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Real-time interactive optical micromanipulation of a mixture of high- and low-index particles

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Abstract: We demonstrate real-time interactive optical micromanipulation of a colloidal mixture consisting of particles with both lower ($n_L < n_0$) and higher ($n_H > n_0$) refractive indices than that of the suspending medium ($n_0$). Spherical high- and low-index particles are trapped in the transverse plane by an array of confining optical potentials created by trapping beams with top-hat and annular cross-sectional intensity profiles, respectively. The applied method offers extensive reconfigurability in the spatial distribution and individual geometry of the optical traps. We experimentally demonstrate this unique feature by simultaneously trapping and independently manipulating various sizes of spherical soda lime micro-shells ($n_L = 1.2$) and polystyrene micro-beads ($n_H = 1.57$) suspended in water ($n_0 = 1.33$).

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1. Introduction

Light carries both linear and angular momenta. Momentum transfer that accompanies light-matter interaction has provided us means to trap and manipulate particles in the mesoscopic scale. Significant developments in the past decades have resulted in a variety of applications of conventional optical trapping in the biological and the physical fields and the emergence of a 'next-generation' of optical micromanipulation schemes [1-5].

In 1970, Ashkin demonstrated that a transparent dielectric micro-sphere suspended in water is radially drawn towards the optical axis of a Gaussian laser beam where the intensity is strongest [6]. He observed this behavior with latex spheres having relative refractive index \( m > 1 \) (where \( m = n/n_0 \) and \( n \) and \( n_0 \) are the refractive indices of the particle and the suspending medium, respectively). Upon radial attraction towards the region of stronger intensity, the high-index particle accelerates in the direction of the Poynting vector due to an axial scattering force. On the other hand, Ashkin noted that for an air bubble (\( m < 1 \)) in water the sign of the radial force due to the intensity gradient is reversed; hence, the low-index particle is repelled away from the beam axis. Ashkin and co-workers later showed that by tightly focusing a Gaussian beam to a high-index particle an axial force due to an intensity gradient is also produced, strong enough to counteract the scattering force, resulting in a stable 3D confinement of the particle [7]. However, a stationary tightly focused Gaussian beam does not provide a confining potential for low-index particles.

Optical trapping of a low-index microscopic particle requires a beam with an annular intensity profile. A straightforward approach is to apply high-speed deflectable mirrors that enable time multiplexing of a desired beam pattern at the trapping plane. Scanning the beam in a circular locus creates a ring of light that confines a low-index particle in its dark central spot [8]. A low-index particle can also be trapped in an optical vortex produced from a focused TEM\(_{01}\)\(^*\) beam [9]. An optical vortex has been used to trap a low-index sphere and a high-index sphere, at the same time, in two neighboring positions along the beam axis [10]. Low-index particles were also trapped between bright interference fringes produced at the focal plane of an objective lens where two coherent plane waves converge [11]. However, dynamic and parallel manipulation of a larger array of high- and low-index particles has not been achieved with the above techniques.

Here, we demonstrate real-time user-interactive manipulation of a mixture of high- and low-index particles by reading out 2D phase patterns encoded onto an input beam by a programmable spatial light modulator (SLM) using the generalized phase contrast (GPC) approach to produce tailored light distributions that result in optical confinement of the mixed particles in the transverse plane. For spherical particles, trapping beams with radial symmetry are utilized. High-index micro-spheres were efficiently trapped and manipulated using trapping beams with top-hat transverse profiles at the trapping plane [12, 13]. On the other hand, low-index particles are trapped using beams with annular transverse profiles [14]. We demonstrate that, unlike other methods, the GPC approach readily provides both the ability to create independently controllable optical traps for high- and low-index particles, and the flexibility to render, in real time, arbitrary dynamics for these two types of particles simultaneously. This exceptional functionality may facilitate particle encapsulation in air-bubbles or in water-in-oil emulsions applied in petroleum, food, and drug processing.

2. Experiment

Trapping and manipulation of colloidal particles is achieved using the experimental setup shown in Fig. 1. The system makes use of a continuous wave (CW) Titanium:Sapphire (Ti:S) laser (wavelength-tunable, Spectra Physics, 3900s) pumped with a CW frequency-doubled Neodymium:Yttrium Vanadate (Nd:YVO\(_4\)) laser (532 nm, Spectra Physics, Millenia V). The Ti:S laser utilizes built-in birefringent quartz filter plates to select the operating wavelength within the near infrared (NIR) spectrum from 700 to 850 nm. In our experiments, the operation wavelength is set to \( \lambda = 830 \) nm. With a maximum pump power of 5.0 W from the Nd:YVO\(_4\), the Ti:S laser provides a maximum power of 1.5 W. The laser is expanded and
collimated before incidence on a reflection-type phase-only SLM. The SLM, employing parallel-aligned nematic liquid crystals (Hamamatsu Photonics), is optically addressed by a VGA-resolution (480x480 pixels) liquid crystal projector element that is controlled from the video output of a computer.

Fig. 1. Experimental setup for simultaneous optical manipulation of high- and low-index particles at the trapping plane. The expanded beam (λ = 830 nm) incident at the spatial light modulator (SLM) comes from a CW Ti:Sapphire (Ti:S) laser pumped by a visible CW Nd:YVO₄ laser. Under computer control, arbitrary 2D phase patterns are encoded onto the reflective SLM. A high-contrast intensity mapping of the phase pattern is formed at the image plane (IP) and is captured by a CCD camera via partial reflection from a pellicle. The intensity distribution is optically relayed to the trapping plane. Standard brightfield detection is used to observe the trapped particles. PCF: phase contrast filter, Ir: iris diaphragm, L1, L2 and L3: lenses, MO: microscope objective, DM: dichroic mirror, TL: tube lens.

We use the SLM to imprint a programmable 2D binary phase pattern (0 or π phase delays) to the wavefront of the 830 nm laser beam. The phase-modulated wavefront is directed into a 4-f filtering system composed of lenses L1 and L2, and a phase contrast filter (PCF) located at the Fourier plane. The PCF is constructed by depositing a 30-µm-diameter circular transparent photoresist (Shipley, Microposit S1818) structure on an optical flat. Centered at the Fourier plane, the PCF introduces a π-phase shift between low and high spatial frequency components of the phase-encoded beam. The diameters of the SLM iris (Ir) and the on-axis PCF are adjusted to optimize the throughput and contrast of the output intensity distribution [15]. A high-contrast intensity distribution, which is geometrically identical to the phase-pattern at the SLM, is generated at the image plane (IP). To monitor the output intensity distribution, a pellicle is inserted in the path and directs a small fraction (~3%) of the light towards a CCD camera. The intensity pattern at the IP is scaled and relayed by lens L3 and the microscope objective (MO) to a conjugate plane (trapping plane). The fluorescence port of the inverted microscope (Leica, DM-IRB) is used to direct the near-infrared laser light to the back-focal plane of the MO via a dichroic mirror. The same MO and a built-in microscope tube lens allow brightfield images to be captured by a second CCD camera.

The quality of the intensity patterns synthesized at the image plane via the GPC approach is depicted in Fig. 2 where variably sized beams with top-hat and annular transverse profiles are generated at different positions at the transverse x-y plane. The condition for achieving
optimal intensity contrast is described in the previous analysis of the GPC method [15]. Optimum phase-to-intensity conversion requires that the ratio of the SLM area encoded with $\pi$ phase shift to that with 0 phase remains less than or equal to 0.25 for the operating diameters of the SLM iris and the PCF. When the condition is satisfied, the maximum intensity of the trapping pattern is approximately four times the average intensity of the SLM input beam.

![Image](image.png)

Fig. 2. (a) Measured high-contrast intensity pattern at the output plane IP. Corresponding surface intensity plots for the representative (b) top-hat (in yellow square) and (c) annular or doughnut (in green square) trapping beams.

A trapping beam with a top-hat transverse intensity profile provides a radially symmetric potential well for a high-index particle as shown in Fig. 3(a). When a top-hat beam is positioned in the vicinity of a high-index particle, the particle gets attracted to the beam axis. We have observed previously that a beam with diameter slightly larger than that of the particle provides better transverse confinement especially when the trapped particle is moved along the horizontal plane [12].

In contrast, a top-hat beam acts as a potential barrier for a low-index particle. Unstable at the beam center, the low-index particle gets repelled to either side of the optical potential as shown in Fig. 3(a). This is evident in the experiment we performed with spherical shells made of soda lime glass material (Polysciences) with de-ionized water as host medium. These air-filled hollow glass spheres have shell thickness of ~1 $\mu$m and outer diameters in the range of 2-20 $\mu$m. The hollow glass spheres with outer diameters greater than 5 $\mu$m effectively behave as low-index particles in water ($n_0 = 1.33$). Similar hollow glass spheres where found to have average density of ~0.2 g/mL and effective refractive index $n_L = 1.2$ [9]. A 6 $\mu$m hollow sphere in the presence of a top-hat beam is shown in Fig. 4. The sequence of images shows the displacement of the low-index particle as a result of its repulsion from the region of stronger light intensity.

A low-index particle finds a minimum potential at the center of the beam with an annular transverse intensity profile as shown in Fig. 3(b). However, unlike the spontaneous attraction of a high-index particle towards the center of a top-hat beam, a low-index particle is not readily drawn to the dark central spot of the annular beam. From the outer region to the dark center of the annular beam, the low-index particle needs to overcome the potential barrier associated with the bright ring of light.
Next, we demonstrate a scheme where we take advantage of the repulsive forces induced by intensity gradients to low-index particles. The sample we prepared contained a mixture of polystyrene micro-spheres (index \( n_H = 1.57 \), Bangs Laboratories) and the low-index hollow spheres in de-ionized water in \( \sim 30 \) \( \mu \)m-thick glass cell. The sample is mounted on the microscope stage. Due to density mismatch, the polystyrene spheres (1.05 g/mL) settle to the bottom surface of glass cell while the air-filled hollow glass spheres (0.2 g/mL) float to the top portion. Axial adjustment of the MO allows us to view the two types of particles. To bring more particles into a particular region, we generate and scan a vertical line beam pattern resulting in the simultaneous deflection of low-index particles in the scan direction as shown in Fig. 5. Raking of the low-index particles is made either by non-mechanical scanning of the linear beam pattern using the graphical user-interface or by horizontal displacement of the microscope stage. This simple procedure allows us to drag a number of low-index particles into the operating region where polystyrene spheres are found directly below.
The ability to interactively generate and change phase patterns at the SLM in real-time allows each doughnut trap to be independently switched on and off, and be transversely displaced such that it correctly coincides with the position of the corresponding particle. In Fig. 6, we demonstrate the steps for trapping low-index particles with doughnut optical traps. In the first frame, a doughnut trap is positioned next to a particle which is located almost outside the field of view. From its initial position, the trap is then positioned directly in the location of the particle and moved slightly to the center of the observation region. In the third frame, a new trap is added by the click of the computer mouse and brought to one of the untrapped particles. The same procedure is done in the succeeding frames until all four particles are trapped as shown in the 15th frame. Once all particles are trapped, they are brought into a diamond formation (20th frame) and then into a linear arrangement (25th frame). The sizes of the particles vary within 6 – 10 \( \mu \text{m} \) and the corresponding doughnut traps are configured with appropriate diameters and thickness by a “click and draw” computer mouse sequence.

The high-index polystyrene spheres are lifted off the bottom surface of the sample cell by corresponding optical traps with top-hat profiles. As the high-index particles accelerate upward, they appear in-focus with the low-index particles pre-positioned at the upper surface of the sample cell. As high-index particles are brought to the upper glass surface by top-hat beams, doughnut optical traps are also created for low-index particles. Figure 7 shows a mixture of high- and low-index particles simultaneously trapped by top-hat and annular trapping beams, respectively. From an irregular spatial distribution, the particles are individually displaced and sorted according to their index contrast with the suspending medium. This process illustrates the versatility of the GPC method in generating trapping patterns with arbitrary (symmetric or asymmetric) spatial configurations in real-time.
Fig. 6. (AVI, 2.512 MB) User-interactive procedure for trapping different sizes of hollow glass spheres using doughnut optical traps.

Fig. 7. (AVI, 1.113 MB) Image sequences of trapping and user-interactive sorting of an inhomogeneous mixture of soda lime hollow glass spheres and polystyrene beads in water solution. (a) The particles are first captured by appropriate trapping beams and then (b-c) displaced one by one. The size of the beam used at each trapping site is proportional to the size of the corresponding particle. Arrows indicate the directions at which particles are transported. (d) Two separate rows of optically trapped high-index (lower row) and low-index particles (upper row). Scale bar, 10 µm.
Aside from the ability to individually manipulate high- and low-index particles, the system also allows one to pre-define the path and the speed of motion of each trapping beam. Such an experiment is illustrated in Fig. 8 where a row of high-index polystyrene sphere and a row of low-index particles are simultaneously set into oscillatory motion by corresponding trapping beams. The limiting factor for the dynamics of the trapping beams (but not necessarily the particle manipulation speed) is the response time of the liquid crystals in the SLM. For our nematic liquid crystal-based SLM, the response time (time needed for one SLM pixel to change between two extreme states associated with phase delays $0$ and $\pi$) is in the order of $\sim 100$ ms. On the trapping plane, this corresponds to a maximum average speed of $\sim 2.5 \ \mu\text{m} \cdot \text{s}^{-1}$ at which a trapping beam can be moved with quantization in displacement at the single pixel-image level. Faster average speeds of moving traps can be achieved by using displacement quantization of more than one pixel. However, this results in a coarser or more discrete motion of the traps. We note at this point that, contrary to other alternatives, the GPC method requires only (but not limited to) binary phase objects to generate 2D intensity patterns with arbitrary symmetry. This robustness permits us to take advantage of the faster response time characteristic to binary SLMs based on other technologies (e.g., ferroelectric liquid crystals, multiple quantum well devices and microelectromechanical system (MEMS) -based devices), and hence to achieve faster, yet smooth, trap displacements. On the other hand, the speed at which a particle can be displaced while maintaining its confinement in the trap depends on the stiffness of the optical trap and the hydrodynamic drag force induced to the moving particle by the viscous medium. The trap stiffness for both the top-hat and annular beams may be improved by increasing the power of the input beam to the SLM.

3. Conclusion

We have demonstrated the use of a real-time user-interactive array of trapping beams with tailored intensity profiles for the interactive manipulation of microscopic particles with opposite index contrast with respect to the suspending liquid medium. High- and low-index particles suspended in water find confining optical potentials in trapping beams with top-hat and annular transverse profiles, respectively. To our knowledge, this is the first demonstration of simultaneous trapping and user-controlled manipulation of multiple high- and low-index particles using optical traps. Arbitrarily shaped trapping beam configurations are obtained from the light-efficient conversion of SLM-encoded phase patterns into corresponding intensity distributions by the generalized phase contrast method. Although in principle the GPC approach is applicable at other operating wavelengths, the use of biologically non-invasive NIR laser source (e.g. 830 nm) makes the current system highly attractive for optical manipulation of colonies of cells in aqueous solutions. Finally, we envision that the technique offers a versatile tool for studying particle dynamics in a variety of aqueous systems.
containing both high- and low-index microscopic objects and has the potential for optically powering specially fabricated microstructures with irregular geometries or inhomogeneous optical properties [16].

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