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Optically driven micromachine elements

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We report on a proof of principle demonstration of an optically driven micromachine element. Optical angular momentum is transferred from a circularly polarized laser beam to a birefringent particle confined in an optical tweezers trap. The optical torque causes the particle to spin at up to 350 Hz, and this torque is harnessed to drive an optically trapped microfabricated structure. We describe a photolithographic method for producing the microstructures and show how a light driven motor could be used in a micromachine system.
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In recent years, the trend toward micronization in research and development has turned toward production of micromachines and molecular motors, which have potential mobility, information transfer and energy efficiency advantages over macromachines. The best known micromachines are the microelectromechanical systems (MEMS), which incorporate mechanics together with electronics on a microscopic scale. Microscopic electromagnetic motors and piezoelectric and electrostatic actuators have been incorporated into MEMS.[1] Other novel driving mechanisms suggested for micromachines include a dielectric fluid motor based on convection,[2] an opto-microengine relying on the same principles as a Crookes' radiometer,[3] and optical angular momentum from a highly focused laser beam.[4] In this letter we use optical torque to drive the rotation of a microfabricated machine element that is confined in an optical tweezers trap.

The torque produced by piezoelectric inchworm motors with diameter of several millimeters can be of the order of 10^{-3} Nm.[5] Here we describe an experiment to harness optical torque to drive the rotation of a micron-sized element, which can be driven with optical torque of the order of 10^{-15} Nm. Recently, controllable rotary motion was observed on a molecular level,[6] where the required torque will be smaller still.

Using optical torque allows rotation of an element without mechanical contact, so the device can be rotated while in a sealed environment. We outline a photolithographic method for producing transparent ''machine elements'' with features on the order of 1 μm, which are then trapped on an optical ''axle'' and caused to rotate about this axle by a nearby spinning particle driven by optical torque.[7] A dual beam optical tweezers trap, steerable in two dimensions as well as having a movable focus,[8] allows the microfabricated element and a birefringent particle to be confined in separate traps and then moved relative to each other. The polarization of the trapping laser beam is responsible for transferring optical torque to the birefringent particle, and when circularly polarized can result in the particle spinning.[7] The spinning of the birefringent particle can induce rotation of the machine element when the spinning particle is brought near the microfabricated structure.

The microfabrication process we describe here is designed to produce large numbers of identical structures for use in our optical torque experiments, where optical tweezers are used to trap and rotate objects with characteristic dimensions of the order of microns. Using optical tweezers places some restrictions on the structure size, shape, and optical properties.

The shapes we produce must be transparent to the trapping laser beam to avoid optical damage, and must have refractive index higher than the surrounding medium (water in our experiments) in order to be optically trapped three dimensionally. We used amorphous SiO_2 (silicon dioxide) as it meets these requirements, being transparent in the visible spectrum with index of refraction 1.46.

A photolithographic *double liftoff* technique, similar to techniques developed for electron-beam lithography,[9] was developed to fabricate the structures. It was possible to use photolithography rather than electron beam lithography because of the large feature size and overall large size. The first step in the fabrication process is to make a glass photolithography mask for the structures using electron-beam lithography. The double liftoff technique is then used to produce free structures in solution.

The first step in the double liftoff technique is the spinning and baking of two resist layers onto a silicon wafer. The resists used were PMMA 4% (bottom layer, 180 nm) and Shipley S-1813 (top layer, 1500 nm). This process is followed by an UV contact exposure of the mask pattern, and the pattern for the desired shape is exposed and developed in the upper resist layer only. The exposed pattern is then developed away, leaving pattern-shaped depressions the depth of the top layer. A SiO_2 layer is deposited onto the patterned resist layers through electron beam evaporation under vacuum. The top resist layer is then completely removed along with the SiO_2 layer lying on it, leaving the shapes on the bottom resist. Slightly dissolving the bottom resist will then release the structures into a liquid suspension.

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The torque transfer experiments require structures that are disk-like and as small as possible in overall size. Using photolithography it is possible to fabricate structures of diameter 10 μm with features on the order of 1 μm. We found that stable trapping of SiO_2 shapes of diameter 10 μm was not possible for thickness less than 0.5 μm, which is the upper limit of thickness achievable with the photolithographic double liftoff method.

The shape of the SiO_2 structures is disk-like. This shape is not the most suitable for optical trapping, rather it is the most suitable shape for this demonstration. We chose to fabricate shapes with six ''teeth,'' to facilitate observation and measurement of rotation.

Optical torque has been transferred to microscopic particles due to photon absorption[10–12] and due to transmission through birefringent materials,[7,13] leading to light induced rotation of the particles. The rotation rates achieved in experiments involving birefringence were much higher than those using photon absorption, as overheating and unwanted radiation pressure forces are avoided, making this type of optical torque more suitable for exploring driving mechanisms for micromachines. Spin rates of up to 350 Hz were achieved for calcite ($CaCO_3$) fragments around 1 μm in size using 300 mW of 1064 nm laser light.

The angular momentum of light is changed on passing through a birefringent material, and by conservation of angular momentum the difference is transferred to the material, resulting in torque being exerted on the material by light. The effects of optical torque on birefringent materials are easily observed using extremely intense light sources and very small particles, as is the case in an optical tweezers trap. When the birefringent particles are confined on the beam axis, linearly polarized light exerts an angle-dependent torque that is minimized when the optic axis of the birefringent material is aligned with the plane of polarization. Circularly polarized light exerts constant torque that causes rotation at constant speed and frequency when the particle is trapped within a viscous medium.[11] Elliptically polarized light results in rotation with constant frequency but position dependent speed, as the ''alignment '' and ''rotation'' torques act simultaneously. These effects have been observed using naturally occurring birefringent material (calcite fragments)[1] and synthetically produced birefringent objects (fluorinated polyimide)[13].

In our experiments we trapped calcite fragments in circularly polarized light, resulting in torque on the calcite given by

$$\tau = \pm \frac{c\varepsilon}{2\omega} E_0^2 \{1-\cos[(n_0-n_e)]\}. \tag{1}$$

Here c is the speed of light, ε is the permittivity of the medium, ω is the optical frequency, E_0 is the electric field strength, k is the free space wave number, d is the thickness of the material, and n_o and n_e are the ordinary and extraordinary refractive indices of the material, respectively. The maximum torque that can be exerted by circularly polarized light occurs when the birefringent material is the correct thickness to be a $\lambda/2$ plate for the wavelength used, corresponding to $kd(n_o-n_e)=\pi,3\pi\ldots$, for example, a calcite particle 1.4 μm thick is a $\lambda/2$ plate for $\lambda=488$nm light. In this case the optical torque is given by $\tau=2P/\omega$. The maximum optical torque available is not large (for example, a 1W beam of 488 nm light would in this case provide torque of approximately 6.1×10^{-16} Nm), however this can still result in very high rotation speeds when the torque is exerted on microscopic particles.

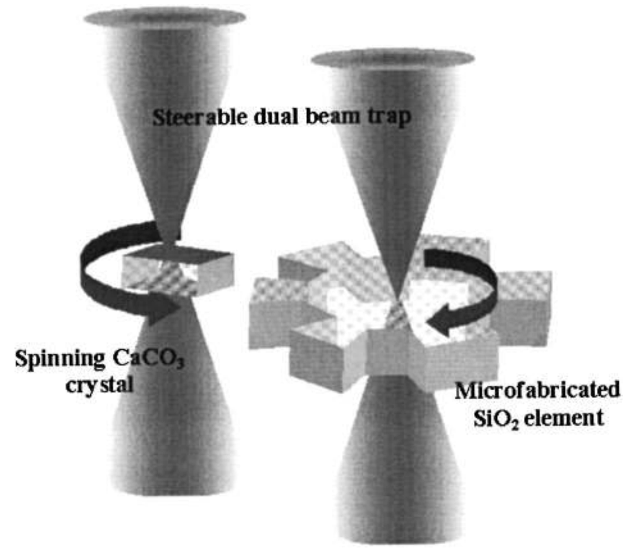

FIG. 1. Pictorial representation of a SiO_2 machine element being set into rotation by a spinning calcite crystal. The rotation is performed in a sealed cell. The details of the steerable double trap setup can be found in Ref. 8.

In this letter we report an experiment where optical torque is transferred to an optically trapped birefringent element, which is then used to drive the rotation of a nearby microfabricated element (a ''cog ''), also optically trapped. Two optical tweezer traps, both steerable in three dimensions, are used to trap and move a calcite fragment and a microfabricated SiO_2 structure relative to each other.

The SiO_2 structure and calcite particle are first trapped in separate traps, then the position of the beam waist of the optical trap is adjusted in the z axis so that the two elements are trapped in the same plane, then when the polarization of the trapping beam is made circular, the calcite begins to spin. The SiO_2 structure does not spin because it is transparent and nonbirefringent, and thus does not absorb or alter the angular momentum of the trapping beam. The two elements are then brought close together, whereupon the SiO_2 structure also begins to rotate. Both elements rotate about their own centers as the optical field of the laser tweezers trap provides an ''optical axle.'' The optical torque is transferred to the second particle via the motion of the surrounding fluid. Figure 1 shows a pictorial representation of the process, and several frames of a video recording of the experiment. In Fig. 2, the spinning calcite is rotating clockwise, causing the SiO_2 structure to rotate anticlockwise.

For this proof of principle demonstration we did not directly measure the rotation speed of the calcite, however by considering the laser power at the beam focus and our previous experiments using calcite, we estimate the rotation speed to be between 100 and 200 Hz. The SiO_2 is rotating at around 0.2 Hz. If we approximate the calcite fragment as a sphere having drag coefficient $D=8\pi\eta a^3$ (where η is the viscosity and a is the radius), and the SiO_2 element as a disc with $D=32/3\,\eta a^3$, we can obtain an estimate of the optical

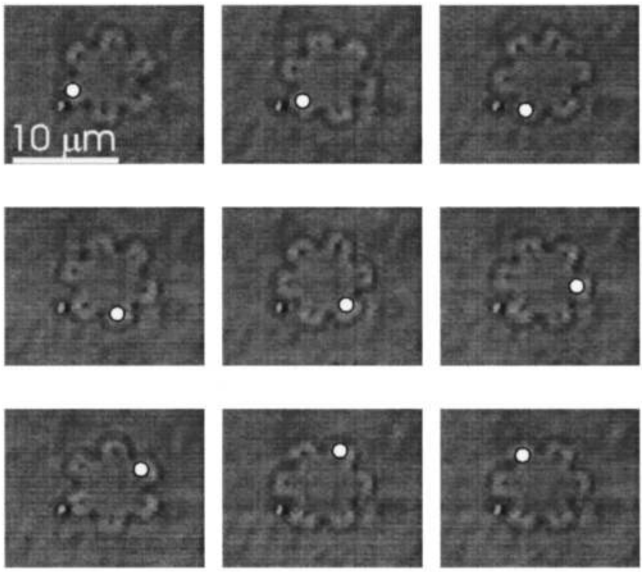

FIG. 2. Nine consecutive frames 0.5 s apart from a video of the experiment, showing the rotation of a SiO_2 structure about its own axis, due to a nearby spinning calcite fragment. The SiO_2 structure is 10 μm in diameter, and the calcite fragment is of the order of 1 μm in size.

torque and the efficiency. Using the viscosity of water at 300 K ($\eta = 8.5\times10^{-4}$ Nsm^{-2}), this corresponds to optical torque on the calcite of around 2.0×10^{-17} Nm, and torque on the 10 μm diameter SiO_2 element of 1.1×10^{-17} Nm, yielding an efficiency of the torque transfer between the two elements of a little over 50%. We estimate the actual efficiency to be somewhat lower due to the irregular shape of the calcite fragment.

Several other possibilities exist for torque transfer between the two elements, and two of these were achieved. With both elements confined in the same optical tweezers trap (calcite fragment on top), the torque is transferred via the fluid interface between the upper and lower surfaces of the SiO_2 and calcite, respectively. In this case both elements rotate with the same sense. If on the other hand the SiO_2 structure is not confined at all, it orbits the spinning calcite fragment, at about 0.1 Hz. Consecutive frames from videos of these two types of torque transfer are shown in Figs. 3(a) and 3(b).

In conclusion, we have developed a photolithography method to produce large numbers of identical SiO_2 structures suitable for optical trapping experiments. These structures have been used in a first principle demonstration of an optically driven motor. Future developments may improve and extend upon the result in a number of ways. Microfabrication of birefringent structures would enable machine elements to be directly driven by light rather than indirectly by a calcite fragment via a fluid interface. Simple birefringent structures of similar size as our SiO_2 structures have already been produced,[13] so production of more complicated shapes may soon be possible. The use of a spinning particle to drive fluid rotation in order to turn biological specimens has already been demonstrated.[14] Another potential use for the rotating structures is a microscopic fluid pump. Mounting a microfabricated birefringent cog onto a microscopic axle may be the next step, allowing production of an optically powered rotor for powering micromachines.

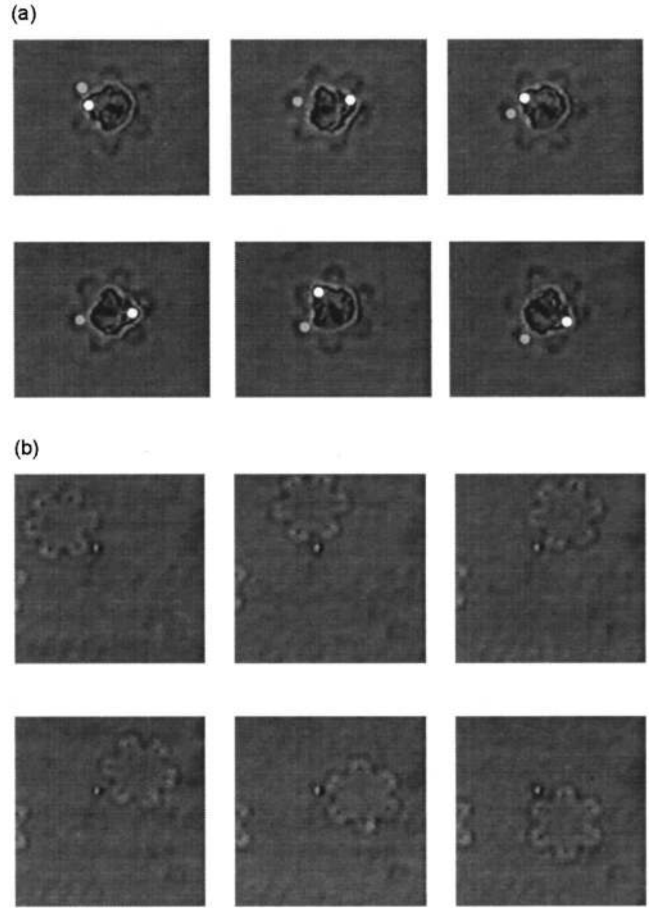

FIG. 3. Other mechanisms for achieving optical torque transfer to a microfabricated structure. (a) The birefringent particle and SiO_2 structure are trapped in the same optical potential, and rotate with the same sense. Frames are 0.2 s apart. (b) The SiO_2 structure is not confined, and orbits the spinning calcite with opposite sense to the calcite. Frames are 1.0 s apart.

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[1] T. Sakakibara, H. Izu, H. Tarui, and S. Kiyama, IEICE Trans. Electron. **E80C**, 309 (1997).
[2] Y. Otsubo and K. Edamura, Electron. Commun. Jpn., Part 2: Electron. **78**, 96 (1995).
[3] K. Kasahara, M. Ota, and M. Sakamoto, Thin Solid Films **282**, 651 (1996).
[4] M. Brooks, New Sci. **157**, 34 (1998).
[5] M. Bexell and S. Johansson, J. Electroceram. **3**, 73 (1999).
[6] N. Kourmura, R. W. Zijistra, R. A. van Delden, N. Harada, and B. L. Feringa, Nature (London) **401**, 152 (2000).
[7] M. E. J. Friese, T. A. Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop, Nature (London) **394**, 348 (1998).
[8] E. Fällman and O. Axner, Appl. Opt. **36**, 2107 (1997).
[9] J. Gold, B. Nilsson, and B. Kasemo, J. Vac. Sci. Technol. A **13**, 2638 (1995).
[10] H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, Phys. Rev. Lett. **75**, 826 (1995).
[11] M. E. J. Friese, J. Enger, H. Rubinsztein-Dunlop, and N. R. Heckenberg, Phys. Rev. A **54**, 1593 (1996).
[12] N. B. Simpson, K. Dholakia, L. Allen, and M. J. Padgett, Opt. Lett. **22**, 52 (1997).
[13] E. Higurashi, R. Sawada, and T. Ito, Appl. Phys. Lett. **73**, 3034 (1998).
[14] S. Bayoudh, M. Mehta, H. Rubinsztein-Dunlop, N. R. Heckenberg, and C. Critchley, J. Microsc. (to be published).