The ability to remotely control matter with lasers has had a major impact in physics and biology, and has now reached the point where researchers can construct new types of material

Optical tweezers: the next generation

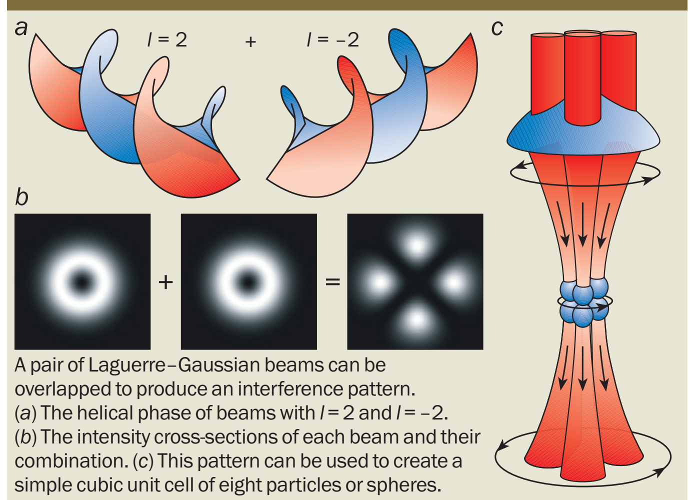
Kishan Dholakia, Gabriel Spalding and Michael MacDonald

JOHANNES Kepler is famous for discovering the laws of planetary motion, but he is less well known for writing what may have been the first science-fiction story to involve space travel. During his observations, the German astronomer noticed that tails of comets always point away from the Sun, which suggested that the Sun was exerting a sort of radiant pressure. This led him in 1609 – the year in which he published the first of his laws – to propose sailing from the Earth to the Moon on light itself. Of course, that was and still is the stuff of science fiction, but 400 years later Kepler's initial ideas about moving matter with light are very much a reality.

While it may not be the most practical way of moving matter at the macroscopic scale, there is intense interest in optical manipulation and assembly at the microscopic scale, not least from biological researchers. Light can move matter because photons carry momentum: a photon of wavelength λ has a momentum $p = h/\lambda$, where h is Planck's constant. Therefore, when an atom emits or absorbs a photon its momentum changes in accordance with Newton's laws of motion. Similarly, when a microparticle changes the direction of a beam of light as a result of reflection or refraction, it will also experience a force (see box on page 32). The upshot is that, in addition to Kepler's radiation pressure, there are other, *gradient* forces that, for small objects, will be sufficient to allow optical manipulation of matter.

The first optical traps were built by Arthur Ashkin at AT&T Bell Labs in the US in 1970. "Levitation traps" used the upward-pointing radiation pressure associated with a stream of photons to balance the downward pull of gravity, whereas "two-beam traps" relied on counter-propagating beams to trap particles. Then, in 1986, Ashkin and colleagues realized that the gradient force alone would be sufficient to trap small particles. They used a single tightly focused laser beam to trap a transparent particle in three dimensions. "Optical tweezers" had arrived in the laboratory.

1 Double helices



A pair of Laguerre–Gaussian beams can be overlapped to produce an interference pattern. (*a*) The helical phase of beams with $l = 2$ and $l = -2$. (*b*) The intensity cross-sections of each beam and their combination. (*c*) This pattern can be used to create a simple cubic unit cell of eight particles or spheres.

Moving particles with light

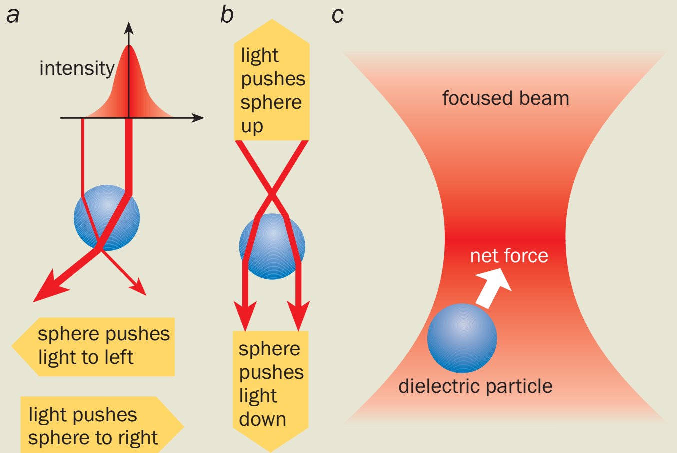
Optical tweezers work because transparent particles with a higher index of refraction than their surrounding medium are attracted towards the region of maximum laser intensity. By moving the focus of the beam around, it is therefore possible to transport the particle. Indeed, with optical tweezers it is possible to grab and move dielectric objects and biological samples – ranging in size from tens of nanometres right up to tens of microns – at will. Although the optical forces might only be of the order of piconewtons, such forces can often be dominant at the micro-level.

For the optical gradient forces to be significant, the laser beam must be tightly focused. This calls for a microscope objective lens with a high numerical aperture (which is a measure of the angle at which the beam approaches the focal point). The same lens may also be used to image the trapped object, but care should be taken to ensure that the laser beam is never allowed to reach the observer's eyes.

In the absence of aberrations, a laser power of about a milliwatt is sufficient to trap a single small, transparent particle – such as a biological specimen – in three dimensions. Although particles that are not transparent may well be pushed out of the focal region, one may stably trap a very wide range of materials by tailoring the wavelength or the beam properties.

Optical tweezers have been widely used for almost two decades in applications as diverse as experiments on molecular motors in biology and the movement of Bose–Einstein condensates in physics. And in recent years the capabilities of single optical tweezers have been greatly extended by the

How optical tweezers work



In a "levitation trap" the laser beam balances the pull of gravity. To "optically" trap a particle in three dimensions it is necessary to exert a "longitudinal" force in the same direction as the laser beam and a "transverse" force at right angles to the beam. The transverse force is created by having the maximum laser intensity at the centre of the beam. (*a*) If the particle is to the left, say, of the centre of the beam, it will refract more light from the right to the left, rather than vice versa. The net effect is to transfer momentum to the beam in this direction, so, by Newton's third law, the particle will experience an equal and opposite force – back towards the centre of the beam. In this example the particle is a dielectric sphere. (*b*) Similarly, if the beam is tightly focused it is possible for the particle to experience a force that pushes back towards the laser beam. (*c*) We can also consider an energetic argument: when a polarizable particle is placed in an electric field, the net field is reduced. The energy of the system will be a minimum when the particle moves to wherever the field is highest – which is at the focus. Therefore, potential wells are created by local maxima in the fields.

development of tailored beams (see box on page 33) and by schemes for generating large numbers of trapping sites and shapes simultaneously. These developments have led to a whole new generation of experiments.

Optical techniques offer a highly controlled driving mechanism that avoids any physical contact with the outside world. This is particularly important when working with biological samples because conventional micromanipulators can clog, contaminate or even react with the system under study. Used in conjunction with more conventional microfluidic drives, optical tweezers could be used to clear minor blockages in microchannels and to optically reroute samples. They could also be used as the basis of other microcomponents such as pumps, valves and reservoirs. In the future it might even be possible to make analytic microarrays that can be dynamically reconfigured for so-called lab-on-a-chip technologies.

Optical rotation

We can think of optical tweezers as a key component in an "optical toolkit" that can be used in a wide range of experimental research. Every toolkit needs rotary drives and the optical toolkit offers several non-contact ways of driving gears in micromachines. While early optical tweezers simply trapped and moved particles, it has now become possible to spin particles at high speeds and also to orient two particles in separate traps and then join them together. There is also immense interest in the use of optical tweezers for fundamental research in physics, such as recent theoretical and experimental work on the orbital angular momentum of light.

Orbital angular momentum is distinct from spin, which is intrinsically linked to the behaviour of the electric field in the light: we commonly associate spin with circularly polarized light and it has a magnitude of $\hbar = h/2\pi$ per photon. Orbital angular momentum, however, is a consequence of inclined wavefronts. Unlike the planar wavefronts that are found in standard beams, inclined wavefronts can be found in special types of light beams (e.g. "optical vortices"), notably Laguerre–Gaussian modes (see box on page 33). Importantly, the orbital angular momentum of light can vastly exceed $\hbar$ per photon.

Optical tweezers offer an ideal way of studying the different types of angular momentum because the torques involved are strong enough to make microscopic particles rotate. In the case of *spin* angular momentum, optical tweezers can be used to make a microscopic analogue of Richard Beth's famous 1936 experiment in which he measured the torque on a suspended quartz wave plate when it was illuminated with circularly polarized light. (The handedness of the light actually changes when it passes through the plate.)

In the modern version of Beth's experiment, Halina Rubinsztein-Dunlop's group at the University of Queensland in Australia used optical tweezers to show that crushed fragments of birefringent material can act like microscopic wave plates and be set into rotation through the same mechanism. Experiments by several groups have also shown that orbital angular momentum can be transferred by absorption or scattering. Both areas of study continue to provide deep insights into this fascinating topic in optical physics.

Péter Galajda and Pál Ormos of the Hungarian Academy of Sciences in Szeged and Eiji Higurashi's group at the NTT Optoelectronics Laboratories in Japan have demonstrated that radiation pressure can easily turn particles that are shaped like fan blades. Galajda and Ormos, for instance, used two-photon polymerization to fabricate tiny optical windmills. The sense of rotation of these windmills can be reversed by forcing the windmill to sit at a different position near the focus of the trapping laser.

Another way to rotate trapped particles is to use a laser beam with an elliptical or asymmetric beam pattern that rotates: the optical gradient force will then drag trapped particles round with it. Such rotating beams can be made by using rotating apertures – this technique was pioneered by Shunichi Sato of Tohoku University in 1991 and was recently improved by Anna O'Neil and Miles Padgett of Glasgow University.

Rotating beams can also be created by interfering a Laguerre–Gaussian laser mode with a Gaussian laser mode (see Paterson *et al.* in further reading). The number of arms in the resultant spiral interference pattern can be tailored to fit the shape of the object that you want to rotate, and the pattern can be set into continuous rotation by creating a frequency shift between the interfering modes. Significantly, by changing the effective path length of one of the interfering beams, we can control the rotation speed or, if required, dictate the orientation of the trapped particles. This technique has been used to rotate and align Chinese hamster chromosomes and also groups of rod-like particles. Indeed it is now possible to orient two, separately trapped particles and then dock them together in lock-and-key assemblies.

Advanced trapping geometries

One of the most exciting developments in optical tweezers in recent years has been the creation of two- and three-dimensional arrays of optical traps. There are several ways to do this but it is not as straightforward as might appear at first glance.

For example, Yusuke Ogura and co-workers at Osaka University in Japan recently used a vertical cavity surface emitting laser (VCSEL) array to create an 8 × 8 array of trap sites. It is also possible to create an array of traps by scanning a single laser beam over different locations. Although each site is only illuminated part time in this time-sharing approach, the average potential well is strong enough to trap a microscopic object provided that the laser "visits" each trap location often enough to overcome any problems due to particle diffusion. However, the most powerful current approach to the creation of multiple traps involves the use of diffractive optical elements to realize holographic optical tweezers.

Traditionally, a hologram is created as an interference pattern between two beams – a reference beam and an image beam that has been reflected from some 3D object. The hologram retains both phase and amplitude information, which means that "replaying" the hologram with a reference beam reforms an exact 3D image of the object. However, the original object is not really required in order to create the hologram, so long as we can calculate what interference pattern its presence would have produced.

This means that rather than taking a 3D "photograph" of an object that already exists, we can use the hologram to create something that does not exist – in this case an array of optical tweezers or traps. To do this we need to use computer-generated holograms. We start with the pattern that we want to create at the plane of the optical tweezers (e.g. a circular trap, a set of line traps or some more complex geometry) and work backwards to compute the hologram that will produce this pattern when illuminated by a standard laser beam.

Holograms can be designed to modulate the amplitude and/or the phase of an incoming beam. However, phase-only modulation has become the preferred mode because the trapping strength depends on the laser intensity and amplitude modulation implies throwing away some of the incident beam energy. For such phase-only holograms, an iterative algorithm is used to calculate the pattern required (see Dufresne *et al.* in further reading). The calculated phase-modulation pattern can then be etched on a glass plate or some other transparent material in surface relief with conventional lithographic processes: the beam is phase modulated because different parts of it have to pass through different path lengths of glass.

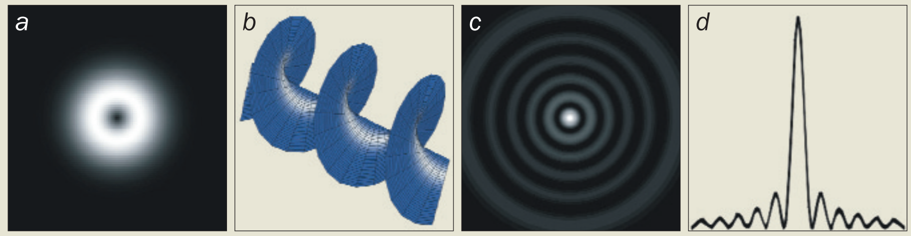
Once a phase-modulation pattern has been etched on a glass plate it cannot be changed. But imagine the possibilities of combining computer-generated holograms with real-time reconfigurability. Recently such dynamic control has become possible.

One way of creating dynamic holographic optical tweezers is to use a liquid-crystal spatial light modulator, as first achieved in 1999 by Yoshio Hayasaki and co-workers at the University of Tokushima, Japan, and by Marcus Reicherter's group at the University of Stuttgart, Germany. By locally (at each pixel) adjusting the orientation (birefringence) of the liquid crystal, it is possible to vary the effective optical path length, thereby creating a phase modulator. Using this technology for holographic optical tweezing, David Grier's group at the University of Chicago has generated nearly 2000 traps in a plane and more than 400 traps in a 3D orthorhombic crystal.

Earlier this year Jesper Glückstad's group at the Risø laboratory in Denmark introduced a technique in which there is a direct correspondence between phase modulation at the spatial light modulator and intensity modulation at the tweezing plane. This reduces the computation times needed for updating the trapping potential and lowers the demands on the spatial light modulator. This method is similar to the phase-contrast imaging method for which Frits Zernike received the 1953 Nobel Prize for Physics.

The technology for spatial light modulators will continue to improve as manufacturers increase the number and density of pixels in devices, and also the number of discrete phase

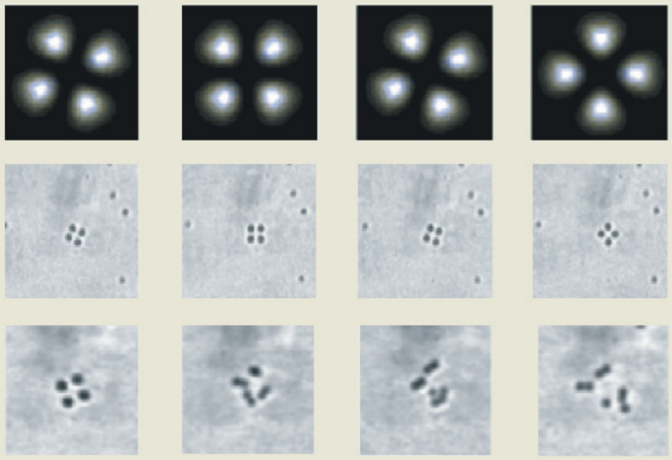
Novel laser beams



V Garcés-Chávez, D McGloin

All photons have intrinsic angular momentum or "spin", so a circularly polarized laser beam can also have spin angular momentum. However, it is also possible to produce laser beams with *orbital* angular momentum. This orbital angular momentum is carried by states of the electromagnetic field that have phase singularities – regions where the phase takes on all values between 0 and 2π, and where the intensity must be zero. In recent years several groups have exploited the properties of a class of laser beams with orbital angular momentum, so-called Laguerre–Gaussian beams, in a range of advanced optical-tweezer applications. Laguerre–Gaussian beams are defined by two integers, l and p, that are related to the azimuthal and radial properties of the beam, and have helical wavefronts that can be used to sweep trapped particles in continuous orbits around the phase singularity. The figures show the intensity cross-section of a Laguerre–Gaussian beam with $l = 1$ and $p = 0$ (*a*) and its helical phase front (*b*). Laguerre–Gaussian beams can be used to rotate trapped particles and also offer enhanced axial-trapping efficiencies by reducing the deleterious effects of radiation pressure. Lasers can also be used to produce other types of beams, such as Bessel beams. The figures show the intensity cross section (*c*) and the intensity profile (*d*) of a zero-order Bessel beam. Bessel beams have various properties that are useful for tweezer applications: for example the central maximum of a zero-order Bessel beam is "non-diffracting", which means that it propagates without much spreading. Bessel beams can therefore be used to channel or guide atoms and micro-particles over extended distances. Particles can also be trapped in the rings of the Bessel beam, and it is also possible to manipulate stacked chains of particles and to rotationally align rod-like particles along the core of the beam. This can be performed in multiple sample cells all arranged along the beam path (see Garcés-Chávez *et al.* in further reading). Higher-order Bessel beams also have orbital angular momentum.

2 Keeping matter in its place



Two Laguerre–Gaussian beams can be overlapped and used to trap particles in a cubic unit cell as described in figure 1. The top panels show the different intensity cross-sections used, and the middle panels show the particles (silica spheres 1 μm in diameter suspended in water). The particles form a cubic structure containing eight particles, although only four can be seen in these images. Note how the orientation of the unit cell rotates along with the beam. The cubic structure falls apart when the laser is switched off (bottom panels).

levels in each pixel and the refresh rate. Combined with improved algorithms, these advances will open up new capabilities in dynamic traps. Of course, the ideal spatial light modulator for optical tweezing would not contain pixels – rather it would offer continuous modulation across its area. This would overcome the intensity losses associated with pixillation and also the problem of "diffraction noise", which is caused by high harmonics that are introduced into the holographic image as a result of the sharply defined pixels.

However, multiple optical tweezers have already been used in a number of applications. Earlier this year Alfons van Blaaderen and co-workers at Utrecht University in the Netherlands used 2D arrays of optical tweezers to template the growth of defect structures within colloid crystals, which represents a step towards the production of photonic band-gap devices. The eventual use of a phase hologram in the manufacture of photonic band-gap materials would represent a dizzying series of interactions between light and matter. The phase hologram – a textured piece of glass – would pattern light by introducing phase modulations in a laser beam. This beam would then create a holographic array of traps, which would be used to pattern matter by organizing microparticles into photonic band-gap materials and devices. And finally, this photonic crystal would create a pattern in light again!

At St Andrews we have used holographic elements to generate Laguerre–Gaussian modes, which we have then used to create 3D cubic structures. This work relies on the ability of tweezers to create stacks or "towers" of particles at a single site. And by combining Laguerre–Gaussian beams to produce interference patterns we can create multiple stacks of particles and rotate these structures as a whole (see MacDonald *et al.* in further reading and figure 1). We have, for instance, created a simple cubic unit cell by assembling four stacks that each contained two particles (see figure 2). These techniques could complement existing approaches to the large-scale assembly of 3D crystalline structures. Moreover, the use of specially designed phase holograms has already extended the capabilities of these new approaches.

Model thermodynamic systems

A holographic array of optical traps can create an array of potential wells that is analogous to the potential-energy landscape experienced by atoms when they land on a crystalline surface. Moreover, we can control the depth of the wells, the lattice spacing, the symmetry and so on in this "virtual substrate". We can also systematically tune the level of disorder: this allows us to observe the competition between particle–particle and particle–substrate interactions, and the effect of disorder on this competition. Such studies are highly relevant to understanding the behaviour of atoms on crystalline surfaces, glass formation, electron transport through charge-density waves, vortices in superconductors and many other areas.

Let us illustrate the potential for multiple, holographically generated optical tweezers with a recent experiment performed on a colloidal system. For our purposes a colloid is a collection of particles undergoing Brownian motion – for example a collection of glass spheres about 10 μm across, or less, suspended in water. In addition to the enormous practical importance of colloidal systems in industry – from paints to pharmaceuticals – such systems easily lend themselves to thermodynamic studies of ordering and phase transitions.

Surrounded by counterions that go into solution, colloidal particles act like a (much larger) model system of ions surrounded by electrons. Moreover, they are analogous in many ways to computational molecular-dynamics simulations because the particles are all the same size (to within 1% or 2%) and the interactions between them can be tuned: we can, for instance, screen out the Coulombic interactions by adding salt to the solution. And unlike simulations, it is easy to work with large numbers of particles (without the limitations of computer memory). Hydrodynamics can also introduce novel features that would have been non-trivial to predict through simulation. Finally, unlike shaken granular systems, which are another popular model system, the statistical dynamics of colloids are characterized by a real temperature.

Other advantages of colloidal systems include the fact that the particles are large enough to be fully imaged with fairly standard equipment and can therefore provide information about the detailed microscopic mechanisms – and the importance of statistically rare events – for various processes (e.g. melting or glass formation) in ways that are not possible with atomic systems.

Moreover, these dynamics can be imaged with standard video techniques: even spheres as small as 0.15 μm can only diffuse a distance that is comparable to their own diameter in about 30 milliseconds. The temporal resolution of a typical video-acquisition system is therefore sufficient for the study of isolated particles, and so we can extract the diffusion coefficient by tracking individual spheres.

As the collection of particles becomes less dilute, it also becomes more ordered and enables colloidal crystals to form: the timescales relevant to crystallization (e.g. the timescales that are relevant to defect motion and sound waves) are also observable. We have, for instance, observed the spontaneous assembly of micro- and nano-components in an optically defined "landscape" of potential energy; colloidal particles with a radius of 0.75 μm have self-assembled into various superlattice structures on top of a "virtual substrate" (figure 3*a*).

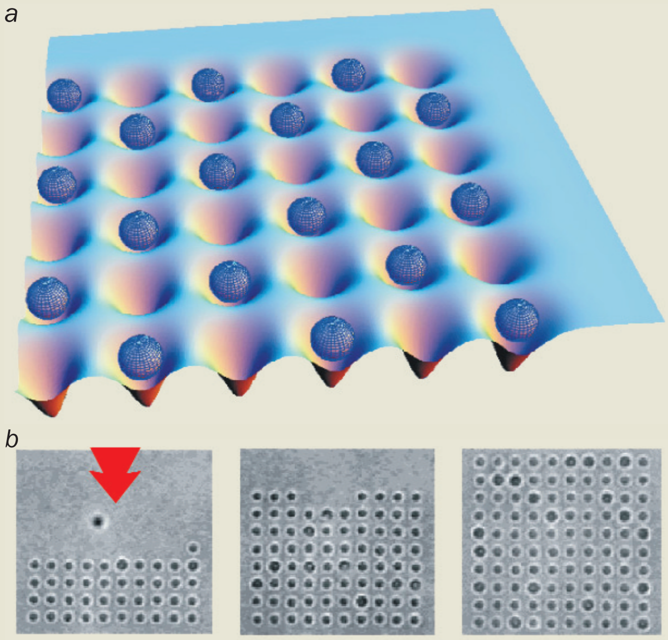
If the trap spacing is small, then reconstruction (superlattice formation) occurs. If the trap spacing is large, then a hierarchy of states containing interstitials can result. The dynamics of such systems are quite rich. Recently one of us (GS), Grier and Pam Korda at Chicago used holographic optical tweezing to study phenomena analogous to the incursion of vortices into a superconducting thin film (see Korda in further reading).

This was achieved by creating an array of optical traps that can "pin" otherwise mobile colloidal particles. By initiating a toroidal convection roll on the far side of a sample cell, we were able to "drive" the colloid into the "pinscape" from each direction. We observed avalanche dynamics and changes in the orientational order of the colloidal crystal as this process – which is driven by advection – occurred. These "virtual substrates" can also be used in experiments that are relevant to dynamic flow, continuously fractionating materials in suspension, and the creation of photonic band-gap devices.

If we want to crystallize an array of monodisperse particles, it may be sufficient to tweeze just the particles at the periphery, or perhaps to pin a few additional sites throughout the array. If external boundary conditions can be applied to initiate crystallization, then tweezing can be used to establish channels and other special features within the array. For interacting particles, both particle–particle and particle–trap interactions play important roles in crystal formation, and the competition between these interactions leads to rich phase diagrams. For example, light-induced melting, multi-stage melting and even re-entrant phase transitions have been observed by Aslam Chowdhury and Bruce Ackerson at Oklahoma State University, by Clemens Bechinger, Paul Leiderer and colleagues at the University of Konstanz in Germany, and in computer simulations by researchers at Harvard University and Los Alamos.

Optical tweezers were also used in a recent experiment with colloidal particles that observed deviations from the second law of thermodynamics under certain conditions. Denis Evans of the Australian National University in Canberra and co-workers showed that entropy could be consumed rather than generated in such a small system over short time intervals. The "violation" of the second law could be seen because we can now observe the dynamics of colloidal systems on sufficiently short length- and time-scales. This work has implications for the operation of nanomachines.

3 Adventures on a virtual substrate



P Korda, G C Spalding and D G Grier

(*a*) An ensemble of particles (blue spheres) can self-assemble onto a holographic landscape that is analogous to the potential surface presented to atoms on a crystalline surface. (*b*) Dynamic control of the holographic image is used to completely fill a tightly packed array (which is defined by the hologram) with silica spheres 1.5 µm in diameter suspended in water. The red arrow indicates the fluid flow that carries the microparticles into the holographic field, where the traps are turned on as the assembly process continues. The images in the middle and on the right show later stages of the filling process. Without dynamic control some traps would not spontaneously fill.

Outlook for optical tweezers

Interest in organizing micro- and nano-components into larger structures stems from many quarters. The technologies described here are relevant to the fabrication of novel chemical sensors and the burgeoning field of microelectromechanical systems (MEMS), as well as to many other fields where progress has been restricted by the need to configure non-lithographic structures at the microscopic level. Optical trapping and the manipulation of large numbers of particles could also make an impact in bioengineering, for example in attempts to control the organization of cells during organ and tissue growth.

Some of the optical toolkit is in place, but it is still evolving. Optical tweezers can now trap, orient and guide particles. Creating optical landscapes and assembling matter in three dimensions will provide new levels of control. Researchers in the field are poised to elucidate new forces (both optical and hydrodynamic) that will be of practical importance to both micromechanical and microfluidic systems, and there are sure to be advances in fundamental research as well. Moreover, the techniques used for optical trapping and the manipulation of large numbers of particles combine well with designs that take advantage of the novel light beams described earlier. It might sound like a cliché but the future for optical tweezers is bright.

Further reading

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