MANIPULATION OF MICROPARTICLES AND BIOLOGICAL CELLS USING LIGHT-INDUCED MARANGONI FLOW

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ABSTRACT

We report a novel technique for the manipulation of biological cells and microparticles using light-actuated Marangoni tweezers (LAMT). Yeast cells and microparticles were trapped at a light intensity of 10^3-10^4 W/cm^2 which is much lower than that required for optical tweezers. Particle manipulation using LAMT offers several advantages such as low power requirements, a trapping force scaling with the particle diameter d (instead of d^3 as with conventional optical methods), and operation at vanishing refractive index contrast between the particle and the liquid.

KEYWORDS: Interfacial transport, Marangoni flow, Optical manipulation, Photoswitchable surfactants

INTRODUCTION

Photoresponsive materials have proven to be useful for microfluidic transport [1,2] as well as for biological and chemical analysis [3]. Among the stimuli sensitive materials, photoresponsive materials offer the added advantage of contactless manipulation and remote programmability. Very recently, particle and oil droplet manipulation at photoresponsive liquid surfaces has been achieved utilizing local changes of the surface tension [1,2]. This light-induced Marangoni flow produces drag forces scaling with the particle diameter d, and is potentially more advantageous for nanoparticle manipulation than the commonly employed optical tweezers, which produce a force scaling with d^3. In our previous work, we reported trapping and manipulation of polymer particles adsorbed at a liquid surface using light-induced Marangoni flow created by a moderately focused UV laser beam (325 *nm* wavelength) [2]. The trapping mechanism relies on the light induced switching between the isomeric states of an azobenzene-based photoresponsive surfactant. The localized photoswitching and resulting gradient in surface tension towards the focal point generate a converging fluid flow. Objects adsorbed at the liquid surface flow towards the focal point where they get trapped. Although this technique could find wide applications in diverse areas, the employment of a UV laser for photoswitching may potentially limit the applicability in biological sciences, especially when manipulating biological cells, DNA etc. In this work, we demonstrate the trapping and manipulation of yeast cells using blue laser light (442 nm wavelength). Compared to the UV laser, 442 nm radiation is less harmful to cells. In addition, the laser light intensity requirement to create a substantial surface tension gradient and a corresponding Marangoni trap is found to be about 10^3 times lower than for commonly employed manipulation techniques based on the electromagnetic gradient force [4,5].

THEORY

The working principle of particle manipulation based on light-induced Marangoni flow is shown in figure 1(a).

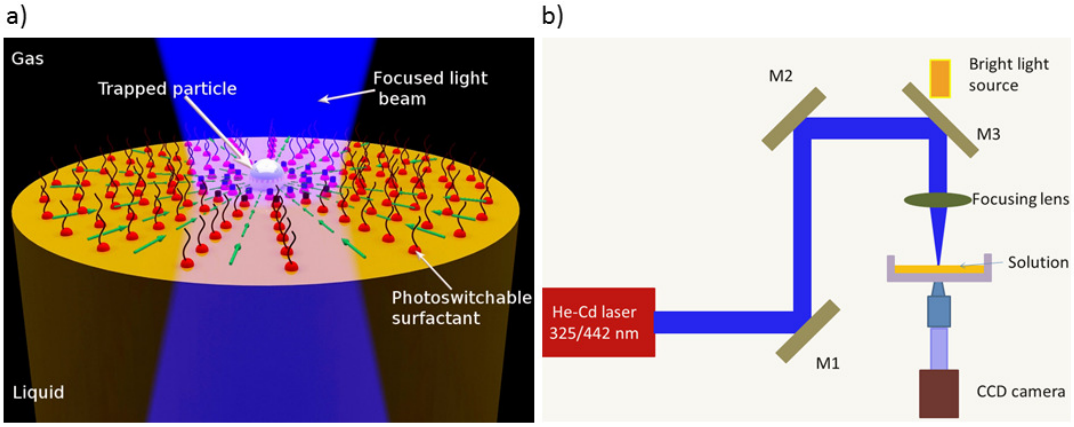

Figure 1: Optically-actuated Marangoni tweezer. a) Principle of Marangoni tweezer b) Experimental setup used for trapping and manipulation of small objects attached to the water-air interface. The focal spot at the liquid surface has a diameter of about 8 µm at 325 nm irradiation.

The photosurfactant material (Diethyleneglycol mono(4',4-butyloxy,butyl-azobenzene) used for the experiments exists in two isomeric states: a *trans* and a *cis* state. The surface tension of such a liquid surface depends on the type of isomer adsorbed to the interface. The *cis* rich surface exhibits a higher surface tension than the *trans* rich surface. The material can be reversibly switched between the two isomeric states upon UV/visible irradiation. The photoswitchable

surfactant-covered liquid surface was illuminated locally with a laser beam. At the irradiated spot, the surface tension increases locally due to the structural changes of the surfactant (*trans-cis* isomerization), resulting in an inward Marangoni flow [2]. This axially symmetric inward Marangoni flow is utilized for the trapping as well as for the transport of the cells/particles adsorbed to the air-water interface.

EXPERIMENTAL

Figure 1(b) shows the experimental setup used for trapping and flow profile diagnostics of small objects adsorbed to the air-water interface. The synthesis of the photosurfactant material incorporating the azobenzene motif was carried out according to ref [6]. A 10 cm planoconvex lens was used for focusing the laser beam (325 nm and 442 nm wavelength from a He-Cd laser) at the air-water interface. The focal spot at the liquid surface has a diameter of about 8 µm at 325 nm irradiation and 11 µm at 442 nm. The converging flow velocity was characterized using Particle Streak Velocimetry. Plane polystyrene beads (Micromod, Germany) of 15 µm diameter were used as tracer particles. Shifting of the laser spot was achieved by tilting the mirror M2.

RESULTS AND DISCUSSION

In order to manifest the laser induced Marangoni flow, a 1 mm thick layer of surfactant solution in a petri dish is irradiated with 325 nm light. As mentioned above, the photoisomerization of the molecule from the *trans* to the *cis* state upon 325 nm irradiation results in the flow of polystyrene tracer particles adsorbed at the interface towards the focal point. Figure 2a shows a typical example of a particle streak image. The corresponding velocity profile at the surface of a 25 µM surfactant solution is shown in figure 2b.

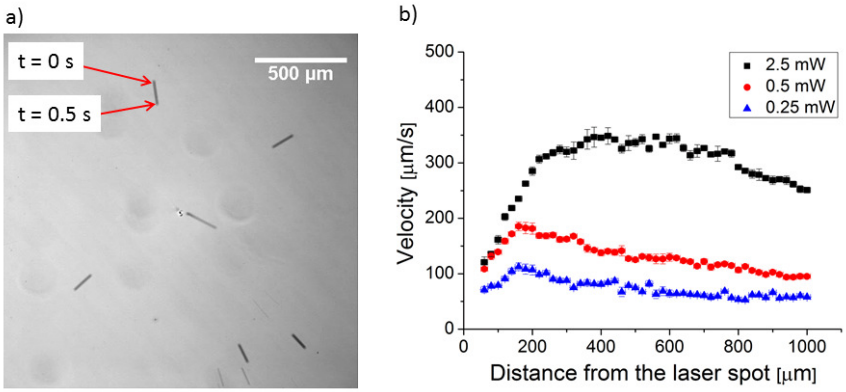

Figure 2: Flow profile characterization using Particle Streak Velocimetry. a) Particle streaks recorded using an exposure time of 500 ms upon irradiation with a 325 nm beam. The particles are attached to the liquid surface.Irradiation starts at t = 0. b) Corresponding flow velocity profiles at the surface of a 25 µM surfactant solution at different laser power levels.

The experiment is repeated at different laser power levels. A maximum velocity of about 400 µm/s is achieved at an incident power of 2.5 mW. The position at which the maximum velocity occurs is far away from the laser spot. The surfactant crowding around the laser focus due to the inward Marangoni flow is probably responsible for this behavior [2]. Figure 3a shows the manipulation of polystyrene particles along the liquid surface achieved by tilting the mirror M2. In similar experiments without surfactants, no trapping or displacement of particles could be achieved, demonstrating that the trapping mechanism is not based on electromagnetic stresses.

Similarly, an inward flow can be generated upon focusing a 442 nm beam onto the surface of a blue adapted solution (photostationary state) [7,8]. It is reported that upon irradiation with intense blue light of such a surface, the composition at the irradiated surface area suddenly changes from almost exclusively *trans* isomers to about 85 % *trans* isomers and 15 % *cis* isomers [8]. This rise in the concentration of the *cis* isomers at the irradiated area triggers an inward flow due to the increase in surface tension. This method was followed to manipulate yeast cells because blue light is potentially less harmful to cells than UV light. The surfactant concentration used for that purpose was 50 µM which is well above its critical micelle concentration (CMC) (1.6 µM for *trans* isomers). A tiny amount of diluted suspension of Baker's yeast cells (size ranging from 5-8 µm) was carefully deposited over the photosensitive liquid film. A single yeast cell was dragged towards the laser focus using the inward Marangoni flow. Figure 3b shows a sequence of images exemplifying the trajectory of a trapped yeast cell (laser power 5 mW) when shifting the laser spot, and figure 3c displays the instantaneous velocity computed from the trajectory. A typical transport velocity of about 5-8 µm/s was achieved at a laser power of 5 mW. When the laser focus is moved with higher velocity, the trapped cell escapes from the trap and can no longer follow the laser spot. Computing the Stokes drag force acting on the cell at the maximum velocity yields a value of about 0.6 pN. To achieve such a trapping force using conventional methods like optical tweezers, about 10^2-10^3 times higher light intensities are required.

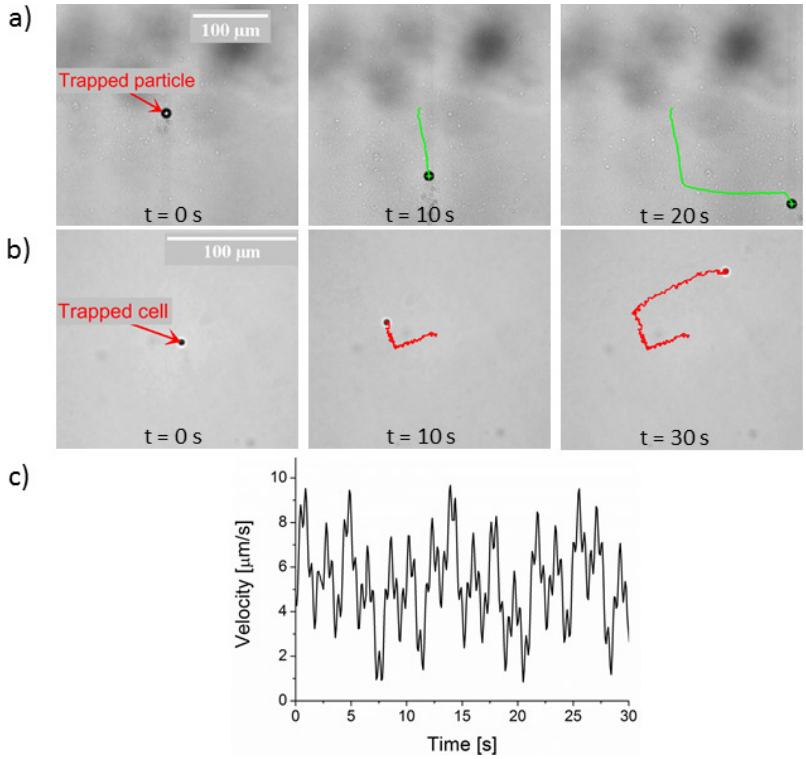

Figure 3: Particle manipulation using LAMT. a) Sequence of images showing the displacement of a 15 µm polystyrene particle using the 325 nm beam at 5 mW. b) Displacement of 7µm yeast cells using the 442 nm beam at 5 mW. c) Instantaneous velocity of the yeast cells as a function of time.

CONCLUSIONS

In conclusion, it has been demonstrated that microparticles and biological cells can be trapped and manipulated based on Marangoni flow generated by photoswitching of a UV-visible light responsive surfactant. The required light intensities for the particle manipulation are much lower than those of conventional optical traps. The trapping and manipulation of biological samples using visible light of comparatively low intensity could find wide applications in biomedical sciences. Furthermore, the hydrodynamic nature of the trapping force can be beneficial when handling nano-objects.

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