Trapping and guiding microparticles with morphing autofocusing Airy beams

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Trapping aerosols with optical bottle arrays generated through a superposition of multiple Airy beams

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We experimentally demonstrate the generation of an array of optical bottle beams by employing multiple self-accelerating Airy beams. This kind of optical bottle array is created by superimposing eight Airy beams along a circle, all with inward acceleration directed towards the center. In addition, we demonstrate stable trapping of multiple absorbing glassy carbon particles using the proposedoptical bottle array.

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Optical bottle beams exhibit finite regions of low (or even zero) light intensity surrounded by regions of high intensity in all dimensions. In the past few years, various techniques have been proposed for generating such beams for applications in optical tweezers and atom traps[1−8]. More recently, bottle beams have been successfully used for trapping and manipulating absorbing particles through the so-called photophoretic force[3,5,8−10]. Photophoretic forces dominate over gradient forces that are typically exerted on transparent particles, as in optical tweezing experiments[11,12]. In such arrangements and under positive photophoretic forces, light-absorbing particles tend to move away from high intensity regions and become trapped in the "dark core" of the bottle beams. Most of the optical bottle beams studied thus far possess only one bottle structure, providing a single trap. To achieve multiple traps, speckle fields[13] and array of bottle beams (ABBs)[14] have been employed. In this letter, we report a novel method for generating ABBs with multiple self-accelerating Airy beams[15,16]; we also demonstrate their applications in trapping absorbing aerosols in air. Using split-step beam propagation methods (BPMs), the generation of ABBs with multiple Airy beams is numerically verified. By employing spatial light modulator (SLM) and computer synthesized phase structures, we experimentally generate the ABBs, and show that glassy carbon particles can be trapped stably in the array. Our scheme can be used in trapping absorbing particles under different configurations in air.

The principle behind generating ABBs using multiple Airy beams is illustrated in Fig. 1. As an example, eight airy beams were symmetrically arranged on a circle in the xy-plane, with the beam propagating along the z axis (Fig. 1(a)). In this configuration, the constituent Airy beams should accelerate towards the center as they propagate along the z axis, so that the combined intensity in the central region increases and eventually reaches a maximum when all beams approach each other. The BPM simulation results are shown in Figs. 1(b)–(h). As expected in an auto-focusing arrangement[17], the beam does not morph into a Bessel beam after the focal point and forms ABBs instead. This is illustrated in the side view intensity distribution in Fig. 1(b) and the transverse intensity patterns in Figs. 1(c)–(h), which are marked at positions 1–6 in Fig. 1(b), respectively, where low intensity cores are surrounded by three-dimensional (3D) high intensity regions. Clearly, several "closed" optical bottles are formed at planes 3 and 5, and more appear thereafter. Moreover, the bottle structures only exist in the central regions of the whole beam, eventually becoming blurry after a long enough distance of propagation (Fig. 1). We attribute the formation of these bottle structures to the intensity oscillations associated with Airy beams[18], reflecting a different mechanism compared with that in Ref. [14]. The beam behaves as an abruptly focusing beam prior to the formation of the first bottle[18] (Fig. 1). Therefore, our approach also features the advantages of abruptly focusing beams[18].

To generate the ABB illustrated in Fig. 1, we used the experiment setup sketched in Fig. 2, similar to what we used previously in generating paraxial and non-paraxial

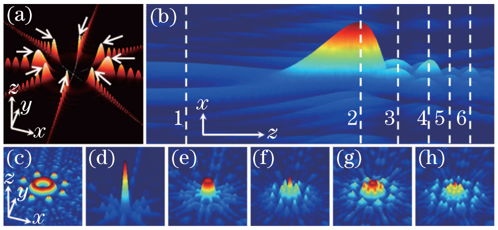

Fig. 1. (Color online) (a) Illustration of the generation of an array of optical bottle beams with eight Airy beams arranged symmetrically in a circle; (b) numerically simulated side-view of the propagation of the eight Airy beams as shown in (a); (c)–(h) snapshots of transverse intensity patterns of the beam at planes 1–6 marked in (b).

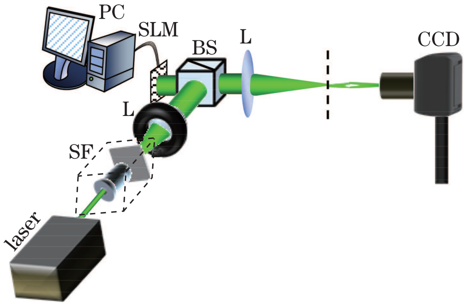

Fig. 2. (Color online) Schematic of experimental setup for generating an array of optical bottle beams. SF: spatial filter; L: Lens; PC: personal computer; BS: beam splitter.

accelerating beams[19,20]. Here, a thin green laser beam was properly filtered and expanded by a spatial filter and a lens, and then reflected by a computer-controlled SLM to a Fourier transform lens. The ABB was generated after the focal plane and then monitored by a CCD camera.

The phase structure on the mask was generated and reconfigured with the computer-controlled SLM, after which the beam transverse structure at different positions was monitored by moving the CCD camera back and forth. The ABB built from eight 1D Airy beams was generated through the phase mask shown in Fig. 3(a). The experimental results and the corresponding numerical results are shown in Figs. 3(b)–(d), where Fig. 3(b) displays the numerical longitudinal beam structure. Snapshots of the transverse intensity patterns at positions 1–6 and the corresponding experimental profiles are shown in Figs. 3(c1)–(c6) and Figs. 3(d1)–(d6). It is clear that an array of "closed-neck" bottle structures forms at positions 3 and 5, and additional bottles follow thereafter, thus representing an ABB. Therefore, the phase mask in Fig. 3(a) turns the Gaussian beam into a single beam with multiple fully closed bottle structures. Our experimental results agree well with the numerical simulations in all cases.

In the experiment, the shape and size of the bottles were varied by changing the phase mask or the focal length of the Fourier lens. For example, by making the distance among Airy beams larger (i.e., by altering the phase mask), the length of each optical bottle became shorter with respect to the width; with a Fourier lens with a shorter focal length, the bottle size became smaller. This can be easily understood as the Airy beam becoming smaller when using shorter focal length lens.

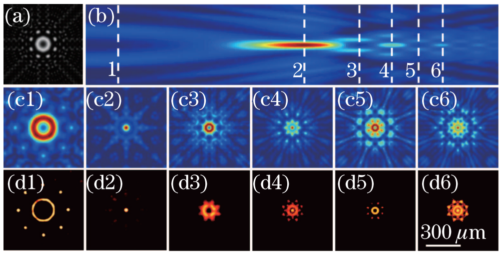

Fig. 3. (Color online) (a) Phase mask for generating eight Airy beams symmetrically arranged on a circle as shown in Fig. 1(a); (b) side-view of the beam propagation numerically retrieved from the phase mask (a); (c) snapshots of transverse intensity patterns of the beam at planes 1–6 marked in (b); (d) experimental results corresponding to (c).

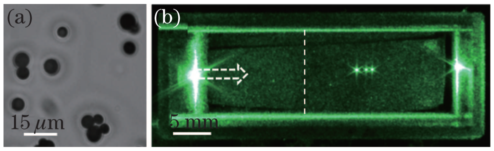

Fig. 4. (Color online) (a) Microscope image of the glassy carbon particles used for trapping; (b) top view photograph of trapped glassy carbon particles as light scatters from these particles; the dashed arrow marks the propagation direction of the bottle beams, and the dashed line marks the focal plane of the Fourier lens.

Recently, we have successfully trapped absorbing aerosols in air[8] using optical bottle beams generated through the Moiré technique[21,22]. In this letter, we demonstrate the application of ABBs for trapping absorbing aerosols into an array. In our experiment, spherical glassy carbon particles were used for trapping. The sizes of these particles ranged from 2 to 12 μm. A typical microscope image of such particles is shown in Fig. 4(a). In our experiment, an objective lens was placed at the focal plane (marked in Fig. 2) to obtain bottles with proper sizes. A glass cuvette was used to isolate particles from the influence of ambient perturbations. A plastic pipette was also used to spread glassy carbon particles around the generated optical bottles. These were done so as to trap multiple particles in an array (Fig. 4(b)).

The typical size of the bottle beams used in the trapping experiment was about 25 μm in diameter and 170 μm in length. By changing the experimental parameters, such as the distance among the Airy beams as well as the focal length of the Fourier lens and objective lens, the bottle size and the spacing between them can be varied with ease. Of course, the trapping is more stable when the bottle size is comparable with the particle size. Given that the bottle length is longer than the width of the ABB, the trapped particles sway back and forth in our experiments, and in some instances, more than one particle is trapped in one bottle. In addition, the particle trapped right after the focal plane (i.e., the first formed bottle) is the most stable one with the brightest scattering pattern (Fig. 4(b)). This is attributed to the fact that the first bottle has much higher intensity and better structure compared with the other bottles (Fig. 3).

In conclusion, we numerically and experimentally demonstrate the generation of arrays of optical bottle beams with juxtaposition of multiple Airy beams along a circle. We demonstrate that such beams can be employed for trapping and manipulating multiple absorbing particles. Our results may find applications in optical trapping and manipulation.

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