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Trapping and manipulation of microparticles using laser-induced optical and thermal forces

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Abstract: We show movements of microparticles using both continuous and discontinuous laser irradiation on an absorbing substrate or colloidal mixture producing optical and thermal forces. We analyze these movements through the tracks of particles.

OCIS codes: (350.4855) Optical tweezers or optical manipulation; (350.5340) Photothermal effects.

1. Introduction

The trapping and manipulation of microparticles has been widely used in biological study for many years. Several techniques have been investigated including dielectrophoresis, electrokinetics, optical tweezers, optoelectronic tweezers, hydrodynamic flow, magnetic tweezers and acoustic tweezers [1,2]. Each technique has specific advantages and disadvantages; dielectrophoresis and electrokinetics techniques are limited with the buffer conductivity and low concentration samples [3,4]. For optical tweezers, only single particles can be manipulated due to the size limitation of the highly focused laser beam [5]. Optoelectronic tweezers devices require lower light intensities compared to optical tweezers, however the technique also requires specific electrical properties from the samples and devices. The hydrodynamic flow approach requires a high flow rate and high purity of the sample solution [3,4]. For magnetic tweezers, samples have to be prelabeled with magnetic materials, this affects the cell viability [1,6]. Acoustic tweezers require a piezoelectric material and ultrasound waves with fixed frequency or narrow frequency range are generated [7]. Some limitations of the above techniques may be overcome by using laser-induced thermal convection flows and photophoresis or thermophoresis due to the thermal gradient. The thermal convection flow is generated by the temperature gradient arising from laser irradiation of a high absorption film or substrate. Due to the effect of the flow, particles can be dragged towards the laser spot [8]. However, if the light intensity is sufficient and the particles are close to the illuminated region, they may move away from the laser beam because of the photophoresis or thermophoresis effect.

In this paper, we investigated the trapping and manipulation of microparticles by laser irradiation of different colloidal samples contained in a thin chamber. We were able to trap large size particles (20 µm in diameter) with a short range force (around the particles diameter) and move smaller ones (4.95 µm in diameter) with a longer range force (around 20 times the particles diameter) under continuous illumination. Furthermore, after adding extra highly absorbing single walled nanotubes (SWNTs), we observed a step like movement of particles upon the start and the end of discontinuous irradiation. The movement of particles was analyzed by particle tracking software (Tracker; v4.95, Douglas Brown, USA).

2. Experimental methods

The experimental setup is shown in Fig. 1(a). The whole setup comprised two systems: a microscope system and a laser system. For the microscope system, a cold white LED array was used as illumination source. Two groups of aspheric condenser lenses with different focal lengths were used to collimate and adjust the size of the light beam, labeled ① and ③. The two irises ② were the condenser diaphragm and the field diaphragm, respectively. The beam after the condenser lens was reflected by a 50:50 beamsplitter ④ and projected into a 4X/10X objective. Part ⑤ was a tube lens which was followed by a CMOS camera with resolution of 1280 x 1024 and a color sensor. In terms of the laser system, an aspheric collimation lens ⑥ with short focal length was used to collect and collimate the beam. Due to the fact that the objective was also used to focus the laser beam during the experiment, two bi-convex lenses (⑦ and ⑧) with different focal lengths were used to ensure the beam was focused on the sample plane. Furthermore, a short pass dichroic filter ⑨ was used to reflect the laser beam into the objective but be transparent to visible light. The particles were manipulated by using a multimode CW laser diode at 808 nm with maximum optical power of 1 W.

In the experiment, colloidal samples were prepared by suspending polystyrene beads (10%w/w, 1.0 µm, 4.95 µm and 20 µm in diameter, Bangs Laboratories) in distilled water with a dilution ratio of 1:100. For the colloidal mixture of single walled nanotubes (SWNTs) and beads, a SWNT conductive ink (1 mg/mL, Sigma-Aldrich Co. LLC) was dispersed in distilled water at ratio of 35 mg:1 mL, which was followed by adding a solution of 4.95 µm polystyrene beads with the same dilution ratio as the colloidal samples. The prepared sample solution was then injected into a thin chamber by pipetting.

To form the thin chamber, two narrow spacers with a certain separation were attached to a silicon substrate. A normal microscope slide cut to appropriate dimensions was then placed on them by gentle pressing. The thickness of the chamber was around 150 µm and is shown schematically in Fig. 1(b).

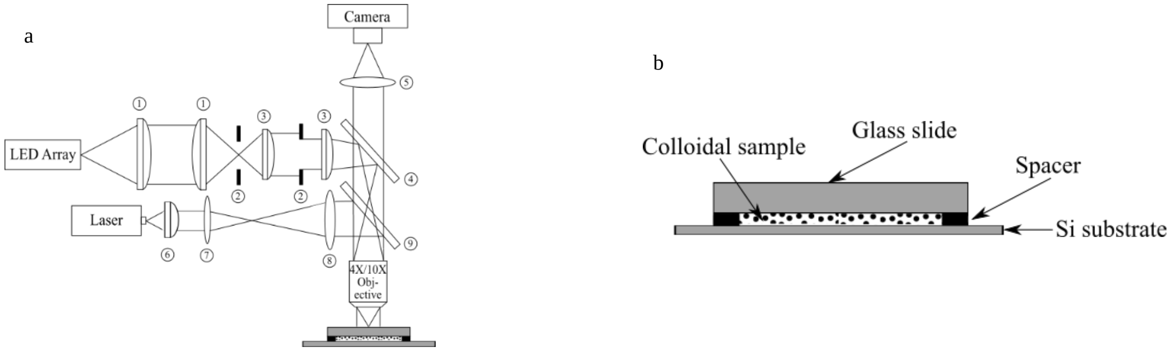

Fig. 1. (a) Schematic of the experimental setup; ① and ③: aspheric condenser lenses with different focal lengths, ②: condenser/field diaphragm, ④: 50:50 beamsplitter, ⑤: tube lens, ⑥: aspheric collimation lens, ⑦ and ⑧: bi-convex lenses with different focal lengths, ⑨: short pass dichroic filter. (b) Schematic of the thin chamber filled with colloidal sample.

3. Results

3.1 Microbead manipulation with a short range force (no more than the beads diameter) with continuous illumination

In this experiment, colloidal solutions were illuminated through a 10X objective by the laser diode operated CW with an optical power on the sample of 460 mW at 1.1 A and spot size of *Φ*2.5 µm in the *x*- and *Φ*52.9 µm in the *y*-direction. During the experiment, microbeads with a diameter of 20 µm were used as the sample solution. The experimental phenomena were recorded at a frame rate of 15 fps and the record time was 57 s. We observed that up to three beads could be trapped and moved simultaneously in 2D by the laser spot, which was probably caused by the optical gradient force. We termed this short range manipulation as the bead needed to be no more than around the beads diameter from the laser spot to experience the force. In contrast, neither of the smaller size beads (1 µm and 4.95 µm in diameter) could be manipulated under the same experimental conditions. Fig. 2(a) and (b) show the original positions of the laser spot and the three beads of interest, and one of the video frames during the trapping and manipulation, respectively.

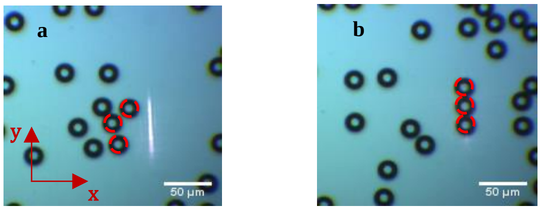

Fig. 2. (a) The original positions of the laser spot and the beads of interest (highlighted by the red dashed circles). (b) One of the video frames during the trapping and manipulation. Laser spot size: *Φ*2.5 µm in the *x*-direction, *Φ*52.9 µm in the *y*-direction.

3.2 Particle manipulation with a longer range force (up to 20 times the beads diameter) with continuous movement and illumination

We used the same conditions as for the first experiment and the movement of five microbeads (with 4.95 µm diameter) was analyzed. In this experiment, we found that most beads around the laser spot moved continuously away from the illuminated region under the continuous irradiation condition, which we believe was caused by photophoresis and thermophoresis due to the thermal gradient arising from the absorbing substrate. However, in the meantime, two beads were trapped by the beam, which may have been the contribution of thermal convection flow. The relevant results are shown in Fig. 3. The positions of the five beads of interest without and with laser irradiation at the very beginning of the video are shown in Fig. 3(a) and (b), respectively. In Fig. 3(c), the color curves show the relevant traces of the particles at the last video frame and the longest distance of one bead movement is around 100 µm.

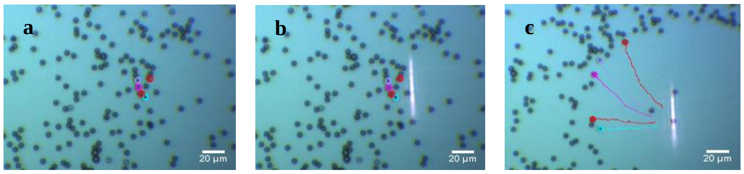

Fig. 3. The movement analysis of the 4.95 µm polystyrene beads (a) without laser illumination, (b) with laser beam at the very beginning, (c) with laser beam at the last frame by software Tracker. Laser spot size: *Φ*2.5 µm in the *x*-direction, *Φ*52.9 µm in the *y*-direction.

3.3 Particle manipulation with discontinuous movement and illumination

In this experiment, the SWNT and bead mixture was illuminated with a discontinuous laser beam. A 4X objective was used to focus the beam. The laser diode was driven under quasi-continuous-wave operation at 10 MHz. The laser beam was opened and blocked manually by a self-made beam shutter. The experimental phenomena were recorded at a frame rate of 7 pfs and the record time was 7.6 s. The movement of one bead with SWNT clusters was analyzed by the same particle tracking software as before. In most cases, the particle of interest moved in the positive *y*-direction in a step like movement once the laser beam was turned on. During the lasing period, after a certain time, the bead moved back rather than continuing to move further. When the beam was blocked, the behaviors of the particle were very similar as the beam was opened except it moved in the negative *y*-direction. The discrete nature of these phenomena was suggestive of it being caused by a thermally generated vibrational shock wave propagating out from the illuminated region, which may have been due to the extremely high absorption of the SWNT clusters. In this case, the bead might experience a thermal shock force coming from the wave, however the physical mechanism is still being investigated. Fig. 4(a) shows one of the video frames during a period when the laser beam was opened. The red circle shows the bead of interest with SWNT clusters which was being analyzed. Fig. 4(b) shows the relationship between the particle movement in the *y*-direction and the laser beam on/off versus time sequence.

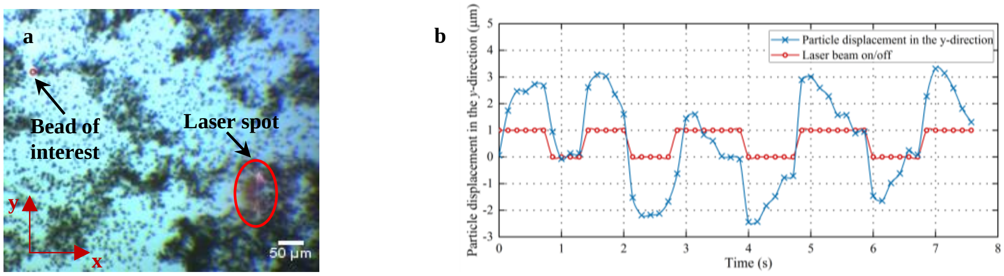

Fig. 4. (a) The movement of the microbead of interest with SWNT clusters in one of the video frames. (b) The plot of the relationship between the particle movement in the *y*-direction and the laser beam on/off versus time sequence.

4. Conclusion

It is possible to trap 20 µm diameter microbeads within a short range (up to 20 µm) of the laser spot with the optical gradient force. For smaller size beads of 4.95 µm, there is a potential way to move them continuously over a longer range (up to 100 µm) by thermal gradient forces which arise from a combination of thermal convection flow, photophoresis and thermophoresis. For the SWNT and bead mixture, the movement of the bead suggests that a thermal shock wave may be created by discontinuous laser illumination.

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