Observation of trapping and transporting air-borne absorbing particles with a single optical beam

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Abstract: We demonstrate optical trapping and manipulation of micron-sized absorbing air-borne particles with a single focused Gaussian beam. Transportation of trapped nonspherical particles from one beam to another is realized, and the underlying mechanism for the trapping is discussed by considering the combined action of several forces. By employing a specially-designed optical bottle beam, we observe stable trapping and optical transportation of light-absorbing particles from one container to another that is less susceptible to ambient perturbation.

OCIS codes: (350.4855) Optical tweezers or optical manipulation; (010.1030) Absorption; (010.1110) Aerosols; (290.5850) Scattering, particles.

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1. Introduction

Optical trapping and manipulation (OTM) has been of strong interest since the early pioneering work of Ashkin and associates [1–3]. Loosely speaking, there are two approaches for OTM of micron- or nano-sized particles: one is based on the radiation pressure and gradient force for trapping transparent or low-absorbing particles as in the case of optical tweezers; and the other is based on the so-called "photophoretic force" for trapping high-absorbing particles as demonstrated recently in a number of experiments [4–7]. Under the influence of the gradient force, non-absorbing particles with positive polarizabilities tend to be attracted into the high intensity region of a Gaussian beam, whereas the radiation pressure pushes them along the beam propagation direction. In a single-beam gradient force optical trap established with a tightly focused Gaussian beam [2], the gradient force right after the focal point not only attracted the dielectric particles to the center of the beam, but also balanced the radiation force along the direction of beam propagation. On the other hand, the mechanism for trapping high-absorbing particles is quite different. Under the action of the photophoretic force, absorbing particles tend to move away (for positive photophoresis) from the high intensity region of a laser beam. For this reason, for decades it was considered that a single Gaussian beam cannot trap or guide absorbing particles. Nevertheless, many efforts have been put into optical manipulation of absorbing particles, as typically the photophoretic force can be orders of magnitude larger than the scattering and gradient force. For example, Lewittes and associates reported optical levitation of absorbing particles by a single TEM_{01} Gaussian beam [8], in which the low intensity region of the laser mode kept the particles in the beam center while the upward radiation force was balanced by the gravity. Later on, it was found that even a TEM_{00} laser beam could be used also for optical levitation of absorbing particles [9,10]. Although there has been a great deal of research in photophoresis and related phenomena over the years [11–17], in many cases the mechanisms for optical levitation and OTM of absorbing particles remained elusive.

Recently, a number of experiments have demonstrated the possibility not only to trap but also to transport light-absorbing micron-sized particles in air by the photophoretic force. Such manipulation relies on the design and generation of optical bottle beams (i.e., beams containing regions of low or zero intensity surrounded by regions of high intensity), either by superposition and reshaping of the optical vortex beams [4–6] or by employing the Moiré techniques with a spatial light modulator [7]. Quite recently, stable trapping and manipulation of air-borne particles was achieved with a single Gaussian laser beam containing multiple "dark traps" resulting from spherical aberration [18]. Yet in another demonstration, air-borne particles were trapped by optical bottle beams formed from superposition of two coaxial conical beams, where single-particle Raman spectra were successfully measured [19].

In this paper, we demonstrate experimentally that optical trapping of absorbing particles in air can be established with a single focused Gaussian beam without the need of specially-designed optical bottle structures [4–7] or gravity-assisted balance [8–10]. We show that the trapping is quite stable inside a glass cuvette, and the trapped particles can be translated either by moving the focusing lens or changing the laser beam power. Furthermore, by using two crossly launched Gaussian beams, we demonstrate the switching of trapped particles from one beam to another at the beam intersection. We explain intuitively the trapping mechanism by considering both the scattering forces and two types of photophoretic forces - one resulting

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from temperature gradient $F_{\Delta T}$ and the other resulting from different thermal accommodation coefficient $F_{\Delta\alpha}$. In addition, by using a fully closed optical bottle beam designed recently [20], we demonstrate stable trapping and transportation of absorbing particles from one container to another without losing them due to ambient fluctuations while exposed in air.

2. Experimental results

Our experiments were carried out with a TEM_{00} Gaussian beam from a Coherent Verdi laser operating at 532nm. Our initial motivation was to trap absorbing air-borne particles by optical bottle beams designed with the assistance of a spatial light modulator (SLM) [7], but we found that absorbing particles such as carbon and silicon particles could be readily trapped by a focused Gaussian beam without the need of any special beam engineering. Importantly, we found that spherical particles cannot be stably trapped as compared to nonspherical particles. Once a particle is trapped, its position can be altered by changing either the laser power or the focusing condition of the beam. When the beam is loosely focused, the particles cannot be stably trapped, but rather driven by the laser beam and move in the direction of beam propagation. As shown in the media file (Media 1), besides the trapped particle pushed forward by the radiation pressure and photophoretic force, there are other noticeable particles moving around the light channel - some move towards the laser source while others move away from the laser source.

Typical experimental results are shown in Fig. 1. With a focused Gaussian beam, we observed that the multi-particles can be trapped both before and after the focal point, as seen in Figs. 1(a, b). For this experiment, absorbing silicon particles of 5-20 µm sizes are used. The laser output power is about 1 Watt, and its beam diameter at the focal point is about 60 µm. A series of experiments shows that the silicon particles can be trapped easily, but the trapping is not very stable and is susceptible to ambient perturbations. It seems that the particles trapped after the focal point are more stable than those trapped before the focal point. Indeed, as the trapped particles were moved out of the glass cuvette (by either moving the glass cuvette or the focused beam), only a few particles trapped after the focal point could remain in the trap [Fig. 1(b)]. By observing trapped particles under microscope, we found that the stably trapped

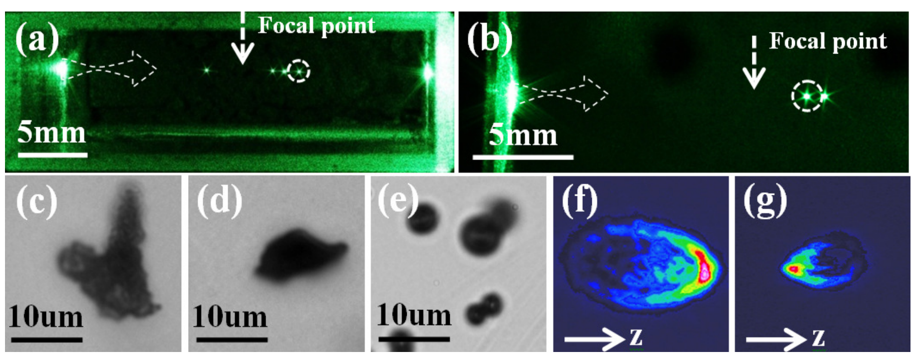

Fig. 1. Trapping of silicon particles by a single focused Gaussian beam. (a) Multi-particles trapped before and after the focal point inside a glass cuvette; (b) A few particles remained in the trap when they were moved out of the cuvette; (c, d) Microscopic image of trapped non-spherical silicon particles; (e) Unstably trapped glassy carbon spherical particles; (f, g) Side-view photographs of scattered light patterns from particles before and after the focal point. In (a, b), dashed circle marks the position of a trapped particle, vertical arrow marks the location of focal point, and dashed horizontal arrow illustrates the input direction and focusing condition of the laser beam. The white arrow s in (f, g) denote the propagation direction of the laser beam. When the beam is loosely focused, the particles cannot be stably trapped but rather driven by the laser beam and move in the direction of beam propagation as shown in the media file (Media 1).

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silicon particles are very irregular and highly nonspherical [Figs. 1(c)-1(d)]. In fact, we also tried other absorbing particles such as graphite and carbon particles, and found that these irregular particles could be trapped while the spherical glassy carbon particles as shown in Fig. 1(e) could not be trapped stably even for a few seconds. Side-view pictures of the near-field scattering light patterns around the trapped nonspherical particles are shown in Figs. 1(f)-1(g). Clearly, the scattering intensity distributions are distinctly different for particles trapped before and after the focal point. For the particles trapped right after focal point, the front surface scatters much more than does the back surface; however for the particles trapped before focal point, the situation is reversed. Such different scattering intensity distribution might cause both the radiation pressure and the photophoretic forces to point towards different directions for the particles at different locations before or after the focal point.

Although the photophoretic force in our experiment might be orders of magnitude larger than the radiation force [6], the latter force may still play a nontrivial role in stabilizing the particle trapping. For these considerations, we gradually increased the laser power from 0.2 Watts to 1.2 Watts after four particles were trapped, one located before the focal point and the other three after the focal point. As shown in Figs. 2(a)-2(b) and Media 2, the trapped particles stay closer to the focal point at lower power, but move further away as the power is increased. Such power-dependent positioning suggests that the trapping mechanism should not be due to the presence of intensity minima as argued in [9] and [10]. Furthermore, we did a series of experiments by keeping the laser output power constant but varying the laser intensity gradient. We found that the particles stay closer to the focal point at a larger intensity gradient (stronger focusing), but move further away from the focal point at a smaller intensity gradient, as depicted in Figs. 2(c)-2(d) and Media 3. It can be seen from Figs. 1 and 2 that the dynamics of particle trapping not only depends on the laser beam properties (power and intensity gradient), but also on the particle properties (size and shape).

As an example of possible applications of the single Gaussian beam trapping technique, we show our experimental demonstration of trapped particles transporting between two laser beams. First, a silicon particle is trapped by a vertically-oriented focused laser beam, as illustrated in Fig. 3(a). Then, another focused laser beam is aimed onto the particle from the horizontal direction. By translating this second beam laterally, the trapped particle can be moved back and forth along the vertical beam path. At some point, the particle breaks away from the binding potential of the first beam, and moves into the second beam as shown in Fig. 3(b). Of course, the first beam can take the trapped particle back from the second beam, and in fact, the particle can be switched back and forth between the two beams as shown in Media 4. Such optical transportation of particles between two Gaussian beams may find various applications in optical manipulation of micro-particles.

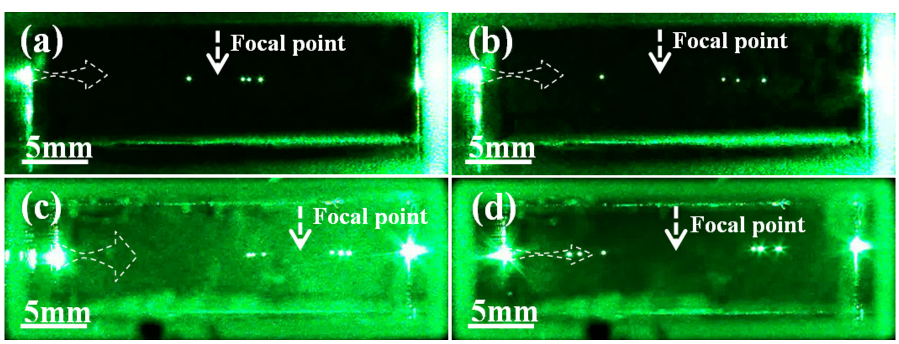

Fig. 2. (a, b) Laser-power-dependent particle trapping at (a) 0.2 Watts and (b) 1.2 Watts when other conditions unchanged (Media 2); (c, d) Intensity-gradient-dependent particle trapping when the laser beam is (c) strongly focused and (d) weakly focused (Media 3). The vertical arrow marks the location of the focal point and the horizontal arrow illustrates the orientation and shape of the trapping beam.

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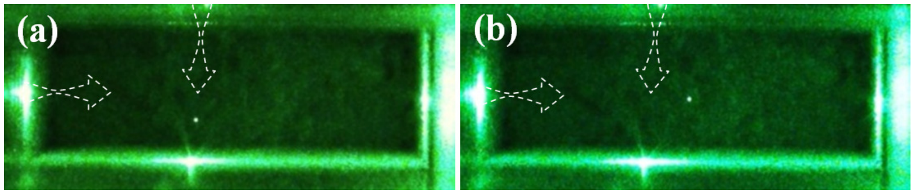

Fig. 3. Particles transportation between two orthogonally oriented Gaussian beams, Media 4. (a) A particle is trapped first by the vertical beam; (b) The particle is taken by the horizontal beam. The dashed arrows illustrate the orientation and shape of the trapping beams.

3. Intuitive explanation

To understand the mechanism behind such particle trapping, it is necessary to review some properties of the photophoretic forces resulting from momentum transfer between particles and surrounding gas molecules. It has been proposed that there are two types of photophoretic forces: one resulting from a temperature gradient $F_{\Delta T}$ and the other resulting from a different thermal accommodation coefficient $F_{\Delta\alpha}$ [11,13]. Absorbing particles illuminated by light may have a nonuniform temperature distribution. Thus, gas molecules with the same average velocity incident onto different part of particles will rebound off with different velocities, resulting in a net force pointing to a direction, say, from the hot side to cold side. As in the case of thermophoresis [21], photophoresis can be either positive or negative. The magnitude of the force is mainly determined by the temperature difference [12,13]. The direction of $F_{\Delta T}$ can be either towards the light source (negative photophoresis, occurring for small particles) or away from the light source (positive photophoresis), as illustrated in Figs. 4(a) and 4(b). Moreover, even when the particles are heated uniformly, there will still be a force $F_{\Delta\alpha}$ purely due to different surface thermal accommodation coefficient α [13]. Worth noting is that $F_{\Delta\alpha}$ does not depend on any temperature difference on the particle's surface, but rather depends on particle geometry. The direction of $F_{\Delta\alpha}$ is particle body-fixed, meaning that it always points from α_1 to α_2 (suppose $\alpha_1 > \alpha_2$), as shown in Fig. 4(c). One of the most interesting properties of such body-fixed force is that it has the ability to rotate irregular particles such that $F_{\Delta\alpha}$ re-directs to the opposite direction of other combined forces such as $F_{\Delta T}$, radiation force, and gravity. This has been used to explain for instance the upward motion of dust particles in air illuminated by sunshine. We believe $F_{\Delta\alpha}$ plays an important role in the single-beam trapping process of absorbing particles reported here.

Now let us look at the combined action of all possible forces in our experimental system. As discussed earlier about Fig. 1, for the particles trapped before and after the focal point of the incident beam, $F_{\Delta T}$ and the radiation force F_R can be either negative (pointing to the light source) or positive (pointing away from the source). The gravity G always points downward. Neglecting buoyancy and other forces due to air turbulence, $F_{\Delta T}$, F_R, G, and $F_{\Delta\alpha}$ will be the main forces involved. For a given direction resulting from the combined action of $F_{\Delta T}$, F_R, and G, for an asymmetric particle $F_{\Delta\alpha}$ tends to rotate so to be in the opposite direction, balancing the action of other forces. Figure 4(d) illustrates one possible situation for a trapped particle, in which $F_{\Delta\alpha}$ is in the opposite direction of the sum of $F_{\Delta T}$, F_R, and G. Under this condition, if $F_{\Delta\alpha}$ is larger than the sum of $F_{\Delta T}$, F_R, and G, the particle will move towards the focal point, so $F_{\Delta T}$ and F_R become larger until $F_{\Delta\alpha} = F_{\Delta T} + F_R + G$. On the other hand, if $F_{\Delta\alpha}$ is smaller than the sum of $F_{\Delta T}$, F_R, and G, the particle will move away from the focal point, so that $F_{\Delta T}$ and F_R become smaller until $F_{\Delta\alpha} = F_{\Delta T} + F_R + G$. If we take into account the forces due to air turbulence, $F_{\Delta\alpha}$ has to self-rotate to balance the combined action of all other forces. This explains why the particle trapping is so sensitive to ambient air perturbations and thus the particles can't be stably trapped when moved out of the glass cuvette.

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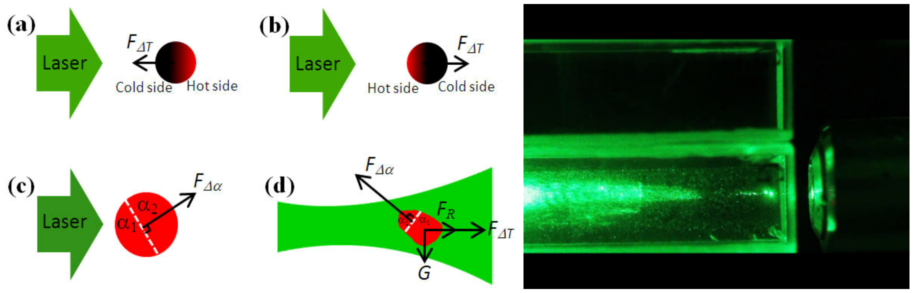

Fig. 4. (left): Illustration of possible trapping mechanism involved in single Gaussian beam trapping. (a, b) show the negative and positive $F_{\Delta T}$ force resulting from temperature gradient, respectively; (c) $F_{\Delta\alpha}$ force resulting from different surface thermal accommodation coefficient; (d) The balance of combined action of gravity (G), radiation force (F_R), and the two types of photophoretic forces $F_{\Delta\alpha}$ and $F_{\Delta T}$. Fig. 4. (right): Observation of particle transportation from one glass cuvette to another by using a specially-designed optical bottle beam (Media 5).

4. Optical transportation of particles with a fully-closed bottle beam

Since the above particle trapping based on Gaussian beams is very susceptible to ambient perturbation as compared to that based on optical bottle beams [4–7], we used our newly designed optical bottle beams [20] for trapping and transporting absorbing particles. The new bottle beam was generated by Fourier-transforming an appropriately apodized Bessel beam whose radial oscillations are chirped by a cubic phase term, thereby creating an elegant optical bottle with paraboloid multilayer boundaries [20]. With such a bottle beam, we observed stable trapping of silicon particles even when the glass cuvette is removed. Furthermore, transporting trapped particles from one glass cuvette to another is realized by using this specially-designed bottle beam as shown in the right panel of Fig. 4 and a recorded video (Media 5). We emphasize that the bottle beam we generated for this trapping experiment has two closed ends, which is quite different from those generated before based on the Moiré techniques [7] or the focusing lens with controlled amount of spherical aberration [18]. The fully-closed bottle beam might serve as a more robust photophoretical trap in open air as it could withstand large air currents or ambient perturbations. Such bottle-based all-optical particle transportation might be particularly useful in applications involving bio-hazardous substances and materials.

5. Summary

We have experimentally observed stable trapping and dynamic transportation of highly absorbing particles by a single optical beam. It has been shown that the particle trapping is not only closely dependent on the laser beam properties (power level and focusing conditions) but also on the shape of the particles. We have demonstrated that the trapped particles can be transferred between two Gaussian beams without any physical contact. We have also demonstrated optical transportation of trapped particles from one glass cuvette to another by using a specially-designed bottle beam. Our results pave may pave way for manipulating absorbing micro- and nano-particles with a single beam, and may find a variety of applications in optics, biology, chemistry, medicine, as well as astronomy.

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