Photophoretic trapping of multiple particles in tapered-ring optical field

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Abstract: We demonstrate the photophoretic trapping of more than several hundreds of absorbing particles by tapered-ring optical traps diffracted from a circular aperture. The experiments with different laser powers show the influence of air flow acting on particles. Three kinds of particles with different densities (about 1~7 g/cm$^3$) and different shapes (spherical, non-spherical) can be trapped. The non-spherical particles (toner particles) disperse in optical field, while the spherical particles (ink droplets and iron particles) arrange as a straight line. More importantly, in the experiments of two counter-propagating tapered-ring beams, the agglomeration of particles is achieved and can help research the dynamics of aerosols.

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References and links

1. Introduction

Since the optical manipulation of particles was realized by Ashkin [1] about 40 years ago, it has been applied widely in biology [2–4], physics [5,6] and material science [7–9]. The best-known example of optical manipulation is trapping and manipulating transparent particles by radiation force [1,10,11]. However, for a light-absorbing particle, the photophoretic force on it is 10^4 times larger than radiation force [12]. It means that the radiation force can be hid by photophoretic force. It is hard for absorbing particles to be manipulated just by radiation force. Fortunately, it has been demonstrated that the photophoretic force can be used to trap and manipulate light-absorbing particles in recent experiments [13–21]. For example, carbon nanoclusters in air can be transported by a dual-vortex optical trap [13]. A single Gaussian beam formed inside the focal volume of a lens with a controlled amount of spherical aberration has been identified that it contains multiple dark traps and can capture airborne absorbing particles [14]. The volume speckle field is used for selective trapping of a few thousand carbon nanoclusters in air [20].

In our previous experiments, a weakly focused beam with tapered-ring optical traps [15] diffracted from a circular aperture was designed to make irregular absorbing particles revolve around optical axis. The laser power is about 50–100 mW. On that condition, the air current with a low speed has weak impact on the particles so that the irregular particles can be driven by tangential photophoretic force to revolve steadily.

In this paper, we demonstrate that the tapered-ring optical traps with high laser power (more than 100 mW) can capture more than several hundreds of absorbing particles due to a large number of enclosed dark traps distributed in the optical field. This method provides a novel idea for the optical manipulation of a large number of airborne particles.

Rising and descending of many absorbing particles with different laser powers showed the marked influence of air flow acting on particles. The particles with different densities (about 1–7 g/cm^3) and different shapes (spherical, non-spherical) could all be optically trapped. More importantly, we institute a two counter-propagating tapered-ring beams system. The agglomeration of particles is achieved and can greatly help research the dynamics of aerosols in air in the future.

2. Simulation and measurement of an optical field

In the simulation of a tapered-ring optical field, the incident beam is supposed as a unit amplitude (A = 1) plane wave with \( \lambda = 532 \) nm. As shown in Fig. 1(a), the beam passes through both a circular aperture of R = 3 mm diameter and a converging lens of focal distance \( f = 50 \) mm. A weakly focused optical field forms behind the converging lens. The center of the circular aperture is defined as the origin of the coordinate system. Z axis is parallel to the incident beam. The distance between the converging lens and the circular aperture is very small and can be neglected. The axisymmetrical intensity of the optical field can be given by (derived from the complex amplitude in Ref [15]. (formula (1)))
where \( r \) is the distance between a point on the diffraction screen and the origin of the coordinate system. The simulated light intensity is shown in Figs. 1(b) and 1(c).

\[
I(r, z) = \frac{4\pi^2 A^2}{\lambda^2 z^2} \left[ r^2 \exp \left( \frac{jkr^2}{2} \left( \frac{1}{z} - \frac{1}{f} \right) \right) \right] \left( \frac{2\pi rr}{\lambda z} \right) r dr
\]

(1)

As shown in Fig. 1(b) which shows the 2D light intensity distribution in the y-z plane (x = 0) [15], there are a lot of weakly focused dark stripes distributed in the 2D optical field. Because the optical field is axisymmetric in three-dimensional space, these stripes form multi-layers tapered traps in 3D optical field. Moreover, as shown in Fig. 1(e), a lot of potential barriers (as marked by black dashed ellipses) with high intensity like railings distribute in the passageways of multilayer tapered traps. These barriers separate the tapered traps into a lot of enclosed dark rings.

Figures 1(c) and 1(d) show the simulated and measured light intensity distribution of one transverse section (z = 48.7 mm). Obviously, the results of experiment and simulation are consistent with each other. The width of each dark ring is about 5~10 micrometers. The particles whose diameters match the dark rings can be captured into these enclosed dark traps when the particles enter the optical field.

3. Reducing laser power

To demonstrate that the novel optical traps can capture a large number of light-absorbing particles, we institute the setup as shown in Fig. 2(a). The initial 532nm laser beam waist is about 2 mm and its diameter on the aperture is expanded to about 16 mm. The toner particle, a common light-absorbing particle with the average density about 2 g/cm\(^3\) and the diameter 5~10 \(\mu\)m, is chosen as the sample to be trapped.
When laser power is larger than 200 mW, the toner particles are trapped quickly near the upper part of optical field once they are sprayed into the transparent glass cuvette (2cm × 2cm × 5 cm) as shown in Fig. 2(b1). That is because the air in cuvette absorbs the heat emanated by trapped particles. These particles absorb light and their temperatures increase. Then, the heat is transferred from the particles into air and causes the increasing of the air temperature. The heated air flows upward and produces upward Stokes’ drag on the toner particles in optical traps. Stokes’ drag is \( S = 6\pi \mu a v \), \( \mu \) is the air viscosity, \( a \) is the radius of a particle, \( v \) is the relative velocity between air and a particle. In the experiments, some non-trapped particles are lightened when they float across the optical field. We find out the trajectories of these particles by analyzing the recorded pictures and measured the displacement per unit of time. By this method, when the laser power is 200 mW (Fig. 2(b1)), the velocities of 20 toner particles are calculated. To avoid overestimating air velocity, the smallest one (12 mm/s) of the 20 velocities is chosen as the air velocity. Actually, the upward air velocity is larger than the particle’s velocity because air needs to overcome particle’s gravity if it can drive the particle to rise. The upward Stokes’ drag on a particle with the radius 5 \( \mu \)m will be \( S = 6\pi \mu a v = 1.96 \times 10^{-11} N \), where \( \mu = 1.73 \times 10^{-5} Nsm^{-2} \). The gravity of the particle is about
\[ mg = (2.0 \times 10^3) \times 4 / 3 \times \pi \times (5 \times 10^{-8})^3 \times 9.8 = 1.02 \times 10^{-11} N \], where the average density of the toner particles is \( \rho = 2.0 \times 10^3 kg / m^3 \). The Stokes’ drag is larger than the gravity (as analyzed in Fig. 2(c1)) so that the particles are pushed up near the upper part of the optical field.

When the laser power is reduced, the temperature of air decreases and then the velocity of air slows down. As shown in Fig. 2(c2), the particles fall down from the upper part to the lower part because the upward Stokes’ drag decreases that can’t offset the gravity ‘G’ and the photophoretic force ‘ \( P_r \)’. In Fig. 2(b1), with a laser power of 200 mW, almost all of the particles are fixed in the upper part of the optical field (above the white horizontal reference line) and just a few particles are fixed in the lower part (under the reference line). When laser power is reduced, the particles fall down slowly. As shown in Fig. 2(b2), when laser power is reduced to 160 mW, there are about 25 particles falling into the lower part. When laser power is reduced to 80 mW (Fig. 2(b4)), there are only a few particles on the upper part of the optical field. The particles’ images become blurry from Fig. 2(b1) to Fig. 2(b4) due to the decrease of scatter light from trapped particles when the light intensity decreases.

4. Dynamic behavior of particles with low laser power

The number of trapped particles in the optical field is proportional to laser power because the photophoretic force is proportional to the light intensity. When laser power is low, the number of trapped particles is small. Moreover, the particles far from the focus start to bounce slightly.

We measured and analyzed the dynamic behavior of trapped particles in the optical field with a low laser power of 30 mW. The light intensity far from the focus is low and the photophoretic force on particles is weak. The impact of air turbulence is relatively strong. Therefore, under air turbulence, only a few particles can be trapped. After about 20 seconds, air turbulence weakens and then more and more particles drifting across the optical field could be trapped easily.

![Fig. 3. (Media 2) Horizontal views of the moving process of particles. The particles move up gradually into the upper part of optical field.](image)

Figure 3 shows the changing of particles’ positions after the particles are sprayed into the optical field. In Fig. 3(a), some particles are captured in the lower part of optical field after 20 seconds. As time goes on, under irradiation of the laser beam, the temperature of surrounding air increases and the upward Stokes’ drag becomes stronger. Almost all the particles surrounded by a white ellipse move up into the upper part of optical field under Stokes’ drag.

5. Trapping of different particles

Figure 4 shows the distribution of different kinds of particles observed simultaneously from both horizontal direction (Figs. 4(a1), 4(b1) and 4(c1)) and vertical direction (Figs. 4(a2), 4(b2) and 4(c2)) with the laser power higher than 400 mW. Figures 4(a1) and 4(a2) show the black toner particles captured by tapered optical traps. Figures 4(b1) and 4(b2) show the trapped spherical black ink droplets with the density about 1 g/cm³ and the diameter 1~2 μm. Figures 4(c1) and 4(c2) show the spherical iron particles with the density about 7 g/cm³ and...
the diameter 5 μm. The above experiments show the optical field’s ability of trapping different kinds of particles. However, their distribution characteristics are quite different. Almost all the particles are captured in the upper part of optical field (see Figs. 4(a1), 4(b1) and 4(c1)). Observed from vertical direction, the toner particles disperse in the optical field as shown in Fig. 4(a2). In contrast, the trapped black ink droplets and iron particles arrange as a straight line above optical axis (see Figs. 4(b2) and 4(c2)).

![Fig. 4. (a) - (c): Distribution of three kinds of particles in tapered-ring traps. The left pictures show the results observed from horizontal direction. The right pictures show the results observed simultaneously from vertical direction. (a1) and (a2) show the distribution of toner particles in the optical field. (b1) and (b2) show the distribution of black ink droplets. (c1) and (c2) show the distribution of iron micro-particle. (d) The image of toner particles under the electron microscope. (e) Analysis of the forces acting on trapped toner particles. (f) The image of iron particles under the electron microscope. (g) Analysis of the forces acting on iron particles.](image)

We made an analysis (see Figs. 4(e) and 4(g)) for the different distribution characteristics of ink droplets, iron particles and toner particles in the tapered optical traps.

As shown in Fig. 4(e), although the upward Stokes’ drag ($S$) is stronger than the downward gravity ($G$), the photophoretic force ($P$) composed of $P_T$ (tangential component) and $P_R$ (radial component) on toner particles is asymmetry and usually has the tangential component ($P_T$) because the shape of toner particle is not spherical [15]. Under the tangential component of photophoretic force, the toner particles deviate easily from the medial surface of optical field (see Fig. 4(a2)). The velocity of air in Fig. 4(a) is about 40mm/s, the upward Stokes’ drag on a toner particle with the average radius $a = 5 \, \mu m$ is $S = 6\pi \mu a v = 6.5 \times 10^{-11} \, N$.

The gravity is $mg = \frac{4}{3} \pi a^3 \rho = 1.0 \times 10^{-11} \, N$, where $\rho = 2.0 \times 10^1 \, kg / m^3$. In Fig. 4(e), the angle $\theta_i$ is any angle between 0° and 90°. $P_T$ and $P_R$ can be given by $P_R = (S-G) \cos \theta_i$ and $P_T = (S-G) \sin \theta_i$. 0°, 30°, 60° and 90° are chosen as the four representative angles so that we can get a series of $P_T$ and $P_R$ as shown in Table 1.

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_R$</td>
<td>5.5 $\times 10^{-11}$ N</td>
<td>4.8 $\times 10^{-11}$ N</td>
<td>2.8 $\times 10^{-11}$ N</td>
<td>0</td>
</tr>
<tr>
<td>$P_T$</td>
<td>0</td>
<td>2.8 $\times 10^{-11}$ N</td>
<td>4.8 $\times 10^{-11}$ N</td>
<td>5.5 $\times 10^{-11}$ N</td>
</tr>
</tbody>
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In contrast, the shapes of iron particle and ink droplet are both spherical. Moreover, the optical field is axisymmetric so that the photophoretic force on them is symmetry (see Fig. 4(e)) and has not the tangential component (only having the radial component ($P_T$)). The direction of Stokes’ drag ($S$) is upward so that the spherical particles (iron particles and ink droplets) can be pushed up to the upper part of optical field and arrange in a straight line.

Therefore, for ink droplet and iron particle, $P=\dot{P}_R=(S-G)\cos 0^\circ=S-G$ and $P_T=0$. In Fig. 4(b), the measured velocity ($v$) of air current is about 35 mm/s, the upward Stokes’ drag on a ink droplet with the radius $a = 0.75$ μm will be $S = 6\pi \mu a v = 8.56 \times 10^{-12} N$. The gravity of the ink droplet is $mg = \frac{4}{3} \pi \rho a^3 g = 1.73 \times 10^{-14} N$, where $\rho = 1.0 \times 10^3 kg / m^3$. The photophoretic force can be express as $P = \dot{P}_R = S-G = 8.54 \times 10^{-12} N$, $\dot{P}_T = 0$. In Fig. 4(c), the measured velocity ($v$) of air current is about 20 mm/s, the upward Stokes’ drag on a iron particle with the radius $a = 2.5$ μm will be $S = 6\pi \mu a v = 1.63 \times 10^{-11} N$. The gravity of the iron particle is $mg = \frac{4}{3} \pi \rho a^3 g = 4.49 \times 10^{-12} N$, where $\rho = 7.0 \times 10^3 kg / m^3$. The photophoretic force can be express as $P = \dot{P}_R = S-G = 1.18 \times 10^{-11} N$, $\dot{P}_T = 0$.

6. Dual-beam system

Based on the above single beam with tapered optical traps, a dual-beam optical traps system is instituted as presented in Fig. 5(a). The counter-propagating beams radiate absorbing particles and generate counter axial photophoretic forces on particles. The particles in optical field are pushed into the junction region of two beams and agglomerate to form micelles.

When the toner particles are sprayed into the glass cuvette and pass through the optical field, they gather gradually in the junction region of two beams by photophoretic force (see Figs. 5(b1)-5(b4)), and then agglomerate into micelles. It’s easy for about 10-20 particles to agglomerate together. After agglomerating in the junction region, the particles will move as a whole if air turbulence happens.

Dozens of experiments are conducted and some micelles often rotate in the dual-beam junction region in almost every experiment. They can keep rotating until outer particles enter the junction region and disturb them heavily. As shown in Fig. 5(c), a micelle composed of more than three particles is rotating clockwise. Its characteristic length is about 25 μm, rotating frequency is 8 Hz and radius of rotation is about 12 μm.

Moreover, a particle revolves anticlockwise around a micelle composed of about ten particles as shown in the latter part of Media 3. The revolving frequency is about 0.5Hz, and the revolving track is not circular, but elliptic, semi-major axis of which reaches 60 microns. The particle revolves stably though the tract is not a circular.

The rotation of the particles or micelles in the junction region is probably caused by the coupling of the photophoretic force with aerodynamic convection.
7. Conclusion

We demonstrate a novel approach for photophoretic trapping of more than several hundreds of absorbing particles by tapered-ring optical traps with micrometer-size dark rings diffracted from a circular aperture.

The experiments with different laser powers show the influence of air flow acting on particles. By changing laser power, we find that, under neither low power nor high power, the heating effect of the laser beam on air cannot be ignored. Therefore, the Stokes’ drag on particles can produce a demonstrable effect on the distribution of trapped particles.

The absorbing particles (toner particle, ink droplet and iron particle) with different densities and different shapes can be trapped. The toner particles disperse in optical field, while the black ink droplets and iron particles are arranged as a straight line above optical axis. Their distribution characteristics are different because the photophoretic forces on particles with different shapes have different directions.

The agglomeration of particles is an important direction in the study of aerosols. A counter-propagating beams system is designed to form the junction region, which can make trapped particles agglomerate under the combined effect of dual beams. It allows us to observe the entire process of agglomeration and analysis the dynamic behavior of micelles in real-time. This method provides a novel way for the study of aerosols’ agglomeration which can be important for greenhouse effect, atmosphere environment [22, 23] and even interstellar dusty plasmas.

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