Flow-assisted Single-beam Optothermal Manipulation of Microparticles

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Abstract: An optothermal tweezer was developed with a single-beam laser at 1550 nm for manipulation of colloidal microparticles. Strong absorption in water can thermally induce a localized flow, which exerts a Stokes’ drag on the particles that complements the gradient force. Long-range capturing of 6 μm polystyrene particles over ~176 μm was observed with a tweezing power of ~7 mW. Transportation and levitation, targeted deposition and selective levitation of particles were explored to experimentally demonstrate the versatility of the optothermal tweezer as a multipurpose particle manipulation tool.

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OCIS codes: (350.4855) Optical tweezers or optical manipulation; (140.6810) Thermal effects; (140.7010) Laser Trapping

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1. Introduction

Single-beam gradient force laser tweezers have been developed and widely used to control and actuate dielectric microparticles and other microscopic objects [1, 2]. The momentum transfer that occurs due to scattering can result in a gradient force that confines the microparticles to the focal region of the tweezing beam. The typical trapping range of a conventional laser tweezer is on the order of only a few microns [3, 4]. Trapping beyond 80 μm is possible below the focal plane with a tweezing power as high as 29 mW, but the range is nevertheless limited to the region illuminated by the tweezing laser [5]. In addition, laser-induced heating in optical tweezers is a known issue and has been a matter of concern [6, 7].

A different approach was recently developed for particle manipulation using thermal tweezers [8–12]. Particles in a temperature gradient experience thermophoretic force and move either toward or away from the heated region. With a single-beam laser optically imposing a temperature gradient inside a particle colloid chamber, thermophoresis and convection together can cause particles to aggregate in a layer close to the bottom of the chamber, thus efficiently redistributing the particles on a 2D plane [8, 9].

We previously proposed an optothermal tweezer for laser manipulation of microparticles in an aqueous medium [13]. Built upon the basis of a conventional all-optical laser tweezer, the optothermal tweezer employs a laser source at 1550 nm, where the optical absorption in water is significantly higher than at shorter wavelengths that are more commonly used [14]. The temperature increase due to laser absorption, however, does not act directly on the colloidal particles as in the case of thermal tweezers. Instead, we were able to use a laser-driven flow to bring particles from beyond the optical field towards a volume where the optical radiation force is dominant, thus extending the tweezing range.

In this study, we further explored the optical and thermal processes in flow-assisted optothermal manipulation of microparticles. Optical-driven thermal effects were observed in a water-based colloid of 6 μm polystyrene particles, including capturing over a long range of ~176 μm with a tweezing power of ~7 mW and levitation in a segregated particle colloid. In addition to aggregation and trapping alone, the rich dynamics in the vertical direction adds a new dimension to particle manipulation and opens up various possibilities for design of schemes. As a first attempt towards proving the versatility of the optothermal tweezer, we experimentally demonstrated three different modes of operation for potential applications, including 1) levitation and transportation, 2) targeted deposition and 3) selective levitation of microparticles in a water-based colloid.

2. Principles

To state the problem, the configuration of the optothermal tweezer is shown in Fig. 1a. A single-beam laser at 1550 nm is focused vertically into a thin chamber filled with a colloid of deionized water and 6 μm polystyrene particles. The chamber is 125 μm thick and sealed with candle wax. As in the case of conventional optical tweezers, the gradient force creates a potential minimum in both the vertical and the lateral direction. Particles that are very close to the focus of the tweezing beam can thus be trapped in the focal region.

By choosing the tweezing wavelength to be 1550 nm, the strong absorption of the tweezing laser power also excites a thermal process that provides a second tweezing mechanism.
Optically induced temperature difference in the water medium results in a pressure gradient through thermal expansion, which, in turn, drives a localized convective flow in the vicinity of the beam focus (Fig. 1b). Particles in the colloid therefore experience a drag force as described by the Stokes’ law. In the lateral direction, the flow can be either radially inward or outward, which facilitates or disturbs capturing of the particles, respectively (Figs. 1c – 1d).

Owing to the small length scale of the chamber in the vertical direction, structural confinement and surface interactions need to be taken into consideration to approximate the effective overall potential (Fig. 1e). With the focus of the single tweezing beam situating inside the chamber, up to three separate local potential minima could occur, among which only the gradient force trap has stable three-dimensional confinement near the beam focus. Gravity, surface attraction and upward Stokes’ drag could create two other minima in the vertical direction close to the bottom and the top of the chamber, which could potentially lead to segregation of the particles into two layers.

The different confinement and range scales of the optical gradient force and the Stokes’ drag offer more complexity than conventional optical tweezers to enable new possibilities in particle manipulation. By adjusting the position of the tweezing beam, it is therefore possible to control the spatial distribution and dynamics of microparticles through properly shaping the system potential.
3. Thermal-induced effects

3.1. Long-range capturing

Figures 2a–2d shows flow-assisted long-range capturing of a 6 \( \mu \)m polystyrene particle. With a stationary beam of \( \sim 7 \) mW positioned at the upper right corner, the particle (circled in red) is captured from a distance of \( \sim 176 \) \( \mu \)m away from the tweezing beam (note that the maximum capture range under the specific configuration is larger than this recorded range). Figure 2e shows the velocity and acceleration of a different captured particle as function of its distance from the beam focus. The effect of the Stokes’ drag is evidenced by the facts that the capture range is much larger than the beam radius of \( \sim 5 \) \( \mu \)m, as shown in the inset, which limits the tweezing range of the optical gradient force, and that the particle maintains a much smaller but relatively constant velocity beyond \( \sim 10 \) \( \mu \)m away from the beam focus.

In this case, the system configuration allows a radially inward water flow to bring the particle into the focal region, where the gradient force then takes effect to further accelerate it towards the beam focus. Effectively, particles that are originally too far from the focus to be captured by the gradient force alone can now fall along a potential curved tilted by the flow drag that is longer in range (cf. Fig. 1c). The defocusing of the captured particle in Fig. 2d is due to its levitation caused by a vertically upward flow near the beam focus, which will be discussed in the following section.
3.2. Segregation and levitation

With the pumping from the optothermal tweezer, particles in the colloid can segregate into two distinctive layers with a vertical separation of \( \sim 90 \, \mu m \) in between (Fig. 3a, cf. Fig. 1e) under thermophoretic repulsion from the most heated region close to the laser focus. In the lower layer, particles are attracted toward and disappear at the focal axis of the tweezing beam, while in the upper layer, particles emerge at and are repelled away from the focal axis (Fig. 3b, (Media1 – Media2), cf. Figs. 1c – 1d).

The disappearing and reemerging of particles is a direct result of levitation of particles from the lower layer to the upper layer, which is driven by a thermal-induced circulation that flows vertically upward between the two layers. Figure 3c shows the transient levitation rate in a particle colloid of a fixed concentration for a tweezing power of \( \sim 4.2 \, mW, \sim 5.6 \, mW, \sim 7 \, mW \) and \( \sim 8.4 \, mW \). The levitation rate increases exponentially as a function of time elapsed after the tweezing laser beam is turned on during the first 1800 seconds, following \( r(P_{op},t) = R(P_{op}) \exp\left[ t/\tau (P_{op}) \right] \), where \( r(P_{op},t) \) is the levitation rate at time instance \( t \) with a tweezing laser power of \( P_{op} \), \( R(P_{op}) \) and \( \tau (P_{op}) \) are the instantaneous levitation rate and stabilization time constants for a given tweezing power \( P_{op} \). Experimentally, \( r(P_{op},t) \) can be obtained by taking the inverse of the average time between two consecutive occurrences of particle levitation with a tweezing power of \( P_{op} \) at time \( t \). The measured values of \( R \) and \( \tau \) in Fig. 3c are summarized in Table 1, which shows the dependency of the levitation rate on the optical tweezing power.

| \( P_{op} \) (mW) | \( R \) (s\(^{-1}\)) | \( \tau \) (s) |
|------------------|-----------------|---------|
| 4.2              | 14.4            | 823.8   |
| 5.6              | 21.0            | 862.2   |
| 7.0              | 37.8            | 1176.0  |
| 8.4              | 107.4           | 1707.0  |

4. Applications

Apart from varying the tweezing power, a different way to change the flow conditions and thus to modify the system potential for various particle manipulation applications is to position the tweezing beam focus at different vertical locations in the colloid chamber. Here we present the experimental configurations for three different modes of the optothermal tweezer.

4.1. Levitation and transportation

Figure 4 shows the levitation and transportation mode of the optothermal tweezer. With the tweezing beam focused at the upper layer in a segregated colloid (Fig. 4a), particles in the lower layer can follow the potential slope tilted by the upward fluid flow to reach the gradient-force trap, where its three-dimensional confinement then allows for transportation of the particle in the lateral direction (Fig. 4b).

Figure 4c (Media3) shows an experimental demonstration of this levitation and transportation process. Initially, there are two particles (circled in green) in the upper layer A and one particle (circled in red) in the lower layer B. After the laser is turned on and focused to layer A, the particle circled in red, being the closest one to the beam focal axis, gets attracted toward and levitated along the beam focal axis to appear in the upper layer A. The beam is then steered laterally relative to the colloid chamber (which is experimentally done by moving the substrate...
Fig. 3. (a) Levitation of 6 μm particles in a colloid segregated into two layers A and B. (b) First row: a particle (circled in red) appears at the center (beam focal axis) of the upper layer A (Media1); second row: a different particle moves towards the center and disappears from the lower layer B (Media2). (c) Transient levitation rate for a tweezing power of \( \sim 4.2 \) mW, \( \sim 5.6 \) mW, \( \sim 7 \) mW and \( \sim 8.4 \) mW.

Compared with conventional optical tweezers, the levitation and transportation mode of the optothermal tweezer provides a faster and more efficient way for particle manipulation applications where the selection of particles is not critical. The process of locating and trapping particles with the short-range gradient force is simplified by the flow-assisted long-range capturing and levitation of particles, which sustain a highly localized particle flux that fall into the gradient-force potential trap as they rise and stop at the beam focus, and only the subsequent transportation of the trapped particle alone would require steering of the tweezing beam.
Fig. 4. Levitation and transportation mode. (a) Tweezer configuration. Particles in the colloid are segregated into layers A and B. (b) System potential in the vertical direction. (c) First row: layer A; second row: layer B. The particle circled in red is attracted toward the beam focus (columns 1 – 2), levitated from B to A (column 3) and transported past the two particles circled in green (columns 4 – 6) (Media3).

4.2. Targeted deposition

Figure 5 shows a slight modification to the levitation and transportation mode. With the beam focus just below the upper layer in the colloid (Fig. 5a), the gradient-force trap can be positioned at a location away from the global potential minimum (Fig. 5b), thus levitating and depositing particles without trapping them. Particles roll along the potential slope past the gradient-force trap to reach the global potential minimum, where there is no longer confinement in the lateral direction, as they rise through the beam focus to stop at the upper layer. Therefore, subsequent movement of the tweezing laser beam does not affect the position of particles already levitated, and this effectively implements the targeted deposition mode. To create a pattern, we simply need to move the tweezing beam in the same lateral plane as if “writing” with particles. Figure 5c (Media4) shows an initial demonstration of the targeted deposition process. Methods need to be explored in order to hold the deposited particles in place on the upper plane.

4.3. Selective levitation

Figure 6 shows the selective levitation mode of the optothermal tweezer. In this mode, the tweezing beam is focused just slightly above the particle to be levitated in the lower layer of a segregated particle colloid (Fig. 6a). With a strong yet highly localized upward flow at the particle position, it is possible for the particle to gain sufficient energy to escape from the gradient-force trap and for levitation to occur (Fig. 6b). The beam focus needs to be some vertical distance away from the particle for the flow to transfer enough kinetic energy to the particle, yet, on the other hand, localization of the upward flow requires that the focus is
positioned close to the particle.

Figure 6c (Media5) shows the experimental demonstration of the selective levitation mode. The tweezing beam is focused very close to the particle circled in red, which is levitated and released from the lower layer. Nearby particles that are $\sim 10 \, \mu m$ away from the levitated particle are not much affected by this action. Ideally, it may be possible to hold a particle at the gradient-force trap as a marker of the beam focus position. This selective levitation process specifically makes use of the temporal short-term effect of the optothermal tweezer as described by the instantaneous levitation rate $R(P_{\text{eff}})$ (cf. Section 4.1 and Fig. 3c) and can be potentially used as a reverse operation of the targeted deposition mode to create negative patterns in the lower layer of the colloid chamber.

5. Conclusion

We demonstrated flow-assisted single-beam optothermal manipulation of 6 $\mu m$ polystyrene particles in a water-based colloid using a tweezing laser at 1550 nm. We observed thermal effects induced by the strong optical absorption in water at this wavelength, including 1) long-range capturing of particles over a distance of $\sim 176 \, \mu m$ from the tweezing laser focal axis using a stationary beam of $\sim 7 \, mW$, 2) segregation of particles in the colloid into two distinctive layers and 3) highly localized vertical levitation of the particles from the lower layer to the upper layer. The levitation rate can be controlled optically through varying the tweezing laser power.

We further implemented three modes of optothermal manipulation for various potential applications. With the tweezing beam focus positioned at the upper layer of a segregated colloid, particles can be captured and levitated from the lower layer and transported laterally in the upper layer. Lowering the position of the focus would remove the confinement in the lateral direction and particles can be deposited at desired locations by laterally steering the tweezing beam. Selective levitation of particles in the lower layer was also realized by directing the beam focus slightly above the particle to be levitated.

The optothermal tweezer has proven its potential as a particle manipulation tool, and we
expect future studies to focus on 1) finite element simulation of the optical, thermal and flow processes, 2) experimental measurements and quantitative analysis of particle drift due to different effects and 3) applications of the optothermal tweezer in opthofluidic and biomedical applications.

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