# A Revolution in Optical Manipulation

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An optical tweezer uses the forces exerted by a strongly focused beam of light to trap and move objects ranging in size from tens of nanometers to tens of micrometers. Since their introduction in 1986, optical tweezers have become a mainstay of research in biology, physical chemistry, and soft condensed matter physics. This review highlights recent advances that promise to take optical tweezers out of the laboratory and into the mainstream of manufacturing, diagnostics, and even consumer products. By providing unprecedented access to the mesoscopic world, the next generation of single-beam optical traps also offers revolutionary new opportunities for fundamental and applied research.

## I. SCIENCE WITH OPTICAL TWEEZERS

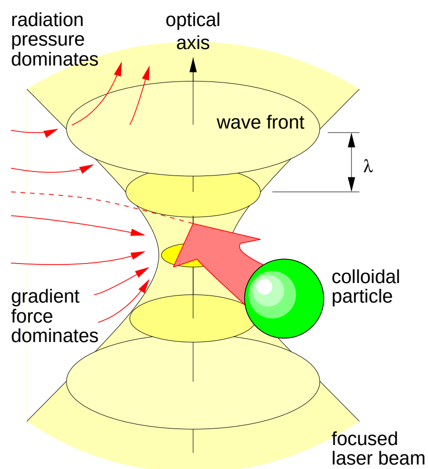


FIG. 1: A strongly focused beam of light creates an optical tweezer. Intensity gradients in the converging beam draw small objects, such as a colloidal particle toward the focus, while the beam's radiation pressure tends to blow them down the optical axis. Under conditions where the gradient force dominates, a particle can be trapped in three dimensions near the focal point.

The frontiers of several branches of science and engineering converge in a domain of physical conditions known as mesoscopia. Mesoscopic systems are characterized by length scales ranging from tens of nanometers to hundreds of micrometers, forces ranging from femtonewtons to nanonewtons and time scales ranging upward from a microsecond. In biology, this range covers many of the inter- and intracellular processes responsible for respiration, reproduction, and signalling. In physics and chemistry, it corresponds to the still-puzzling interface between classical and quantum mechanical behavior, made all the more perplexing by the general inapplicability of statistical many-body theory in this realm. The promise of mesoscopic engineering has been held in check by the need for tiny motors to drive micromachines, and for robust human-scale interfaces to atomic-scale nanotechnology. Until quite recently, the options for manipulating, analyzing, and organizing mesoscopically textured matter have been limited. A new generation of techniques based on the forces exerted by carefully sculpted wavefronts of light offer precisely the level of access and control needed for rapid progress across all of these fields.

Many of the most powerful optical manipulation techniques are derived from single-beam optical traps known as optical tweezers, shown schematically in Fig. 1, which were introduced by Arthur Ashkin, Steven Chu, and their coworkers at AT&T Bell Laboratories[2,3]. An optical tweezer uses forces exerted by a strongly focused beam of light to trap small objects. Although the theory of optical tweezing is still being developed, the basic principles are straightforward for objects much smaller than the wavelength of light, or much larger. Small objects develop an electric dipole moment in response to the light's electric field. Generally speaking, this is drawn up intensity gradients in the electric field toward the focus. Larger objects act as lenses, refracting the rays of light and redirecting their photons' momentum. The resulting recoil draws them toward the higher flux of photons near the focus[4]. This recoil is all but imperceptible for a macroscopic lens, but can have a substantial influence on mesoscopic objects.

Optical gradient forces compete with radiation pressure due to momentum absorbed or otherwise transferred from the photons in the beam, which tends to blow particles down the optical axis like a fire hose. Stable trapping requires the axial gradient force to dominate, and can be achieved if the beam

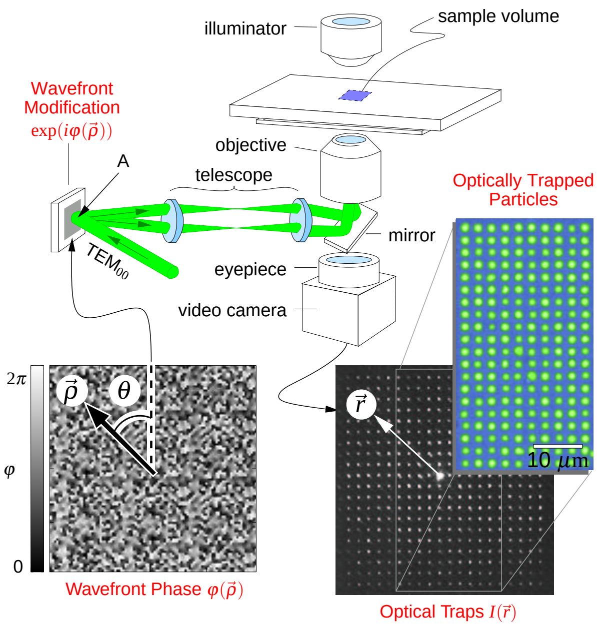


FIG. 2: Creating large numbers of optical tweezers with computer-generated holograms. Projecting a collimated laser beam through the input pupil of a strongly converging lens such as a microscope objective creates a single optical tweezer. The telescope in this implementation creates an image of the objective's input pupil, with the optical axis passing through point A. Multiple beams passing through point A therefore pass into the objective lens to create multiple optical traps. A single $TEM_{00}$ laser beam can be spilt into an arbitrary fan-out of beams all emanating from point A by an appropriate computer-designed diffraction grating centered there. The example phase grating $\varphi(\vec{\rho})$ creates the $20 \times 20$ array of traps shown in the video micrograph. These are shown trapping 800 nm diameter polystyrene spheres dispersed in water. Adapted from Ref. [1].

diverges rapidly enough away from the focal point. For this reason, optical tweezers usually are constructed around microscope objective lenses, whose high numerical apertures and well corrected aberrations focus light as tightly as possible.

Optical tweezers can trap objects as small as 5 nm[5,6] and can exert forces exceeding 100 pN[7–9] with resolutions as fine as 100 aN[10–12]. This is the ideal range for exerting forces on biological and macromolecular systems and measuring their responses. Biological and medical applications of optical tweezers have been reviewed extensively[3,13,14]; just a few examples suggest the range of activities. Optical tweezers have been used to probe the viscoelastic properties of single biopolymers such as DNA, cell membranes, aggregated protein fibers such as actin, gels of such fibers in the cytoskeleton, and composite structures such as chromatin and chromosomes. They also have been used to characterize the forces exerted by molecular motors such as myocin, kinesin, procecssive enzymes and ribosomes. Such measurements have revealed that cells use mechanical forces not only for mobility, motility, and chromosome sorting during reproduction, but also for regulating gene transcription, inter- and intracellular signalling, and respiration. As a natural extension of these studies, optical tweezers have shown great promise for intracellular surgery, for instance in modifying the chromosomes of living cells[15]. On larger scales, optical tweezers are useful for selecting individual microbes from heterogeneous populations. Their ability to transport and modify cells precisely have led to clinical applications in such areas as *in vitro* fertilization[16].

In the physical sciences, optical tweezers' unique ability to organize matter noninvasively has led to a burst of activity in classical statistical mechanics, including the first direct measurements of macromolecular interactions in solution[17]. Each new round of measurements has led to surprises, including the discovery of anomalous attractions between like-charged colloidal particles[18], oscillatory colloidal interactions mediated by the entropy of smaller entities in solution[19–22], and hydrodynamic fluctuations that may be interpreted as transient violations of the second law of thermodynamics[23].

In all of these cases, and a great many more, fundamental insights emerged from manipulating specially chosen systems at just one or two discrete points. New frontiers of science and engineering would present themselves if optical traps could interrogate more general and more complex systems at many points at once, if they could induce chemical as well as physical transformations, and if they could exert torques as well as forces. Recent advances in physical optics reveal that precisely such multifunctional optical traps can be crafted from single beams of light by subtly modifying their wavefronts. The result optical micromanipulators provide unprecedented access to the microscopic world.

## II. HANDS IN THE MICROSCOPIC WORLD

Figure 2 schematically depicts an optical tweezer system in which a strongly converging objective lens focuses beams of laser light into optical traps. A collimated beam passing straight into the lens' input pupil comes to a focus in the middle of the objective's focal plane, where it forms a trap. Sweeping the angle of incidence translates the trap across the field of view. Diverging the beam causes it to focus downstream of the focal plane, while converging it moves the focus upstream.

Translating an optical trap, creating multiple optical traps, and then converting these into multifunctional optical traps all are greatly facilitated by first forming an image of the lens' input pupil with the telescope in Fig. 2. Any beam passing through the pupil's image, centered at point A in Fig. 2, also passes through the actual pupil and forms a trap. Tilting the beam as it passes through the image scans the optical trap. A single rapidly scanned optical tweezer can trap multiple particles by dwelling briefly on each before moving on to the next[25–27]. The extent and complexity of such time-shared trapping patterns is limited by the time required to reposition multiple wandering particles. Scanned optical tweezers, furthermore, are restricted to the lens' focal plane. Even so, scanned optical tweezers have proved extremely useful for organizing planar assemblies of colloidal particles[28], for testing new ideas in statistical mechanics[29], and for measuring macromolecular interactions[30].

Placing a diffractive beamsplitter at point A converts a single input beam into several beams, each of which forms a separate optical trap. Such a beamsplitter can be implemented as a computer-generated hologram, and the resulting trapping patterns have come to be known as holographic optical tweezers (HOTs)[31,32]. To see how this works, consider multiple beams all passing simultaneously through point A on their way to being focused into optical traps. Their superposition creates a distinctive interference pattern centered at point A. Imprinting this pattern onto the wavefronts of a single input laser beam transforms the one beam into the several, and thus forms the same pattern of optical traps.

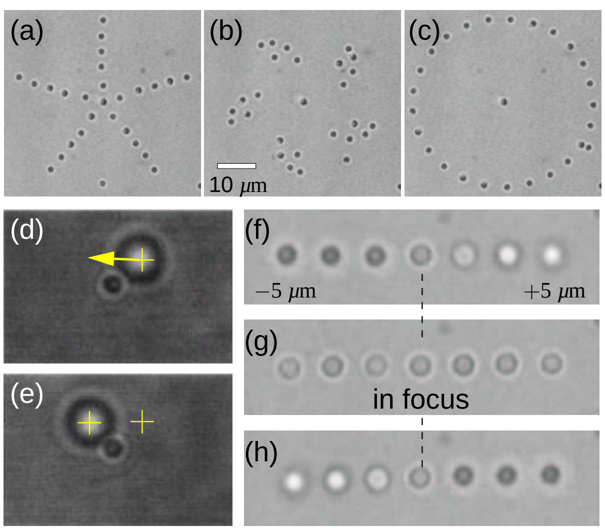


FIG. 3: Two- and three-dimensional configurations of optical tweezers created from a single laser beam with a computer-designed hologram. of a single beam's wavefront. (a), (b), and (c): Thirty-six water-borne polystyrene spheres, 800 nm in diameter, are trapped in a plane and reconfigured with dynamic trapping patterns, from Ref. [1]. (d) and (e): Two 1 $\mu$m diameter silica spheres being moved past each other in two different planes, from Ref. [24]. The spheres' different appearance results from their different heights relative to the microscope's focal plane. (f), (g), and (h): Seven 1 $\mu$m diameter silica spheres being moved up and down through seven different planes, from Ref. [1].

The input beam's electric field, $E(\vec{\rho})\, \exp(i\varphi(\vec{\rho}))\, \hat{\epsilon}$, around point A is characterized by a real-valued amplitude, $E(\vec{\rho})$, and phase, $\varphi(\vec{\rho})$, both of which depend on position transverse to the optical axis, and a polarization vector $\hat{\epsilon}$ describing the field's orientation. A multi-beam interference hologram generally would modify both the amplitude and the phase of the input beam, with the amplitude modifications diverting power away from the optical traps. Fortunately, a variety of iterative optimization algorithms have been developed[1,24,32] to create equivalent holographic beamsplitters that modify only the phase of the input beam. Such a phase-only diffractive optical element (DOE), also known as a kinoform, was used to create the 400 optical traps shown in Fig. 2.

The full utility of holographic optical tweezers is realized when a computer-addressed spatial light modulator (SLM) is used to project sequences of trap-forming kinoforms in real time. An SLM imposes a prescribed amount of phase shift at each pixel in an array by varying the local optical path length. Typically, this is accomplished by controlling the local orientation of molecules in a layer of liquid crystal, although arrays of microelectromechanical (MEMS) mirrors also are becoming available for SLM applications. Slightly displacing the traps from one pattern to the next transfers particles along arbitrary three-dimensional trajectories[1,24,33], animating matter with light in much the same way that cartoons animate light with matter. Figure 3 shows this principle in action.

In a variation on this theme, the generalized phase contrast (GPC) technique converts a pattern of phase modulation across an SLM's face directly into the corresponding intensity modulation in the objective lens' focal plane[34], and thus creates arbitrary planar trapping patterns. The conversion involves an annular phase plate similar to that used in phase contrast microscopy. This approach bypasses the need to calculate holograms, and thus is extremely efficient. The limited spatial resolution of existing SLMs currently limits GPC to creating lateral traps, rather than three-dimensional optical tweezers, but still has proved useful for rapidly organizing small objects in thin samples[35].

Even static arrays of optical traps have exciting and surprising applications. For example, an array of traps can continuously sort fluid-borne particles, playing much the same role as the gel in gel electrophoresis. The array sorts particles on the basis of their differing affinities for optical traps and an externally applied driving force. Inclining a regular array with respect to the driving force deflects the selected fraction so that it can be collected separately from the other, undeflected fraction[36]. Unlike most sorting techniques that operate on discrete batches of samples, optical fractionation works continuously, and can be dynamically optimized by adjusting the wavelength, intensity and geometry of the trap array. Moreover, because optical fractionation relies on object's abilities to hop from potential well to potential well, it is exponentially sensitive to particle size, and so promises unparalleled size resolution[37].

An array of traps also may be viewed as a tailor-made potential energy landscape for interacting colloidal particles. How strongly interacting systems evolve on modulated substrate potentials is a classic problem in statistical physics, and colloid in modulated optical fields constitutes a rare model system whose microscopic interactions can be measured and controlled as its macroscopic thermodynamic properties unfold[38,39]. Insights obtained from studying optically modulated colloid are relevant to such analogous systems as atoms adsorbed on crystal surfaces, electrons passing through charge density waves and two-dimensional electron gases, magnetic flux quanta passing through defects in type-II superconductors, and motor proteins translating along filaments in living cells. Early studies demonstrated that modulation along even one direction can freeze a two-dimensional colloidal fluid[40,41]. Deeper modulation actually melts the substrate-induced crystal[42] by suppressing inter-row coupling[43]. More recent studies have demonstrated still other intriguing behavior such as rotational melting in an array of multiply-occupied traps[39,44] and have shed new light on the mechanisms by which magnetic flux lines invade superconductors[38,39].

Time-varying potential energy landscapes created with dynamic optical traps promise new insights into molecular motors' operation by providing a powerful experimental system with which to study thermal ratchets[29] and related models in non-equilibrium statistical mechanics[45]. Once perfected, such ratchet potentials also will be useful for dynamically sorting mesoscopic objects and transporting them through tiny integrated laboratories for processing and testing[46].

All such studies provide valuable insights into how nature creates and exploits hierarchically organized structures. Once these principles are understood, they will be extraordinarily useful for creating new materials and devices to order. Until then, many of the most interesting three-dimensionally structured functional systems can be assembled using large numbers of optical tweezers operating in concert. Indeed, optical tweezers have an essentially unique ability to construct three-dimensional heterostructures with features ranging in size from a few nanometers to a few millimeters. The real power of this approach only becomes apparent when optical trapping is combined with other techniques to create permanent structures with embedded functionality.

## III. OPTICAL TWEEZER NANOFABRICATION

Once assembled, tweezer-organized structures can be fixed in place, for instance by sintering or gelling. The tweezers themselves can be used in this process. In particular, the intense illumination at an optical tweezer's focus is ideal for driving photochemical reactions. If the reaction rate depends strongly on intensity, the resulting spatially-resolved photochemistry can yield features smaller than the wavelength of light.

The first such application of optical tweezers involved the spatially resolved photo-oxidation of bi-

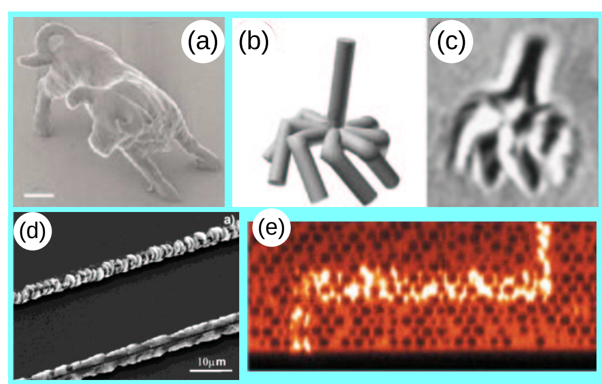


FIG. 4: The diffraction-limited focus of an optical tweezer is ideal for spatially localized photochemistry. (a) A photopolymerized sculpture whose finest features are roughly 100 nm across. From Ref. [47]. (b) Solid model of a photopolymerized turbine with submicrometer features. (b) The actual turbine shown suspended in water, from Ref. [48]. (d) Fine lines of $MoS_2$ deposited on a glass substrate by photoreduction of an aqueous salt solution, from Ref. [49]. (e) A three-dimensional fluorescent polymer structure embedded in a colloidal crystal, from Refs. [50] and [51].

ological materials such as chromosomes[52,53], essentially creating a scalpel from light. Optical scalpels and scissors have been used for surgery on living cells[16,54] as well as for ablating sub-wavelength structures into microscopic substrates[55].

Spatially-resolved photochemistry using optical tweezers has been used to fabricate small complex three-dimensional structures such as the examples in Fig. 4. Figures 4(a), 4(b) and 4(c) show three-dimensional plastic structures created by multiphoton photopolymerization in scanned optical tweezers. The smallest features in Fig. 4(a) are about 100 nm across. The tiny turbine in Figs. 4(b) and 4(c) not only was created in this way, but also was trapped and spun on its axis with an optical tweezer[48]. Arrays of interlocking turbines and gears assembled and driven by light already have been demonstrated[48]. Still other photochemical transformations provide opportunities for optical tweezers to create three-dimensional electronic and photonic structures. The fine lines of $MoS_2$ in Fig. 4(d) were patterned on glass by photoreduction of aqueous salts, and similar results have been obtained in silver, gold, and oxidized copper[49].

Beyond creating structures *de novo*, spatially-resolved photochemistry also can be used to modify pre-existing structures. The three-dimensional optical waveguide structure in Fig. 4(e) demonstrates this principle. Here, a self-assembled crystal of colloidal silica spheres was perfused with a photosensitive precursor and selectively patterned with an optical tweezer to create the embedded polymer structure shown in Fig. 4(e)[50]. Filling the gaps with a high-index material and then dissolving away the spheres and polymer would leave a tweezer-drawn waveguide pattern embedded in the otherwise self-assembled photonic crystal[56]. This hybrid approach to creating hierarchically structured materials could sweep away many of the practical hurdles that have prevented self-assembled systems from making bigger inroads in photonics and electro-optical systems[51].

Using large numbers of optical tweezers to organize prefabricated nanometer-scale parts and simultaneously to stitch them together with spatially-resolved photochemistry would yield a whole new category of hierarchically-structured materials and devices. Such scale-spanning heterostructures would provide the building blocks for sensors, photonic devices, and a host of other technologies. Hierarchically structured micromechanical systems hold similar promise for optomechanical and microfluidic applications. In this case, optical trapping also solves the outstanding problem of actuating such small devices. Some aspects of this solution involve the unusual and counterintuitive properties of traps created with newly discovered modes of light.

## IV. OPTICAL ACUTATORS

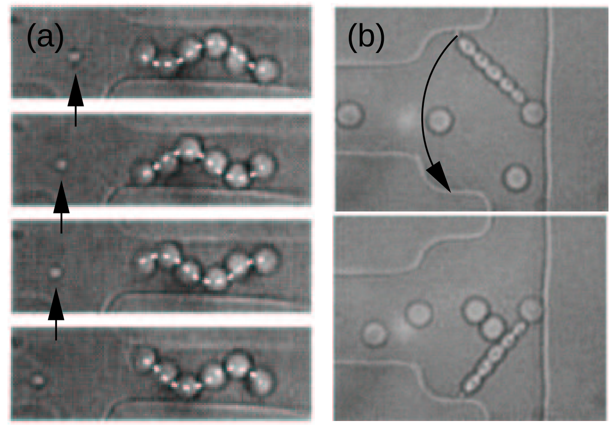


FIG. 5: Optical pump (a) and valve (b) constructed of colloidal particles in microfluidic channels activated with optical tweezers. The flow of water created by the colloidal peristaltic pump is visualized by the tracer particle indicated with an arrow. The colloidal valve flap is flipped with an optical tweezer and directs particles either downward (top) or downward (bottom). Adapted from Refs. [57] and [58].

Using conventional optical tweezers as actuators for micromachines is likely to speed the adoption of lab-on-a-chip and related technologies for medical diagnostics, environmental testing, and point-of-use microfabrication. Dynamic optical tweezers can both organize and drive devices such as the micrometer-scale hydraulic pump shown in Fig. 5(c). The microscopic valve flap in Fig. 5(b) is an example of a photopolymerized colloidal heterostructure both assembled and actuated with optical tweezers[58].

Modifying the optical tweezers' wavefronts transforms them into whole new categories of optical traps, some of which already have found applications as actuators for unconventional micromachines. Some of the most useful of these are based on exotic modes of light whose properties only recently have been elucidated.

Figure 6(a) demonstrates how the deceptively simple phase profile $\varphi(\vec{\rho}) = \ell\theta$ transforms the parallel wavefronts of a $TEM_{00}$ laser mode into the corkscrew topology of a helical mode[60]. Here, $\theta$ is the azimuthal angle around the optical axis and $\ell$ is an integer winding number also known as the topological charge. The modified beam no longer focuses to a point because the helical topology fosters destructive interference along the optical axis. Instead, it

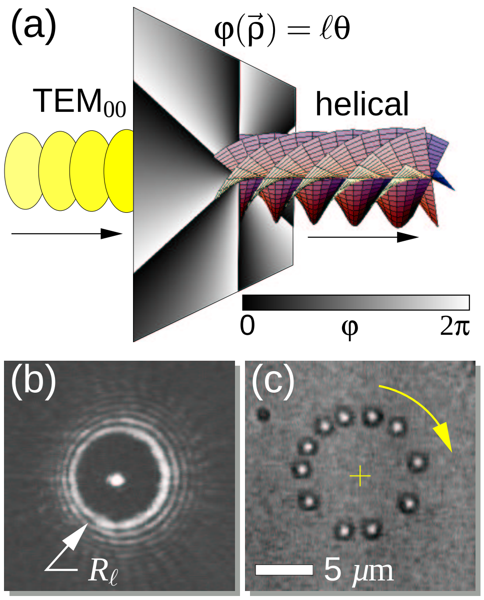


FIG. 6: (a) The helical phase profile $\varphi(\vec{\rho}) = \ell\theta$ converts a $TEM_{00}$ laser beam into a helical mode whose wavefronts resemble an $\ell$-fold corkscrew. (b) Rather than focusing to a point, a helical mode focuses to an optical vortex whose radius $R_\ell$ is proportional to its pitch, $\ell$. (c) A single colloidal particle trapped on the optical vortex travels around its circumference, driven by the helical beam's orbital angular momentum. This multiple exposure shows 11 stages in one 0.8 nm particle's transit in 1/6 sec intervals. Adapted from Ref. [59].

converges to a ring of light, as shown in Fig. 6(b). The dark focus is suitable for trapping reflecting[61], absorbing[62], or low-dielectric-constant[63,64] objects that would be damaged or repelled by conventional optical tweezers. Because such traps lack the radiation pressure due to axial rays, they also can make more efficient traps for large dielectric objects than conventional optical tweezers[65–67]. Smaller dielectric particles are drawn to the ring's circumference, as shown in Fig. 6(c).

What really distinguishes these ring-like optical traps is their ability to exert torques as well as forces[61,62,68]. Just a decade ago, Allen demonstrated that each photon in a helical mode carries an orbital angular momentum $\ell\hbar$ in addition to its intrinsic spin angular momentum[60]. This orbital angular momentum takes the form of a tangential component to the beam's linear momentum density that can be transferred to illuminated objects[59,69,70]. A single colloidal microsphere is shown circulating around such a topological ring-trap under the influence of the optical angular momentum flux in the time-lapse photograph of Fig. 6(c). Such toroidal torque-exerting traps have come to be known as optical vortices[71] or optical spanners[72] and they have potentially widespread technological applications. Studying objects' motions in optical vortices also has provided valuable insights into the interplay of photon spin and orbital angular momentum[59,61,68–70,73] which have been useful in elucidating the quantum mechanical nature of helical beams.

An optical vortex's radius, $R_\ell$, increases with topological charge[59,74], so that the intensity pattern can be tailored to different applications. For example, a properly scaled ring of light can be projected onto the teeth of a microfabricated gear thereby creating a reliable micrometer-scale motor. The distributed drive made possible by projecting multiple optical vortices also should help to alleviate problems associated with friction in micromechanical systems. The spin angular momentum carried by circularly polarized optical tweezers similarly has been used to apply torques to birefringent components[75–77]. Using an SLM to control the polarization of multiple optical tweezers then opens up still more possibilities for extensive micromachines assembled and driven with light.

Some micromechanical applications may require no microfabrication at all. Rapidly circulating particles entrain flows that can mix and pump extremely small volumes of fluid. This solves a problem in microfluidic systems whose laminar flows are ideal for transporting minuscule quantities of reagents, but do not promoting mixing when needed. Furthermore, the holographic optical tweezer technique can project multiple optical vortices, such as the $3\times 3$ array in Fig. 7(a), each with an individually specified intensity and topological charge[1]. Cooperative flows in such arrays can be reconfigured dynamically by modifying the trap-forming hologram, opening up the possibility of adaptive microfluidics on length scales ranging all the way do to tens of nanometers.

Other variations on this theme yield a family of distinct optical micromanipulators, each with its

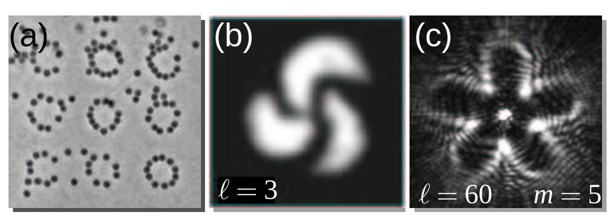


FIG. 7: Generalizations of the optical vortex principle. (a) An array of $\ell = 30$ optical vortices created from a superposition of helical beams, from Ref. [1]. (b) An optical rotator created by interfering an $\ell = 3$ optical vortex with a plane wave. From Ref. [78]. (c) An optical rotator created with a 5-fold modulation of the helicity of an $\ell = 60$ optical vortex. From Ref. [59].

own applications. For example, superposing a helical beam with a conventional beam not only visualizes the helical wavefronts' structure, as in Fig. 7(b), but also creates an oriented intensity pattern useful for orienting asymmetric objects[78]. Superposing instead a helical mode with its mirror-image counterpart creates three-dimensional arrays of discrete traps that can be rotated arbitrarily in three dimensions by varying the beams' relative phase[79]. Modulating the helical pitch of an optical vortex results in another class of optical rotators[80], an example of which appears in Fig. 7(c). Further generalizations create intensity patterns related to the caustics seen at the bottom of swimming pools and can move objects along complex trajectories transverse to the optical axis, all with static holograms and no moving parts. Still other superpositions focus to micrometer-scale dark regions surrounded by light on all sides known as optical bottles[81]. These are useful for trapping very small dark-seeking objects, including clouds of ultracold atoms[81]. Holographic arrays of optical bottles therefore should be useful for manipulating atoms[82], perhaps for quantum computing applications, and will help to extend pioneering efforts to apply optical tweezers in atomic physics[83,84].

Whereas azimuthal phase modulations extend optical tweezers into optical micromanipulators transverse to the optical axis, radial modulations create axial devices, again with an intriguing twist. The simplest nontrivial radial phase profile modification, $\varphi(\vec{\rho}) = \gamma\rho$, transforms a $\mathrm{TEM}_{00}$ beam into an approximation to a Bessel mode, a beam that propagates without diffracting even when focused to a wavelength-scale cross-section. The associated optical trap can extend for millimeters along the optical axis, as demonstrated in Fig. 8, and can push particles precisely over very large distances[85]. The extended range of Bessel-beam arrays should increase the throughput of optical fractionation by orders of magnitude. Still more remarkably, Bessel beams are impervious to distortions by intervening particles and surfaces[86], reconstructing their wavefronts as they propagate away from disturbances. Combining Bessel beams' robustness against diffraction with helical modes' orbital angular momentum yields optical devices that can reach deeply into complex systems to apply both forces and torques where needed.

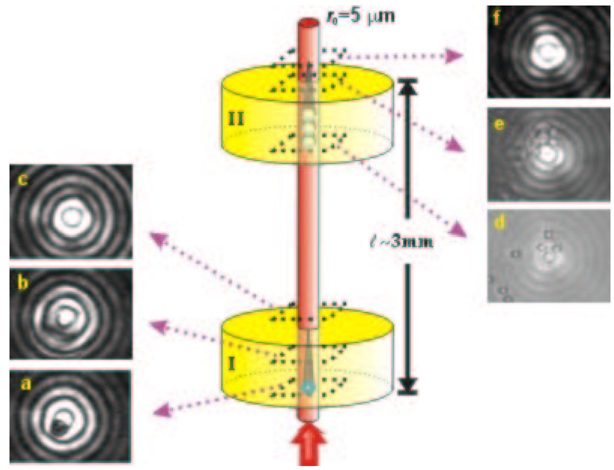


FIG. 8: The radial phase profile $\varphi(\vec{\rho}) = \gamma\rho$ creates a diffractionless Bessel beam that focuses to a long axial trap. Here, the same beam is shown trapping multiple colloidal particles in two separate sample chambers separated by 3 mm. Distortions due to a particle trapped in plane (a) heal themselves in planes (b) and (c). The process is repeated for the same beam in planes (d), (e) and (f). From Ref. [86].

## V. PROSPECTS

Being able to reach into the microscopic world dexterously and non-invasively at many points at once, being able to cut, assemble and transform with nanometer precision and sub-micrometer resolution, and being able to do all these things with a single instrument promises revolutionary advances across many disciplines. The foregoing sections highlight just a few of these advances. In particular, wavefront engineering provides a straightforward means to create large numbers of optical traps in arbitrary three-dimensional configurations, to move them freely and independently in three dimensions, and to transform them into optical vortices, optical bottles, Bessel traps, and a host of other all-optical tools.

As tools for biology, multifunctional optical traps will facilitate new approaches to cell sorting, macromolecular purification, intracellular surgery, embryonic testing, highly parallel drug screening among a great many other possibilities. The same tools have immediate applications for organizing mesoscopic matter into heterogeneous hierarchically structured three-dimensional functional systems, such as photonic circuit elements, integrated sensor arrays, and high-density data storage devices. Combining this organizational capability with optical-tweezer-based spatially-resolved photochemistry suggests bright prospects for optically assembling new materials and devices with features ranging from nanometers to millimeters and beyond.

In micromechanics and microfluidics, appropriately sculpted wavefronts of light can easily control motions and flows on length scales that have challenged other technologies. In so doing, optical micromachines should help to hasten the adoption of lab-on-a-chip devices for diagnostics, sensing, testing, pathology, and drug discovery. The same wavefront-shaping techniques can sort and purify materials in these tiny flows and direct them toward further stages of purification and analysis. Optical testing and manufacturing thus could be highly integrated, with a single instrument providing flow, sorting, organization, synthesis, and assembly.

In all of these areas, the emerging generation of optical manipulation tools should help to bridge the chasm between our macroscopic world and applications based on the physics, chemistry, and biology of microscopic systems.

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