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Actuation of microfabricated tools using multiple GPC-based counterpropagating-beam traps

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Abstract: We explore the functionalities of a generalized phase contrast (GPC) -based multiple-beam trapping system for the actuation of various microfabricated SiO₂ structures in liquid suspension. The arrays of optical traps are formed using two counterpropagating light fields, each of which is spatially reconfigurable in both cross-sectional geometry and intensity distribution, either in a user-interactive manner or under computer supervision. Design of microtools includes multiple appendages with rounded endings by which optical traps hold and three-dimensionally actuate individual tools. Proof-of-principle demonstrations show the collective and user-coordinated utility of multiple beams for driving microstructured objects. The potential to integrate these optically powered microtools may lead to more complex miniaturized machineries – a closely achievable goal with the real-time reconfigurable optical traps employed in this work.

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10. The peer-review process made us aware of a recent article [S.L. Neale, M. P. MacDonald, K. Dholakia and T. F. Krauss, “All-optical control of microfluidic components using form birefringence”, Nat. Mat. 4, 530-533 (2005)] that shows rotation of a microfabricated structure in a circularly polarized light due to form birefringence.
1. Introduction

Optical forces permit the non-contact handling and controlled manipulation of fluid-borne microscopic objects. Aside from spherically symmetric particle, which is readily trapped in three-dimensional potential well created either by a pair of counterpropagating Gaussian beams [1] or by a single-beam gradient trap known as optical tweezers [2], microfabricated objects with anisotropic geometries have been actuated using optical means. One of the key motivations for synthesizing custom-shaped structures is geared towards realization of miniaturized machines, which mimic or perhaps even outperform their macroscopic analogues – e.g. their fabrication or operation can be made highly parallel. Optical tweezers formed by a tightly focused linearly polarized laser beam has been utilized both for rectilinear [3,4] and angular [4] control of tools such as micromechanical mass-spring system, and hinged submicron tweezers and needles. Linear momentum carried by optical tweezers could also induce torque to illuminated object that is artificially shaped to have rotational symmetry, thereby causing it to rotate [5-7]. Birefringent materials have been micromachined and shown to angularly align itself with the polarization direction of the laser tweezers [8] and can be made to rotate about its axis at rates up to hundreds of Hertz when trapped by circularly polarized light [9-10]. To our knowledge, previous demonstrations of light-driven translational and rotational control of microfabricated elements have been limited to use of single laser trap directly actuating one microtool.

Here we describe the first demonstration of a combined use of multiple real-time reconfigurable optical traps for efficiently manipulating microfabricated objects and demonstrate various actuation schemes (i.e. translational, rotational and angular control) we have achieved as a result of having a plurality of optical manipulators. Manipulation of shape-defined structures with multiple traps has not been exhibited previously either with time-shared, holographic or generalized phase contrast (GPC) -based optical trap arrays. These multiple-beam trapping techniques are well-known for their ability to manipulate a plurality of microspheres. In this paper, we also report the efficacy of the GPC-based counterpropagating-beam trap arrays in actuating microstructures fabricated to have flat or specifically coinlike handles (instead of trivial spherical endings). These specific structures may be highly difficult to, in the same manner, trap and manipulate using holographic or time-shared tightly focused optical traps since, both theoretically [11] and experimentally [12], flat coinlike microdisks are known to align their longest diagonal with laser tweezers’ propagation axis.

Optical traps are formed by first synthesizing a desired intensity pattern at an image plane via the GPC method [13,14]. As a highly contrasted image of a phase object encoded on a spatial light modulator (SLM), the efficiently synthesized intensity pattern is proportional to the time-averaged, squared modulus of a linearly polarized field distribution projected at the image plane. An array of polarizing components placed immediately after the image plane adjustably modulates the spatial polarization distribution of the incident field. By placing relay optics and a polarizing beam splitter along the field’s path, two beam patterns (s-
polarized and p-polarized) are created and are then directed to a sample chamber with opposite Poynting vectors, thereby forming multiple counterpropagating-beam traps for microparticles in the sample [15-17].

The succeeding section describes the fabrication procedure and design considerations of the microstructures. In Section 3, we outline some experimental results showing various ways of driving these microtools with the use of real-time adjustable optical traps. Finally, we give our concluding remarks and future outlook on this work.

2. Design and fabrication of micromachine elements

We make microstructures by etching elements with lithographically defined shapes from a uniformly deposited thin layer of SiO$_2$ material. The following straightforward and simple procedure is used: 1.0 μm-thick layer of SiO$_2$ is uniformly deposited on both sides of a standard silicon wafer (100). On another wafer, a 1.5 μm-thick photoresist is spin-coated followed by a 30-minute HMDS (hexamethyldisilazane) treatment in an oven. Geometrical shapes of the microtools were defined by standard UV lithography of the photoresist to form a mask. After development of the photoresist, the pattern is transferred to the SiO$_2$ layer by an anisotropic reactive-ion etch and the remaining resist residue is removed in acetone. The microtools are then released completely from the wafer by under-etching the structures in an isotropic silicon etch consisting of HF and HNO$_3$ (1:2). The acidic solution containing the microtools is then passed through a mechanical filter followed by addition of water to stop the slow etching of the tools and to ensure the removal of the remaining HF and HNO$_3$. Finally, the water solution containing the microtools is slowly heated in a Petri dish, allowing the microtools to be dried and viewed under a microscope. Some prototypical microtools we have designed are based on simple polygons or include multiple appendages with coinlike disks at their endings (or vertices for polygonal structures) by which counterpropagating-beam traps would hold and control individual tools. Examples are these structures are shown in Fig. 1. The currently employed fabrication procedure allows us to synthesize structures of defined lateral shapes and of uniform thickness. More intricate 3D structures with finer features resolved down to an order of 100 nm could be synthesized using two-photon polymerization techniques [3,4] or by multiple electron beam lithography steps. For simple structures, photolithography offers vast parallelism due to the small size of the individual microstructures, giving literally millions of structures from a single four-inch silicon wafer.

![Fig. 1. SEM images of SiO$_2$ microfabricated structures.](image-url)
3. Actuation of microtools by multiple counterpropagating-beam traps

The optical setup for generating a reconfigurable array of counterpropagating-beam traps has been described in detail elsewhere [15-17]. Briefly, the multiple traps result from two geometrically similar and reconfigurable transverse intensity patterns that are projected to the sample coaxially but in opposing manner by two identical objective lenses facing each other. A typical intensity pattern would be an array of tophat-profiled beams, which together with the other oppositely propagating set of beams create a collection of three-dimensional (3D) optical traps in the sample region. The setup has been optically engineered such that opposing beams have orthogonal polarization (s-polarized and p-polarized) and that each pair has adjustable power difference but preserved power sum. All these controllable features enable the user to specify the number of traps, each trap’s lateral extent (or shape), and to define the 3D positions of trapped particles.

So far, the GPC-based 3D optical manipulation system has only been applied to large ensembles of colloidal microspheres [16]. In this work, the system’s efficacy for powering and actuating specially fabricated and shaped glass structures with micrometer dimensions and submicron features is demonstrated. Functionally shaped micro/nanofabricated structures and their manipulation by multiple optical traps have more potential applications in the horizon which are not viable with colloidal spheres. As described in the previous section, one prototype microstructure was fabricated to include handle-ended limbs extending from the main body of the structure. Shown in Fig. 2(a) are user-positioned optical traps that hold a prototypical structure by their rounded handles. To make the microstructure lie on a particular plane perpendicular to the optical axis (z-axis), the symmetrically positioned pairs of counterpropagating beams must possess identical power differences in their s- and p-polarized

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Fig. 2. Explanatory illustration of an optically actuated four-limbed micofabricated structure. (a) Respective counterpropagating-beam traps, formed by s-polarized (down-pointed arrows) and p-polarized (up-pointed arrows) beams, are positioned at all four circular handles. Arrow length is proportional to beam power. (b) Purely translational displacement Δr of the structure in 3D. (c) Angular orientation of the structure about a line parallel to the x-axis. (d) Angular orientation about a line at 45° with x-axis and y-axis.
components. Figure 2(b) shows the whole microstructure displaced in 3D but without any angular displacement. This purely translational displacement $\Delta r$ of the structure’s center-of-mass can be decomposed into displacements $\Delta x$, $\Delta y$ and $\Delta z$ along $x$, $y$ and $z$ directions, respectively. While $\Delta x$ and $\Delta y$ are defined by a common position displacement of the trap centers in the $xy$-plane, $\Delta z$ is governed by the power differences of the $s$- and $p$-components of the traps. Introduction of displacements $\Delta x$, $\Delta y$ and $\Delta z$ can be implemented either sequentially or simultaneously. In Figs. 2(c) and 2(d), angular orientation or tilt about different horizontal axes (lying on the $xy$-plane) is shown possible by alteration of individual power differences in some or in all optical traps.

Dry microstructures lying on a Petri dish were extracted by repeated discharge and suction of 100 $\mu$L distilled water using a manual pipette. The sample channel made from bonded pieces of microscope coverglass is then filled with the liquid containing the microstructures by capillary effect. Next, the sample is mounted on a motorized $xyz$-translation stage that allows its high-precision positioning between two opposing objective lenses. Digital video microscopy is employed to monitor and grab images of the structures through one of the objective lenses.

One of the microstructure we have located and manipulated is the four-limbed object shown in Fig. 3. In this figure, different actuation schemes of the structure are demonstrated. Using the procedures described in Fig. 2, we are able to perform the following: (i) tilt the structure in a manner that allows us to examine its flatness (Fig. 3(a)); and (ii) lift the structure along the $z$-axis making its image out of focus (Fig. 3(b)). Additionally, we are able to rotate the structure about its center (at typical rates of ~4.5 rpm) while keeping it lie on the $xy$-plane (Fig. 3(c)). This is done by simultaneously setting the four counterpropagating-beam traps in circular orbital motion in the transverse plane while maintaining them in square-configuration. The sense of rotation can be set clockwise or anti-clockwise, at will.

![Fig. 3](image_url)

Fig. 3. Experimental results showing optical actuation of a microstructure. (a) Angular reorientation showing approximately 80° maximum angular deflection, which allows visual inspection of the structure’s flatness. (b) Axial displacement of the structure. (c) Rotation of the structure about a normal axis through its center. Scale bar, 20 $\mu$m.
4. Conclusion

We have shown the performance of multiple counterpropagating-beam traps, obtained from a GPC-based trapping system, for real-time and computer-controlled actuation of microfabricated SiO₂ elements in liquid host medium. The user-coordinated utility of a collection of optical traps has enabled us to translate, rotate, or angularly tilt microtool-prototypes in 3D. The ability of the GPC-based system to specify the number of traps and reconfigure the individual location of each trap’s potential minimum in 3D shows a strong aptitude for integrating optically driven microelements that may be assembled, by light itself, into functional upper-hierarchy micromachines in the future. In practice, such integration is expected to require a larger number of trapping beams and thus entails high-power laser sources (typically ~10 W of raw output power). Our current GPC system based on liquid-crystal-based SLM technology may likely not withstand this amount of energy. However, next-generation GPC-based optical trapping system with a relatively high input laser power tolerance is currently being developed [18].

The low efficiency of acquiring a number of structures that can be readily manipulated in the trapping region is an issue of concern—a matter we are currently addressing by improving our sample filtering procedures. Moreover, the microstructures may be optimized to increase trapping stability and improve actuation control both by fabricating spherical (alternative to coinlike) handles and by employing higher refractive index materials such as polymers. Furthermore, the ability to precisely customize the shape of microtools towards specific applications is expected to be a key issue in future works.

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