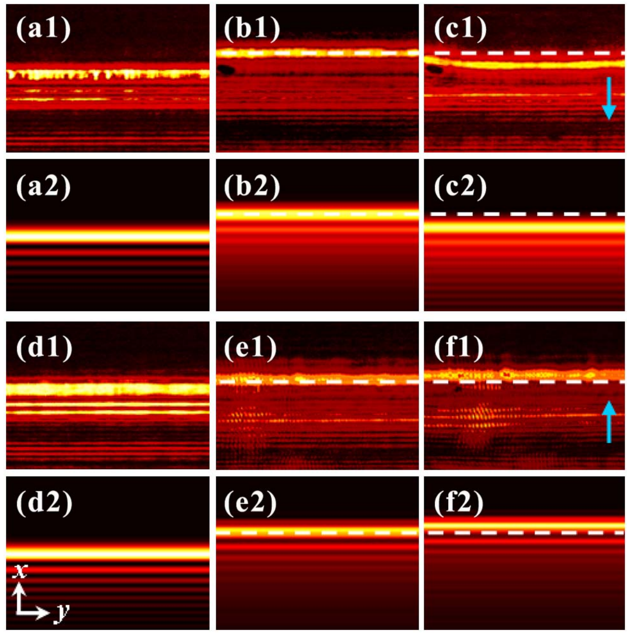

Fig. 3. (Color online) Experimental (a1)–(f1) and numerical (a2)–(f2) results showing acceleration suppression (a)–(c) and enhancement (d)–(f) of the 1D Airy beam. Shown from left to right are input, output after 10 mm of propagation through a uniform (middle) and graded (right) index medium. White dashed lines mark the output beam position from the uniform medium for reference. Arrows in (c1), (f1) indicate the refractive-index gradient.

For the 1D case, an extraordinarily polarized truncated Airy beam with a central lobe about 32 μm (corresponding to $x_0 \approx 12\,\mu$m) is generated by a spatial light modulator, as described in our previous work [7]. The beam is launched along the z direction with its input shown in Figs. 3(a) and 3(d). The Airy beam exhibits normal acceleration/bending along the x direction, as shown in Figs. 3 (middle panels) after 10 mm of propagation through the uniform crystal (without bias field). When a transverse refractive-index gradient is induced (corresponding index gradient is about 0.45/m at a bias field of 4.2 kV/cm) in an antiparallel direction with respect to the x axis, the central lobe of the Airy beam shifts downward after propagation [Figs. 3(c1) and 3(c2)] in comparison with the uniform case [Figs. 3(b1) and 3(b2)], representing the slowdown of its acceleration. However, keeping all conditions unchanged but simply reversing the intensity gradient of the white-light beam (parallel to the x axis), the output position of the Airy beam moves upward [Figs. 3(f1) and 3(f2)], indicating enhanced acceleration of the Airy beam. In both cases, the Airy beam with either enhanced or reduced acceleration maintains its profile. It should be noted that the intensity of our Airy beam is set at a low-power level to prevent the nonlinear index change induced by the Airy beam itself [11], and the diffusion-induced self-bending [10] does not play any role here. These experimental results agree well with our theoretical predications.

A series of experiments was also performed to manipulate the acceleration of the 2D Airy beams. Typical results are shown in Fig. 4, obtained with an Airy beam of 34 μm FWHM in the central lobe and under a bias field of

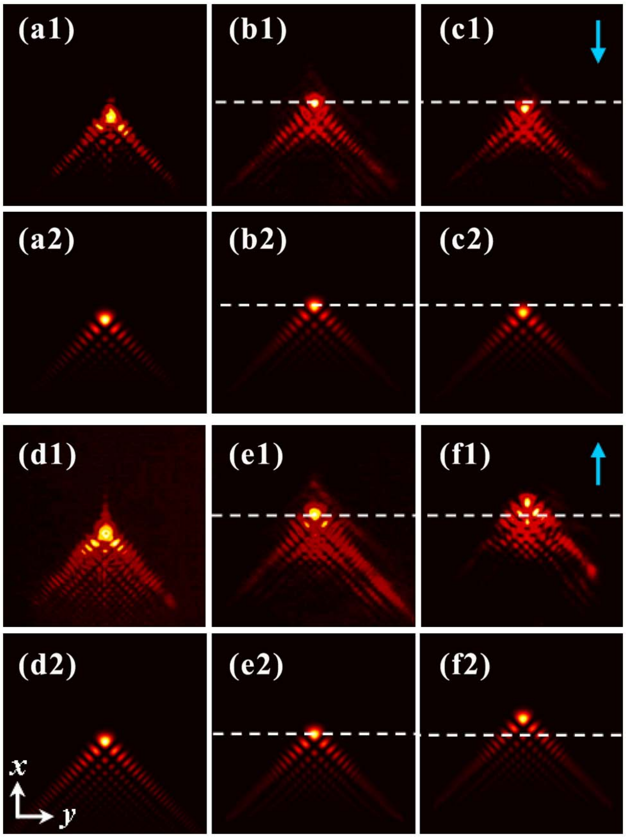

Fig. 4. (Color online) Experimental (a1)–(f1) and numerical (a2)–(f2) results showing acceleration suppression (a)–(c) and enhancement (d)–(f) of the 2D Airy beam. Other descriptions are the same as those for Fig. 3.

3.4 kV/cm. For better visualization of the 2D Airy beam output position, the input beam is oriented symmetrically relative to the x axis as shown in Figs. 4(a1) and 4(a2), while the index gradient is still along the x direction. Under this configuration, the 2D airy beam can only bend along the x direction, but rotating the beam itself or the graded index medium would lead to acceleration control in other directions. As in the 1D case, antiparallel [Fig. 4(c1)] and parallel [Fig. 4(f1)] refractive-index gradients lead to slowdown [Figs. 4(c1) and 4(c2)] and expedition [Figs. 4(f1) and 4(f2)] of the accelerating Airy beam as compared with free-space or uniform medium propagation. Again, good agreement can be seen between the experimental results [Figs. 4(a1)–(f1)] and numerical simulations [Figs. 4(a2)–(f2)].

In summary, we have demonstrated that active acceleration control of Airy beams can be achieved by engineering the refractive-index gradient of the medium. Although the results presented here are for conventional 1D and 2D Airy beams, the scheme could also be applied to recently proposed circular Airy beams, whose abrupt autofocusing feature might be better optimized for a number of applications [16–19].

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