Tunable Optical Bottle Beam Generated via Self-bending Airy Beam Arrays

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Abstract We theoretically demonstrate a novel optical bottle beam that is produced by exploiting the self-bending characteristic of circularly arranged Airy beam (AB) arrays. The AB arrays propagate with an inward acceleration to generate such an optical bottle beam, whose size can be flexibly controlled by changing the spacing distance between ABs in the input plane. Moreover, the intensity of our proposed optical bottle beam is significantly increased in the output plane by superposing multiple coherent ABs, as compared to the case of the conventional Gaussian beam (GB). Numerical simulations are performed, the results of which show that the tunable optical bottle can be formed by exploiting the self-bending property of ABs. Some possible applications are also discussed. We believe that the intriguing characteristics of the tunable optical bottle can lead to novel techniques in medical treatment and atom manipulation.

Key words optical bottle beam; Airy beam; self-bending; manipulation and trapping

OCIS codes 350.5500; 050.1940; 070.6120

自弯曲艾里光束阵列产生的可调局域空心光束

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摘要 利用艾里光束自弯曲特性,提出一种新的艾里光阵列产生的局域空心光束。这些艾里光束阵列以环形排列,当它们向前传播的同时又以向内的方向加速传播,从而形成环形局域空心光束。通过调节在初始输入平面上环形艾里光束阵列之间的间隔距离,可以很灵活实现调控局域空心光束大小。与传统的高斯激光叠加相比,多艾里光束的无衍射特性及相干叠加使得输出能量大大提高。数值模拟结果表明通过环形艾里光束的自加速特性可以形成局域空心光束。该灵活可控的局域光束可以为原子捕获与生命细胞操控提供更好的灵活性。

关键词 空心局域光束;艾里光束;自弯曲;捕获与操控

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1 Introduction

The trapping and manipulation of particles with optical tweezers were first demonstrated two decades ago[1], and to this day remain a very active research field[2-5]. Optical tweezers[6-8] utilize optical radiation pressure to confine and manipulate transparent particles as well as atoms, molecules, cells, etc. According to the relative refractive index of a particle and the surrounding medium, the particles are trapped either in the intensity minima or maxima of the beam. In order to generate such an optical potential well and achieve trapping, optical bottle beams have been proposed[9]. Such beams

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consist of regions of zero intensity surrounded by regions of higher intensity[10-13].

In the past few years, various techniques have been proposed for generating such beams for applications relating to optical tweezers and atom traps. This includes the mechanical angular scanning of a laser beam[14] and the use of optical diffractive elements. Many of these techniques involve vortices: for example, optical beams carrying phase singularities. The vortex beam possesses a core with a vanishing intensity that coincides with the location of the phase singularity. The vortices are routinely generated by the use of phase masks, spiral phase plates, or spatial light modulators[15-17]. It has been shown that, similarly to the optical spin momentum, the orbital angular momentum carried by the vortex beam can be transferred to trapped particles, thereby inducing a rotation. However, it is difficult to adjust the size of the optical bottle beam using these methods owing to the fixed optical elements. Furthermore, the low intensity of the conventional optical bottle beam limits its application as a result of relatively long propagation distances in many cases.

In 2007, Christodoulides proposed and realized self-bending (i.e., self-accelerating) optical Airy beams (ABs)[18-21], which have garnered much research interest recently. This provoked us to generate optical bottle beams by employing ABs. In this letter, we report on an approach for generating optical bottle beams by employing this self-bending characteristic through arranging ABs in circular arrays. We also theoretically demonstrate the mechanism of our proposed optical bottle beam by performing numerical simulations, thereby verifying its effectiveness. The results demonstrate that the size of the optical bottle beam can be flexibly controlled by adjusting the spacing between ABs, and that the intensity of the optical bottle beam can be significantly enhanced as compared to the conventional Gaussian beams (GBs).

2 Theory

We first investigate the self-bending behavior of optical Airy wave packets by considering the paraxial equation of diffraction that governs the propagation dynamics of the electric field envelope E associated with planar optical beams.

$$\mathrm{i}\frac{\partial E}{\partial \xi} + \frac{1}{2}\frac{\partial^2 E}{\partial s^2} = 0 . \tag{1}$$

In Eq.(1) $s = x/x_0$ represents a dimensionless transverse coordinate, x_0 is an arbitrary transverse scale, $\xi = z/(kx_0^2)$ is a normalized propagation distance (with respect to the Rayleigh range), and $k = 2\pi n/\lambda_0$ is the wave number of the optical wave. Equation (1) admits of the following Airy nondispersive solution:

$$E(s,\xi) = A[s - (\xi/2)^2]\exp[\mathrm{i}(s\xi/2) - \mathrm{i}(\xi^3/12)] . \tag{2}$$

It is clear that at the original position $\xi = 0$, the solution evolves into the known Airy wave $E(s,\xi = 0) = A(s)$. Equation (2) distinctly illustrates that the intensity profile of the Airy wave remains constant during propagation. Figure 1(a) depicts the diffraction-free and self-bending propagation of such an ideal Airy wave packet as a function of the distance ξ. From Eq. (2) we can conclude that the AB follows a parabolic trajectory in the $s-\xi$ plane and is reflected by the term $s - (\xi/2)^2$, which is depicted in Fig. 1(b). The acceleration dynamics can be clearly seen in Fig. 1(a), where the beam's parabolic trajectory becomes evident. This characteristic is rather interesting when it propagates in free space.

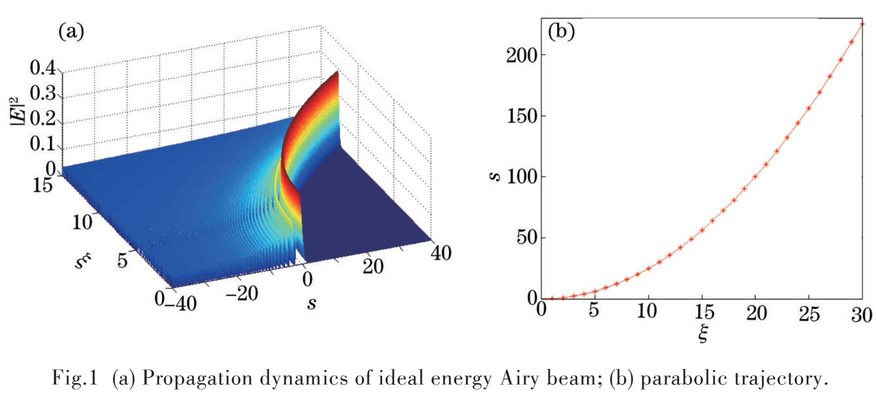

Fig.1 (a) Propagation dynamics of ideal energy Airy beam; (b) parabolic trajectory.

To demonstrate how to generate the tunable optical bottle beam by employing circular AB arrays, we begin by considering four 2D ABs as input beams, which can be expressed by:

$$A_{4-\mathrm{Airy}} = f(x)\cdot f(y) + f(-x)f(y) + f(x)f(-y) + f(-x)f(-y)\ , \tag{3}$$

$$G_{4-\mathrm{Gauss}} = g(x,y+d) + g(x,y-d) + g(x+d,y) + g(x-d,y)\ , \tag{4}$$

where $A_{4-\mathrm{Airy}}$ represents the superposition of four ABs. For comparison, Eq. (4) characterizes the superposition of four 2D GBs. $f(x)$ and $g(x,y)$ can be expressed as:

$$f(x) = A[(x+d)/b]\exp[(x+d)/b]\ , \tag{5}$$

$$g(x,y) = \exp[-(x^2+y^2)/b^2]\ , \tag{6}$$

where A denotes Airy function, d is the spacing distance between ABs, and b represents the beam size of main lobe of the AB. For the sake of simplicity, we omit the phase term and only keep the amplitude in Eqs. (5) and (6).

To simulate the superposition and propagation process and thereby obtain the optical field distribution for any propagation distance, $z-$ numerical simulations are performed based on angular spectrum propagation theory. The optical field distribution $E(x,y,z=0)$ can be written in terms of its angular plane wave spectrum $A(\xi,\eta)$ at the original plane z=0:

$$E(x,y,z=0) = \iint_{\infty} A(\xi,\eta)\exp[\mathrm{j}2\pi(x\xi + y\eta)]\mathrm{d}\xi\mathrm{d}\eta\ , \tag{7}$$

where (ξ,η) denotes the spatial frequency coordinates in the x and y directions at the Fourier plane, respectively, and $A(\xi,\eta) = F[E(x,y)]$. Here, $F[\cdot]$ refers to the Fourier transform. Therefore, the optical field distribution in any plane $z = z_i$ can be expressed as:

$$E(x,y,z=z_i) = \iint_{\infty} A(\xi,\eta)\exp[\mathrm{j}kz_i\sqrt{1-\lambda^2\xi^2-\lambda^2\eta^2}]\exp[\mathrm{j}2\pi(x\xi+y\eta)]\mathrm{d}\xi\mathrm{d}\eta\ . \tag{8}$$

To compare equally a generated optical bottle beam with the GB, we input the same intensity and provide the same parameters for GBs and ABs. Here, the input beam size b is set to 1.25 mm, and the spacing distance d is set to 2 mm. Figures 2 (a1) and (a2) demonstrate the original superposition intensity distribution of four ABs and four GBs, respectively. The output intensity distributions are displayed in Figs. 2(b1) and (b2) after a propagation distance of about 280 mm. The maximum superposition output intensity of the four ABs is increased to 3.89 times higher than input intensity. However, the maximum output intensity of the four GBs is as low as 1.15×10^{-5} times of input intensity with the same propagation distance. This clearly shows that the superposition efficiency of multiple ABs is much higher than that of multiple GBs.

There are two factors that contribute to this distinctly increased intensity: self- bending and diffraction- free characteristics. Because each AB propagates inward owing to the self-bending property, and the spacing distance between

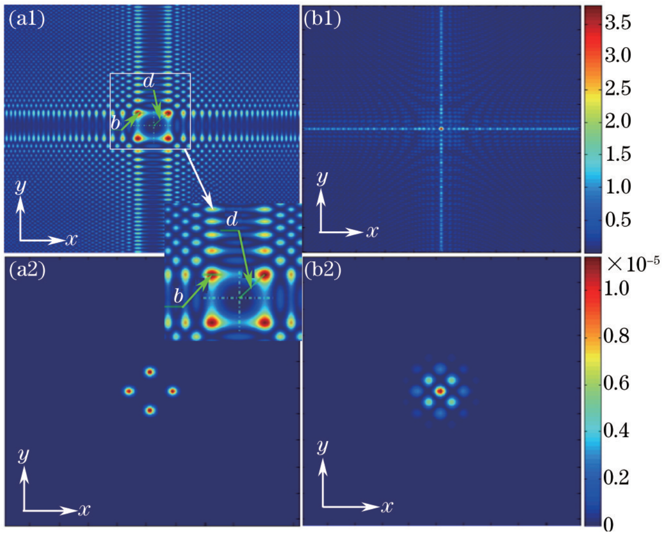

Fig.2 Cross-sectional intensity distribution of superposition beam in the xy plane. (a1) and (a2) show the input Airy beams (ABs) and Gaussian beams (GBs), respectively. (b1) and (b2) show the output intensity of ABs and GBs after a propagation distance of 280 mm

them becomes much smaller, eventually the synthetic beam becomes focused as each AB propagates forward. Moreover, ABs remain diffraction-free in propagation; as a result, the superposition intensity comes to be greatly improved.

3 Simulations and discussion

As can be seen from Fig. 2, four ABs cannot generate a relatively perfect optical bottle beam. To demonstrate the tunable ideal optical bottle beam and verify the expansibility of superposition of our proposed method, we investigated the superposition of sixteen ABs to generate a perfect optical bottle beam with the proposed method. The multiple ABs are uniformly distributed in a circle. The simulation results are presented in Fig. 3, for which the parameters of spacing distance and beam size are the same as those in Fig. 2. It is obvious that the optical bottle beam generated by sixteen ABs is extremely similar to that of four ABs. However, the difference is that the intensity of the sixteen-AB array displays a continuous and circular distribution, whereas the four-AB array shows a discrete distribution.

As shown in Fig. 3(c), the size of the optical bottle beam becomes increasingly smaller with the increasing propagation distance, as compared to Fig. 3(b). Eventually they evolve into a focused beam and generate the maximum intensity, as shown in Fig. 3(c). At this point, they continue to propagate independently and forward, and eventually diverge, as shown in Fig. 3(d). Compared to the optical bottle beam of the four- AB array, the output intensity is stronger and more concentrated, and increases by a factor of 49 at the same focal position compared to original input intensity. It should be noted that the multiple-AB array tends to focus automatically without any auxiliary components or equipment. The special merit will contribute to applications in the medical field, among others.

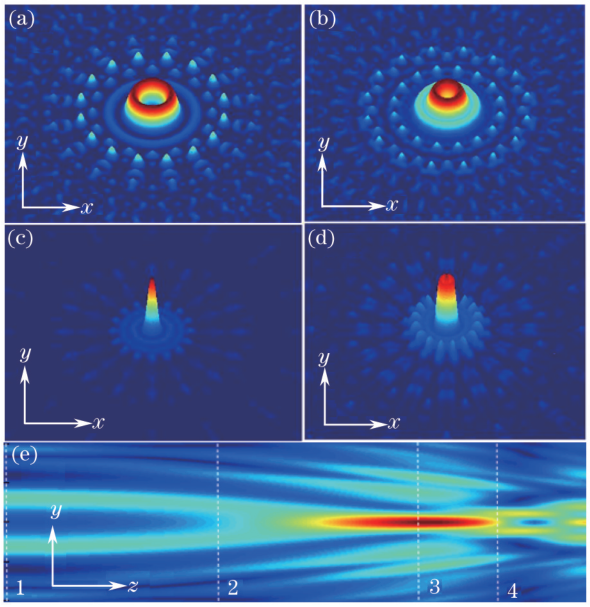

Fig.3 Intensity distribution of optical bottle generated by sixteen Airy beams (ABs) at (a) z=0, (b) z=190 mm, (c) z=280 mm, and (d) z=370 mm. (e) The evolution of the intensity distribution along the z direction. The cross-sectional intensities of positions 1~4 correspond to Figs.3 (a)~(d), respectively

As demonstrated in Figs.3(a) and (b), optical bottle beams are generated in the direction of propagation (i.e., the z direction)beams. One notable difference is that the diameters of optical bottle arrays are variable with different propagation distances. Figure 3(e) clearly shows the evolution of the intensity distribution at different propagation distances along the z direction. Different from the traditional single optical bottle beam, the optical bottle beams may provide multiple trapping and manipulation.

To manipulate atoms and cells easily, the size of the optical bottle often needs to be adjustable. In our proposed optical bottle beam, we can freely control the spacing distance d of AB arrays at the input plane in order to flexibly adjust the optical bottle size. To demonstrate the tunable optical bottle, ten ABs are considered as the original input beams. For comparison, different spacing distances d are assigned but with the same beam size (i.e., b=1.25 mm). The simulation results are shown in Fig. 4. We can achieve a smaller optical bottle in the input plane with a smaller spacing distance.

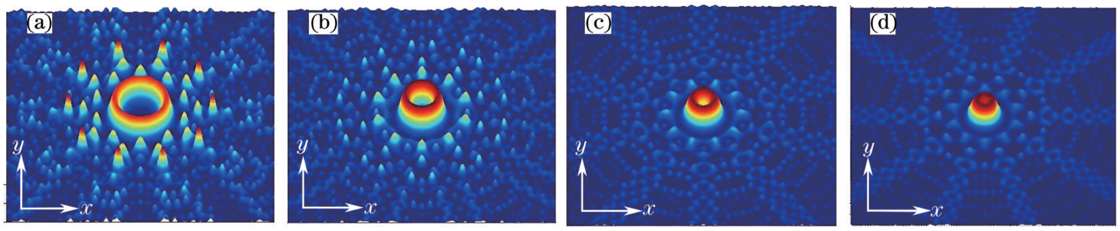

Fig.4 Intensity distribution of tunable optical bottle beam in the xy plane with different spacing distances. (a) d=4 mm, (b) d=2 mm, (c) d=1 mm, and (d) d=0.5 mm

In the meantime, if the spacing distance d becomes larger, the position of automatic focusing of the optical bottle becomes farther away from the input plane. Figure 5 demonstrates the intensity propagation with different spacing distances d. It can be seen that the larger spacing distance becomes, the farther the focused intensity is able to propagate. For instance, in Fig. 5(a) with d=1 mm, the focus is located 230 mm from the input plane; whereas in Fig. 5(b) with d=2 mm, the focus is located nearly 280 mm from the input plane.

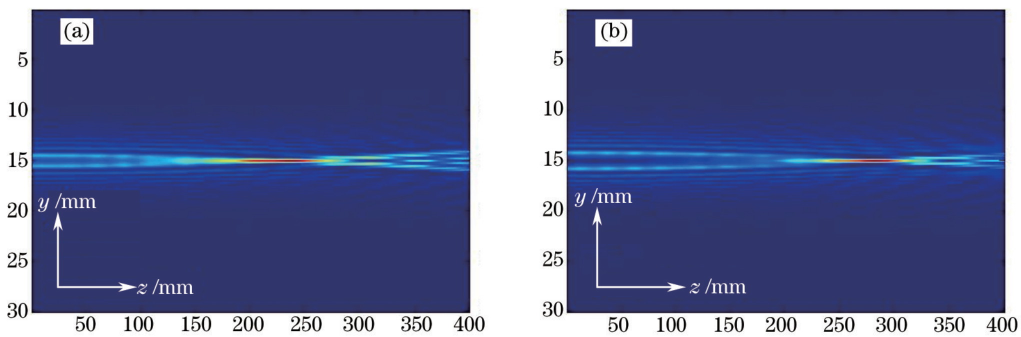

Fig.5 Intensity distribution of the focus of different spacing distances of four Airy beams (ABs) with b=1.25 mm. (a) d=1 mm, and (b) d=2 mm

4 Conclusions

In summary, we have discussed and theoretically analyzed tunable optical bottle beams generated by exploiting the self-bending characteristic of ABs. Their size can be flexibly controlled by changing the spacing distance of ABs at the input plane. Numerical simulations show that the proposed optical bottle beam can be acquired by superposing multiple ABs arranged in a circle. Moreover, as a result of coherently superposing multiple ABs, the intensity at the output plane is significantly increased compared to that of a conventional GB. It is believed that the intriguing characteristics of tunable optical bottle beams can give rise to novel techniques in medical treatments and atom manipulation. Next research is to trap atom by employing such optical bottle beams in our experiment.

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