Manipulation of aerosols revolving in taper-ring optical traps

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We designed taper-ring optical traps by a weakly focused laser beam through a circular aperture. By railing-like potential barriers, these optical traps are partitioned into enclosed rings, in which irregular light-absorbing microparticles can be driven by photophoretic force to revolve around optical axis in air. The diameter of revolution can reach about 700 μm, which is much larger than that in traditional optical traps based on radiation pressure and gradient force. More importantly, multiple particles were driven to revolve simultaneously in different planes in air for the first reported time to the best of our knowledge. © 2013 Optical Society of America

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Since Ashkin and co-workers [1,2] realized the optical trapping of particles in 1986, optical tweezers technology has become an important tool for manipulating microscopic particles [3,4], living cells [5], nanoparticles [6], and atoms [7]. By using some optical tweezers with angular momentum, multiple particles have been manipulated and revolved simultaneously in regions with high light intensity in a plane perpendicular to the optical axis [8–12]. These optical tweezers utilize radiation pressure and gradient force to trap particles in high light intensity region. In order to fix the particles on a certain position of the optical axis, microscope objectives with a high numerical aperture are adopted to obtain the strongly focused laser beams. However, this method not only restricts the diameter of revolution under 100 μm but also makes it difficult to drive particles to revolve in different planes perpendicular to the optical axis [8–10].

Fortunately, a microscope objective with a high numerical aperture is not necessary in another optical trapping method utilizing photophoretic force that can trap light-absorbing particles in a low light intensity region [13–17]. Actually, illuminating a light-absorbing particle from one side by light in air generates a differential in surface temperature. The surrounding gas molecules rebound off the surface with different velocities and that generates a net pressure on the particle. This effect is known as photophoresis [18]. A rough comparison [19] between the photophoretic force \( F_{pp} \) acting upon a particle with zero thermal conductivity and the radiation pressure force \( F \), \( F_{pp}/F \approx 6 \times 10^{5} \), shows that photophoretic force is five orders of magnitude larger than pressure force at room temperature. Thus it is easier to trap and manipulate particles in air by utilizing photophoretic force.

To research the dynamics of aerosols, we designed an optical tweezers method utilizing photophoretic force. By a weakly focused laser beam through a circular aperture, the designed taper-ring optical traps can drive light-absorbing particles to revolve simultaneously with larger radii around the optical axis in different planes.

\[
u(r_1, z) = \frac{2\pi A \exp(jkz)}{j2z} \exp \left( \frac{jkr_1^2}{2z} \right) \int_0^R J_0 \left( \frac{2\pi rr_1}{Jz} \right) rdr, \tag{1}\]

where \( A \) is the amplitude of the incident beam, \( \lambda = 532 \) nm is the wavelength, \( f = 50 \) mm is the focal length of lens L3, \( R = 3 \) mm is the aperture radius, \( r \) is the distance between a point on the diffraction screen, and the origin of the coordinate system. In this simulation, the integral step, \( dr \), is 1 μm and the steps in the observation space are 1 μm (in the \( z \) direction) and 0.5 μm (in the \( r_1 \) direction).

The light intensity distribution by simulation is shown in Fig. 1(a). A single Gaussian 532 nm beam is expanded by lens L1 = 25 mm and lens L2 = 200 mm. Then it passes through circular aperture A with sharp edge (with a diameter of 6 mm) to form a diffraction field. Lens L3 = 50 mm abutting against aperture A is used to make the field weakly focused. Particles sprayed into a transparent glass box (2 cm × 2 cm × 5 cm) containing the focus of lens L3 will be captured by the optical field. Two groups of microscope systems are used to observe the particles suspending near the optical field in the box from the horizontal direction (microscope MO1, CCD1) and the vertical direction (microscope MO2, CCD2).

When simulating the light intensity distribution of the optical field, the incident light is simplified into a unit amplitude plane wave. The circular aperture center is defined as the origin of the coordinate system. The complex amplitude of the optical field can be expressed as
The areas of the two inclined faces of the particle are assumed as triangular prism [see Figs. 2(a) and 2(b)]. The areas of the two inclined faces of the particle are $S_1 = S_0/\sin \alpha$ and $S_2 = S_0/\sin \beta$. The photophoretic force perpendicular to the surface of a particle is proportional to light intensity $I$ [19]. Thus, the proportional relation photophoretic forces on the two faces can be written as $F_1 \propto IS_1 \cos \alpha$, $F_2 \propto IS_2 \cos \beta$. Then the resultant photophoretic force in the tangential direction ($T$ direction) of one circle is expressed as

$$F_T = F_1 \sin \alpha + F_2 \sin \beta \propto IS_0 (\cos \alpha - \cos \beta). \quad (2)$$

If $\alpha > \beta$, the particle will move upward [anticlockwise motion in Figs. 2(a)]; otherwise, it will move downward (clockwise motion).

When a particle is driven by the tangential photophoretic force to begin revolving in a ring, the opposite air resistance ($S$) will act upon it. The air resistance, Stokes’ drag, is expressed as $S = 6\pi\mu v = 6\pi\mu ar\omega$, where $\mu$ is the medium viscosity, $a$ is the radius of one particle, $v$ is the velocity of revolution, $r$ is the radius of revolution, and $\omega = 2\pi f$ is the angular frequency of revolution. The particle will accelerate until the increasing air resistance can balance the tangential photophoretic force, and then it will revolve with a certain speed due to $F_T = S$. Because of the proportional relation of $F_T \propto I$, the air resistance should have the same relation with the light intensity, $S \propto I$. Moreover, the relation between the air resistance and the angular frequency is $S \propto \omega(= 2\pi f)$. Consequently, the frequency $f$ is conjectured to be proportional to the light intensity $I$, i.e., $f \propto I$. 

If the trapped light-absorbing particles are irregular in shape, the photophoretic force will probably not be zero in the tangential direction. Thus, the particles will revolve along the rings and the centripetal force can be provided by the adjacent bright ring. The diameters of circular motion are equal to those of the corresponding dark enclosed rings.

To analyze qualitatively the circular motion of the irregular particles in the dark ring, the profile of the particles is assumed as triangular prism [see Figs. 2(a) and 2(b)]. The areas of the two inclined faces of the particle are $S_1 = S_0/\sin \alpha$ and $S_2 = S_0/\sin \beta$. The photophoretic force perpendicular to the surface of a particle is proportional to light intensity $I$ [19]. Thus, the proportional relation photophoretic forces on the two faces can be written as $F_1 \propto IS_1 \cos \alpha$, $F_2 \propto IS_2 \cos \beta$. Then the resultant photophoretic force in the tangential direction ($T$ direction) of one circle is expressed as

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In addition, according to the 3D light intensity distribution [see Fig. 1(c)], there are a lot of potential barriers (as marked by black dashed ellipses) with high intensity like railings in the passageways of the multilayer taper rings. These barriers can confine the particles to move only in the dark enclosed rings that are distributed in different planes perpendicular to the optical axis and have different diameters.

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To demonstrate that the optical tweezers can drive particles to revolve and control the revolution frequency by adjusting light intensity, the toner particles were employed in the experiments.

As common light-absorbing particles with average density about 2 g/cm³, the toner particles are irregular in shape with sizes varied from 1 to 15 μm, as shown in scan electronic microscope image [see inset in Fig. 3(a)]. When we sprayed them into the glass box, these particles across the optical field were trapped easily and some of them revolved steadily. A typical example of one particle revolving is presented in Figs. 3(a) and 3(b) (Media 1).

For controlling the revolution frequency of a particle as predicted in the above qualitative analysis, the beam power was changed periodically in the range of 65–100 mW [see Fig. 3(c)]. The images of the revolving particle were recorded by a high-speed camera with a frame frequency of 500 fps along the x axis. In these images, the positions of the particle on the y axis were traced to calculate the revolution frequency of the particle. The frequency varies synchronously with the light intensity, while the orbit of the revolution does not change. Figure 3(d) shows that the revolution frequency of the particle is approximately proportional to the beam power. It is consistent with the result of our qualitative analysis.

Because the frequency varies within the range of 16–31 Hz in the above experiment, the range of the air resistance can be evaluated, \( F = 6 \pi \mu a \omega r = (5.5–10.9) \times 10^{-12} \text{N} \), where \( a \) is assumed as 5 μm, \( \mu = 1.73 \times 10^{-6} \text{Nms}^{-2} \) for air at room temperature, \( r = 34 \mu \text{m} \), \( \omega = 2 \pi f = (0.995–1.96) \times 10^{2} \frac{\text{rad}}{\text{s}} \). The variation range of the centripetal force is \( F = m \omega r = (4/3 \pi \rho a^{2} \omega r = 0.35 \times 10^{-12}–1.37 \times 10^{-12} \text{N} \), where the average density of the toner particles is \( \rho = 2.0 \times 10^{3} \text{kg/m}^{3} \). Both the centripetal force and the air resistance are in the range of pN. The centripetal force can be balanced by the radial component of the photophoretic force and the air resistance can be balanced by the tangential component.

Theoretically, the region closer to the focus of Lens L3 has higher light intensity. Thus the photophoretic force is stronger, and then the particle in this region can revolve with a higher frequency. The revolution frequency of a particle close to the focus reached 300 Hz with a beam power of 150 mW. If the light intensity is low enough, one particle can revolve with a low frequency in air and even be stopped or restarted by adjusting beam power.

As shown in Fig. 1(c), a lot of dark enclosed rings are distributed in different planes perpendicular to the optical axis so that the trapped toner particles can be driven to revolve simultaneously in different planes. Furthermore, the flexible three-dimensional manipulation of these revolving multiple particles can be achieved by moving lens L3. A typical experimental demonstration of moving revolving multiple particles along the x axis is presented in Fig. 4.

Figures 4(a)–4(c) are vertical views of the moving process observed by the microscopic imaging system (MO2, CCD2). The revolution trajectories of the particles are marked by white ellipses and can be observed more clearly from Media 2. In order to discern the moving direction of the particles more clearly, we use another microscopic imaging system (MO1, CCD1) to observe the changing of the images from the x direction [see Figs. 4(d)–4(f)]. The orbits of the particles change little during the moving process in these figures. Thus the moving direction of the revolving particles is consistent with that of lens L3. The images of the particles are blurred [Fig. 4(d)], when the particles are away from the focus plane of the microscope MO1 [Fig. 4(a)]. And then it will turn clear [Fig. 4(e)] when the particles come close to the focus plane [Fig. 4(b)]. Moreover, we also realized the
movement along the z axis and y axis by moving lens L3, which was fixed on a three-dimensional mobile platform.

As shown in Fig. 1(c), the dark rings have different diameters so that the light-absorbing particles can revolve simultaneously with different diameters. The particles may revolve with bigger diameters in the region further to the focus of Lens L3 because the diameters of the rings are several hundred micrometers or several millimeters.

We demonstrated that the largest diameter of revolution reached 700 μm (see Fig. 5 and Media 3), which is much larger than that in traditional optical traps based on radiation pressure and gradient force. The two particles in Media 3 revolve in opposite directions because the directions of the tangential component of the photophoretic forces on the particles are opposite.

In conclusion, we design the optical traps with multi-layer taper rings to drive the irregular light-absorbing particles to revolve in air. The revolution frequency can be controlled by adjusting light intensity. The diameter of revolution can be much larger than that in the traditional optical traps utilizing the radiation pressure and the gradient force. The optical tweezers method has important significance for researching the dynamic characteristics of aerosols, which contribute to the atmosphere greenhouse effect [3,20,21].

Moreover, because a lot of dark enclosed rings are distributed in different planes perpendicular to the optical axis, the method can not only make multiple particles rotate simultaneously in different planes but also realize the flexible three-dimensional movement of these particles rotating simultaneously. The outstanding ability may find wide applications in optical, engineering, biological, and atmospheric sciences.

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References
18. F. Ehrenhaft, Phys. Z. 18, 352 (1917).