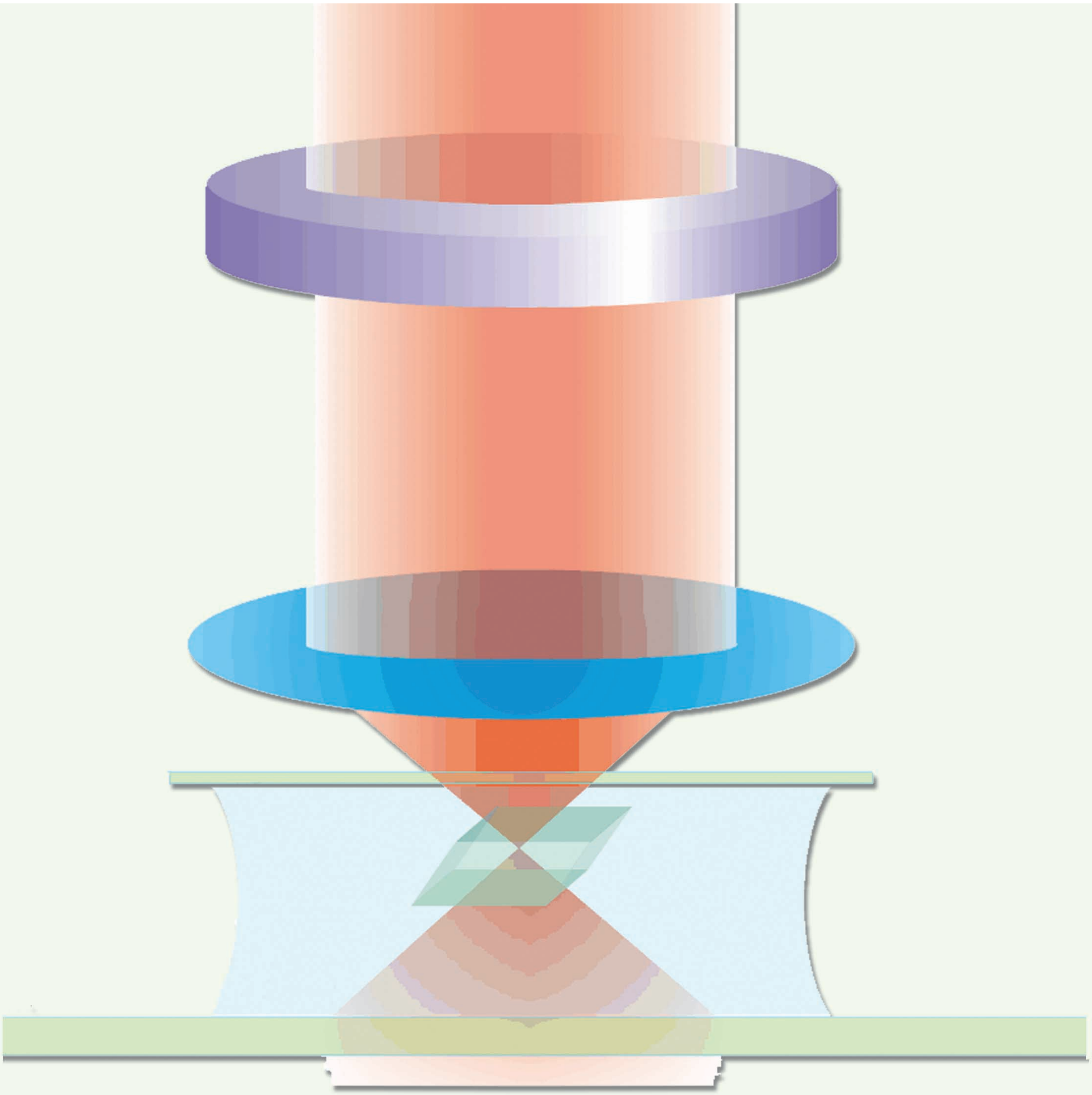

Light-Driven Micromachines

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It isn't uncommon for scientists to be inspired by science fiction, and good science fiction has a strong basis in real science. Modern science fiction is well populated with "nanobots" and "microbots," tiny robots that are injected into the bloodstream where they perform tasks ranging from repairing damage and curing diseases to controlling human thoughts and actions. The miniature robot concept may seem far-fetched today, yet technological advances in the area of micromachine research are bringing the possibility of devices like this much closer to reality.

Micromachines have potential advantages over macromachines in their mobility, information transfer rates, and energy efficiency. The best-known micromachines are the microelectromechanical systems (MEMS) that incorporate mechanics and electronics on a miniature scale. More along the lines of the fictional nanobots, microrobots have been fabricated with "elbows" and "fingers" that are capable of manipulating micrometer-sized objects.[1] Production of working micromachines has motivated research into microdevice production methods, surface engineering of the substrates, and driving mechanisms for the machines. Microscopic electromagnetic motors and piezoelectric and electrostatic actuators have been incorporated into MEMS. More novel driving mechanisms that avoid contact with the macro world suggested for micromachines include a dielectric fluid motor based on convection, an opto-micro-engine based on the same principles as a Crookes' radiometer, and the use of optical torque from strong sources of laser light.

Microdevices are getting smaller and are actually becoming nanodevices, and laser light has played a role in many of the advances that are making this possible. Together with other modern technologies, lasers have been used in almost all aspects of micro- and nanodevice research, including fabrication, construction, and as a source of torque to provide a driving mechanism. Laser light has been used to polymerize resins to produce structures with nanometer-sized features[2] and to bring together parts of a two-element moving microsystem.[3] In these and other experiments, light was also used to drive the rotation of the elements. The invention that has made these advances more possible is the *optical tweezers*,[4] an arrangement of optics and lasers that can be used to manipulate tiny objects and that provides an extremely intense source of light (around 10^{10} Wm^{-2} even in a low-powered system).

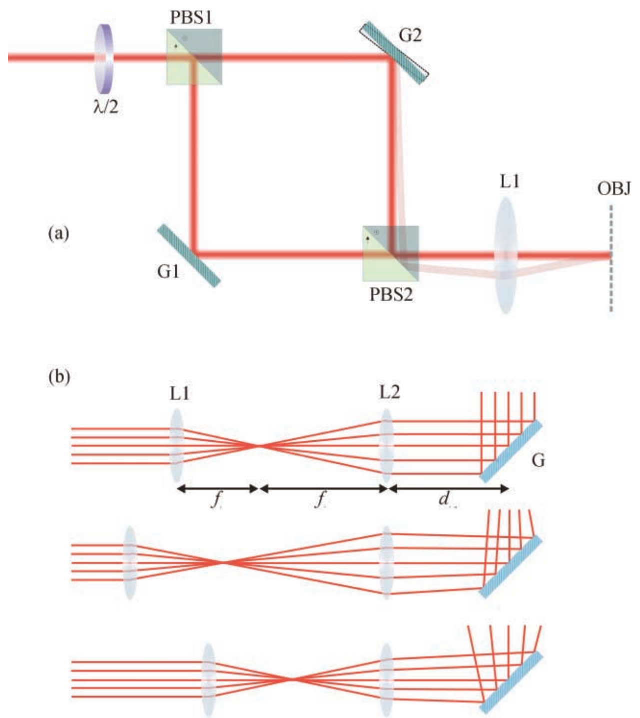

Figure 1. Laser beam configuration for multiple beam three dimensionally steerable optical tweezers setup.

(a) After passage through the first polarizing beam-splitting cube PBS1, the two beams are reflected off two gimble-mounted mirrors, G1 and G2, and are recombined on the second polarizing beam splitter PBS2. Lens L1 images the faces of G1 and G2 onto the exit pupil of the objective. Thus, tilting of G1 and G2 changes the angle at which the light enters the objective, enabling translation of the trapping beam in the xy plane.

(b) [After Fällman and Axner, Appl. Opt. **36**(10), 2107 (1996)]. Optical arrangement for manipulation of the z-position of the trapped object. This is achieved by the introduction of two lenses, L1 and L2, into the basic setup. L1 is mounted on a translation stage. Changing its position with respect to L2 alters the divergence of the beam without changing the spot size on the gimble-mounted mirror G. The face of G is then imaged onto the back pupil of the objective. The changes in beam divergence change the z-position of the beam waist.

Optical tweezers

Optical tweezers is the name that has been given to the single-beam gradient optical trap, an apparatus that in the most basic form consists of one very tightly focused laser beam. When laser light is focused to the smallest possible spot size, the intensity gradient near the focus is large, and gives rise to forces on transparent objects with different refractive indices to their surroundings. These forces enable the tiny objects to be confined in the beam focus and moved relative to their surroundings. Also present due to the tight focus is the extremely high intensity needed for performing experiments such as the modern "Beth's experiment," which will be described below.

The force exerted on transparent particles in a tightly focused laser beam is the same as a charged particle experiences when there is an electric field gradient present: whenever the particle moves from the most intense region, there is a restoring force pushing it back. This *gradient force* is the one acting on particles when the strong source of laser light is transmitted through them. A component of the

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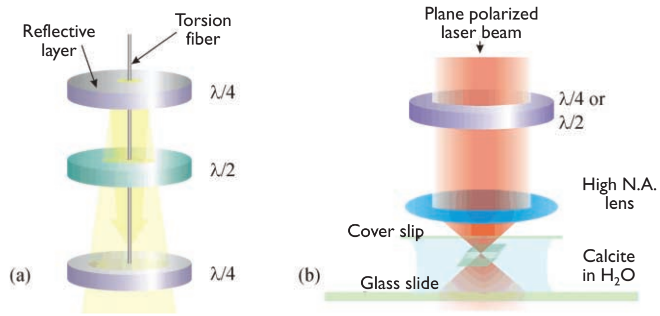

Figure 2. Schematic diagram for measurement of torque produced by polarized light as in the original Beth's experiment, (a), and as performed when using birefringent crystals in optical tweezers with polarized laser beams, (b).

(a) Linearly polarized light is passed through a birefringent material of the correct thickness to produce circularly polarized light (λ/4), at 45° to the optic axis of the material. The circularly polarized light is then passed through a λ/2 plate that reverses the handedness of the polarization, transferring angular momentum to the λ/2 plate. Two passes through a λ/4 plate flip the handedness again so that the second pass through the λ/2 plate transfers angular momentum in the same direction as the first, doubling the effect. The λ/2 plate is suspended on a torsion fiber and the period of oscillation is measured. In this experiment, 2ℏ per photon is transferred to the suspended plate.

(b) Basic setup for a single-beam gradient optical trap with the addition of wave plates, enabling optical-tweezers-based measurement of transfer of angular momentum of light to a birefringent micro-sized object. The optical setup consists of one laser beam with controllable polarization brought to a tight focus by a high-numerical-aperture objective lens, and a micrometer-sized object placed in a liquid solution between a microscope slide and a cover slip. The intensity gradient near the focus is large, giving rise to forces on the object. These forces enable the object to be confined in the beam waist and to be moved relative to the slide, if the slide is placed on a moveable stage.

For studies of angular momentum transfer from light to micrometer-sized objects, a plane polarized laser beam is passed first through either a λ/2 or λ/4 plate, and then through a fragment of calcite crystal. Because of its birefringent nature, the crystal acts as a wave plate. On passage through a birefringent material, the ordinary and extraordinary components of the incident light will undergo different phase shifts, introducing rotation of the electric field vector. The angular momentum of light will change and a corresponding torque on the material will occur. Depending on the state of polarization of the light incident on the crystal, the particle will align to the plane of polarization (linearly polarized incident light) or spin with constant rotation frequency (circularly polarized incident beam).

light may be reflected from the particle surface, and this reflection also gives rise to a force, because there is a change in the momentum of the light that must result in a change in the momentum of the particle. This force is called the *radiation-pressure* force. In a normal optical tweezers arrangement, the particles that can be optically trapped and manipulated are highly transparent, with a higher refractive index than their surrounding medium. For such materials, the gradient- and radiation-pressure forces combine to produce a restoring force that acts in all dimensions, so the particles are confined on all axes. Once a particle is confined in the beam focus, it can be manipulated by moving either the laser beam or the surroundings, which usually consist of a fluid medium sandwiched between a glass microscope slide and a coverslip.

Figure 2(b) shows the most basic optical tweezers setup as used in the modern version of Beth's experiment. More sophisticated optical arrangements allow increased flexibility and the possibility of some experiments that are truly exciting. For example, more than one laser beam can be introduced into the high-numerical-aperture objective lens at different angles [Fig. 1(a)], allowing multiple traps to be present and enabling the simultaneous manipulation of several particles. Changing the angles at which these beams enter the objective moves the beams around in the trapping plane; this approach is more useful for manipulation than is moving the surroundings, since it means the multiple beams can be moved independently of each other. Introduction of extra lenses into the basic setup [Fig. 1(b)] means the trapping plane can be moved vertically as well as horizontally, and if phase plates or wave plates are introduced into the light path, many different types of light fields with interesting properties can act on the particles.

Light as a source of torque

There are two basic ways that light can be used to drive the rotation of an object. In the first case, the torque originates from the light itself carrying angular momentum which can then be transferred to the object by processes such as transmission, reflection, and absorption. Types of light carrying angular momentum include elliptically polarized beams and beams with helical phase structure. In the second category, the torque originates from the shape of the object. Radiation pressure can act on asymmetries in the object's shape in a similar way to the way wind acts on the blades of a windmill: light deflected by the particle exerts torque to drive rotation.

Angular momentum caused by polarization

Scientists have known for a long time that certain types of light carry angular momentum, so that in principle it could be used to exert torque on an object. In practice, however, the effects of optical angular momentum are hard to observe, because they represent very small quantities. For example, the angular-momentum flux carried by a circularly polarized 10 mW HeNe laser beam is of the order of 10_{-18} Nm, which is millions of times smaller than the torque driving the balance wheel of a mechanical wristwatch. Each photon of circularly polarized light carries $\pm\hbar$ of angular momentum.

In his now famous experiment, carried out in 1936,[5] Richard Beth made the first measurement of torque produced by light, using a series of wave plates suspended on a torsion fiber [see Fig. 2(a)]. When linearly polarized light is passed through a birefringent material of the correct thickness (λ/4), it becomes circularly polarized. If this circularly polarized light is passed through a λ/2 plate, the handedness of the polarization is reversed, and in the process, angular momentum is transferred to the plate. In Beth's experiment, circularly polarized light was passed twice through a λ/2 plate suspended on a torsion fiber, and the period of oscillation was measured. Beth was able to confirm that the sign and magnitude of the effect agreed with theory.

To observe the same torque, a modern version of this experiment [Fig. 2(b)] uses laser light, optical tweezers, and microscopic wave plates, on the basis of the same idea that lies behind the use of circularly polarized light to drive the rotation of microscopic elements.[6] A laser beam is focused to a very small spot, providing an extremely intense light source, and is passed through fragments of calcite crystal. Because of their birefringent nature, calcite particles can act as wave plates; for example, a calcite particle 3 μm thick is a λ/2 plate for 1064 nm light. On passage through a fragment of calcite, the ordinary and extraordinary components of the incident light will undergo different phase shifts and the electric field vector will rotate [Fig. 3(a)]. As this results in a change in the angular momentum carried by the light, there will be a corresponding torque on the material. Depending on the polarization of the incident beam, the particles either become aligned with the plane of polarization (and thus can be rotated through specified angles) or spin with constant rotation frequency.

Polarized light can also exert torque on an object if the material is absorbing. In this case, if the light carries both linear and angular momentum, both will be absorbed by the material. Not only does the rotating object feel force in the direction of light propagation, it is also heated as it absorbs energy from the field. This means that high rotation speeds cannot be achieved, since the increase in laser power required to increase the spinning rate will burn the rotating element. Although the phenomenon is quite interesting scientifically, because of these extra effects it is less useful as a possible driving mechanism for rotating microscopic objects.

Helical light and propeller beams

The source of the polarization torque is the rotation in time of the electric field vector of the light field. Light can also exert torque if the wave front associated with the field is rotating in time. Here the wave has a helical phase structure [Fig. 3(b)], while its electric field may be rotating or not. We call the angular momentum from polarization *spin* angular momentum, and the angular momentum due to the helical structure *orbital* angular momentum. Just as passing light through a wave plate can produce circularly polarized light, helical light can be produced when light is passed through a phase plate (often a computer-generated holographic pattern). Combinations of the two are of course possible if the light is prepared using both wave and phase plates.

Depending on the type of phase plate used, light with many intertwined helices can be created. Orbital angular momentum can be transferred to an object by absorption or reflection, and can also be used to spin tiny particles trapped using optical tweezers.[7] When light absorption is the cause of the angular momentum transfer, both spin and orbital angular momentum can be transferred to the material at the same time. It is then possible to change the rotation rates of the spinning objects by a simple rotation of the wave plates, or by reversal of the helicity of the wave.

One of the well-known types of helical light is the Laguerre-Gaussian (LG) laser mode. Each photon of an LG beam carries $l\hbar$ of orbital angular momentum, l being the number of intertwined helices. So even though the heating effects and radiation pressure force occurring due to absorption of the field are present, much larger amounts of angular momentum can be present in such fields than is possible using polarized light alone. The quantity l is known as the "charge" of the laser mode. If phase plates were made to produce extremely high-charge LG beams, this type of light possibly could be used to drive rotation of objects despite the unwanted heating effect.

LG beams were recently used in a novel way, that does not depend directly on their orbital angular momentum, to rotate microscopic particles[8] [see Fig. 3(b)]. An LG charge three beam was interfered with a plane wave, to produce a spiral interference pattern with three arms within an optical tweezers trap (described in the following section). The arms of the pattern rotate when the path length of the interferometer is changed, so particles that are trapped in the bright regions of the arms are rotated too. These "propeller beams" offer a technique that does not depend on intrinsic properties of the particles (e.g., on birefringence) and also avoids absorption of the field. The method requires that the particles be transparent and have a higher refractive index than their surrounding medium.

Optical tweezers and light-driven machines

Microscopic particles trapped in the tightly focused beam of an optical tweezers trap often tend to rotate, either due to their own shape or through interaction

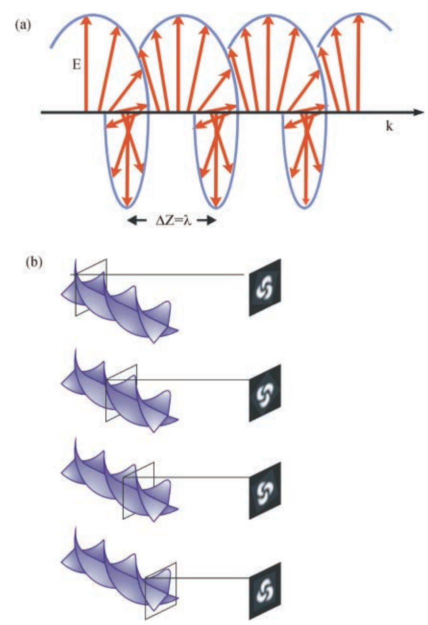

Figure 3. (a) The electric field vector of circularly polarized light. Each cycle, the electric field vector rotates 2π radians. The rotation of the electric field vector at the optical frequency is associated with the spin-angular momentum of a circularly polarized photon.

(b) [Figure by K. Dholakia, School of Physics and Astronomy, St Andrews University, Scotland.] The phase fronts of an LG beam of charge l = 3, and the intensity pattern when interfered with a plane wave. Such a wave with a helical-phase structure can be produced, for example, by passing a Gaussian beam through a holographically produced phase plate. After passing through such a plate, the helical wave can carry $l\hbar$ angular momentum, where l is known as the charge of the light mode. This helicity can then be combined with the rotation of the electric field vector or can be used alone. The intensity pattern when interfered with a plane wave is the configuration used in the propeller beam experiments.[8]

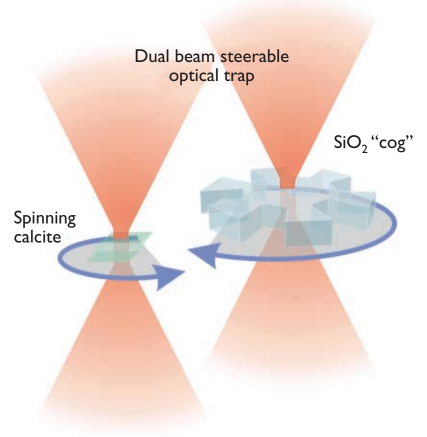

Figure 4. Optically driven and assembled micromachine. Dual fully steerable optical tweezers are used. The first trap is used to trap a birefringent crystal, the second is used to trap the "cog." The light providing the trapping is circularly polarized and the crystal rotates. The other trap provides the means for bringing the "cog" close to the spinning crystal, so that the rotation of the cog is induced. The torque here is transferred from the rotor to the machine element via the fluid surroundings. The dual optical tweezers provide axles for the rotor and the machine element.

with light carrying angular momentum. Both these effects have been used to drive the rotation of microscopic machine elements.

In a recently reported method of building microscopic light-driven rotors,[2] optical tweezers were used in both the production and manipulation of the rotors. Microscopic particles of arbitrary shape were produced by a two-photon polymerization method. The group used a resin that, when polymerized, results in a glass-like material with refractive index n=1.56, ideal for handling with optical tweezers. The light source for the polymerization process was an Ar-Ion laser, which at the focus was intense enough to initiate two-photon excitation. To build the structures, the beam focus was moved along a preprogrammed trajectory and a three-dimensional shape was built up from the line along which the resin was hardened. Using this method, arbitrary shapes with features of about 0.5 μm could be constructed. The researchers experimented with different shapes including helix, sprinkler, and propeller, and found that the most efficient shape for rotation was the sprinkler shape, with an added central linear axis to improve stability in the optical tweezers trap. Using 20 mW in the optical trap produced rotation rates of several hertz.

By use of this method, a complex micromachine consisting of two engaged cogwheels rotated by a light-driven rotor was constructed. The rotor was held and driven by optical tweezers and the cogwheels rotated on axes fixed to the glass surface. The same techniques could be used to produce much more complicated arrangements, offering a promising method for constructing micrometer-sized, light-driven machines.

Micromachine elements have also been driven by light by transferring the angular momentum from photons to a microscopic particle, which was then used to drive rotation of a microfabricated element.[3] Once again, optical tweezers played an important role in the experiment. Two fully steerable traps were used to hold and manipulate the light-driven rotor and the microfabricated element. The rotor consisted of a microscopic fragment of birefringent calcite, which could be induced to spin at hundreds of hertz when trapped in circularly polarized light. The microfabricated elements were made of SiO_2 using a photolithographic double-liftoff technique, and were cog-like shapes 10 μm in diameter and 0.5 μm thick.

Once trapped, the rotor was moved next to a trapped cog (Fig. 4). When the light was circularly polarized through rotation of a λ/4 plate, the calcite spun, inducing rotation of the nearby cog. In this experiment, the torque was transferred from the rotor to the machine element via the fluid between them. The optical tweezers acted as an axle for both particles to rotate about.

This proof-of-principle experiment has at least one obvious drawback: energy is being lost to the fluid that could be used to drive the element. If the machine elements could be made from a birefringent material, then light could be used to drive the elements directly, eliminating the need for the calcite.

Production of more complicated shapes may soon follow, because simple birefringent structures of a similar size to these cogs—and which show the same behavior in polarized light as calcite—have already been produced.[9] The advantages of light-driven microscopic rotors and machine elements are obvious: the non contact nature of the driving mechanism means that these micromachines can be operated in any microscopic systems that are accessible by laser light. Microrotors may find application as instruments for measuring properties of biological systems such as torsional elasticity of biological polymers or microscopic viscosity. Spinning birefringent particles have already been used to turn biological specimens so they can be viewed from different angles[10] and for studies of cell membranes. With further advances in fabrication materials and methods, the manufacture of microscopic fluid pumps for extremely localized delivery of chemicals will become possible. Optical tweezers and optical scissors have been joined by the optical spanner and the propeller beam, providing tools to trap, manipulate, cut, align, turn over and rotate a wide range of micro and nano objects. It seems certain that these laser tools will continue to make their mark in the world of micro-engineering.

The references to this article appear on p. 60, OPN's reference page.

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