Microoptomechanical pumps assembled and driven by holographic optical vortex arrays

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Beams of light with helical wavefronts can be focused into ring-like optical traps known as optical vortices. The orbital angular momentum carried by photons in helical modes can be transferred to trapped mesoscopic objects and thereby coupled to a surrounding fluid. We demonstrate that arrays of optical vortices created with the holographic optical tweezer technique can assemble colloidal spheres into dynamically reconfigurable microoptomechanical pumps assembled by optical gradient forces and actuated by photon orbital angular momentum.

The ever-shrinking scale and increasing complexity of microfluidic systems has created a need for new methods to pump and steer fluids through micrometer-scale channels. Approaches based on hydraulic control [1] and electroosmosis [2] are ideal for many applications and can be implemented flexibly with rapid prototyping methods, and mass-produced with lithographic techniques. They require external control apparatus, however, and are not easily reconfigured in real time. Elegant microfluidic pumps created by driving colloidal particles with actively scanned optical tweezers [3] require in situ assembly and so do not lend themselves to low-cost or highly integrated systems.

This Letter describes a new approach to microfluidic control based on the properties of generalized optical traps known as optical vortices [4, 5, 6] that are capable of exerting torques as well as forces. In particular, we employ the recently introduced holographic optical tweezer technique [7] to create arrays of optical vortices that organize fluid-borne colloidal particles into rapidly circulating rings, thereby generating fluid flows with pinpoint control and no moving parts.

Our method builds on the insight [8] that helical modes of light carry orbital angular momentum that can be transferred to illuminated objects [9, 10, 11, 12]. Strongly focusing such a beam with a high numerical aperture lens creates a variant of an optical tweezer [13] known variously as an optical vortex, optical spanner, or optical wrench [4, 5, 6]. The necessary helical modes are easily generated from conventional Gaussian TEM$_{00}$ beams with computer-designed diffractive mode converters [4] designed to imprint the helical phase function $\exp(i\ell \theta)$ onto the light’s wavefronts. Here, $\theta$ is the azimuthal angle around the beam’s axis, and $\ell$ is an integer winding number describing the helix’s pitch. Such a beam focuses to a ring of light rather than a bright spot because destructive interference cancels the beam’s intensity along its axis. The radius of the dark central core increases linearly with $\ell$ [11].

Dielectric objects comparable in size to the wavelength of light are drawn by optical gradient forces toward an optical vortex’s bright ring, and are driven around its circumference by the tangential component of the beam’s...
momentum flux. Colloidal particles dispersed in a viscous fluid can be stably trapped near the focal plane. Their circulation around the ring entrains flows in the surrounding fluid that can be harnessed for controlled transport at extremely small scales.

A single optical vortex does little more than stir a micrometer-scale volume. Arrays of optical vortices, however, can excite larger flows. We create such arrays using the holographic optical tweezer technique \[7, 14\] in which a computer-generated hologram splits a single laser beam into multiple independent beams, each of which can be focused into a separate optical trap. Each diffracted beam, moreover, can be transformed by the same hologram into a helical mode with an individually specified winding number, \( \ell \) \[14\]. The phase hologram, \( \varphi(\vec{r}) \), shown in Fig. 1(a) encodes the \( 3 \times 2 \) array of optical vortices whose focal waists appear in Figs. 1(b) and 1(c). The upper row of optical vortices has topological charge \( \ell = +21 \) and the lower has opposite helicity, \( \ell = -21 \). The two rows therefore exert torques with opposite senses.

We use a liquid crystal phase-only spatial light modulator (SLM) (Hamamatsu X7550 PAL-SLM) to imprint the trap-forming phase pattern, \( \varphi(\vec{r}) \), onto the collimated beam provided by a diode-pumped frequency-doubled Nd:YVO\(_4\) laser (Coherent Verdi) operating at \( \lambda = 532 \) nm. The SLM can selectively shift the light’s phase between 0 and \( 2\pi \) radians with 150 calibrated phase gradations at each 40 \( \mu \)m wide pixel in a 480 \( \times \) 480 array. Positioning the SLM in a plane conjugate to the input pupil of a 100\( \times \) NA 1.4 S-Plan Apochromat oil-immersion objective lens ensures that each beam diffracted by the phase modulation imposed by the SLM passes through the input pupil and forms an optical trap. The resulting intensity distribution shown in Fig. 1(b) was imaged by placing a mirror in the objective’s focal plane and collecting the reflected light with a monochrome CCD camera. A linear spatial filter aligned with the pump’s axis in an intermediate focal plane blocks the undiffracted portion of the input beam, which otherwise would create a strong optical tweezer in the middle of the field of view.

Optical vortices are very sensitive to aberrations both in their shape and also in the distribution of light around their circumference. Brightness variations are particularly problematic because particles tend to become localized by optical gradient forces in the brightest regions \[11\]. As little as \( \lambda/10 \) of coma can prevent a single particle from circulating around an optical vortex. These distortions are exacerbated in arrays of optical traps created with non-ideal phase masks, so that even a well-aligned optical train results in warped, nonuniform rings such as those in Fig. 1(b). Fortunately, we can correct for the measured aberrations in our optical train \[12\] by appropriately modifying \( \varphi(\vec{r}) \). The optimized phase profile combines the functions of a beam-splitter, a mode-switcher, and an adaptive optical wavefront corrector and yields the uniform optical vortices in Fig. 1(c), each of which can induce a single particle to circulate freely \[11\].

We projected this trap array into a colloidal dispersion of 800 nm diameter silica spheres (Bangs Laboratories catalog number SS03N) dispersed in a 12 \( \mu \)m thick layer of water between a glass microscope slide and a #1 cover slip. Spheres are drawn to the focal rings and immediately begin circulating, with those in the upper row cycling clockwise and those in the lower row moving counterclockwise. To prevent particles escaping from the rings along the axial direction, we focused the optical vortex array about \( h = 2 \) \( \mu \)m below the upper glass surface. A typical snapshot of the optically organized structure appears in Fig. 1(d). This is the first demonstration of motion driven by a heterogeneous array of optical vortices.

Each ring in Fig. 1(d) has a radius of \( R = 1.9 \pm 0.1 \) \( \mu \)m. The rings’ centers are separated by \( 6.6 \pm 0.2 \) \( \mu \)m in each row, and the rows are separated by \( 9.1 \pm 0.2 \) \( \mu \)m. The entire pattern is centered symmetrically on the optical axis. All of these dimensions, including the position and geometry of the array, are easily changed by appropriately modifying \( \varphi(\vec{r}) \) \[14\]. The choice of winding number, \( \ell = \pm 21 \), was found to optimize the optomechanical efficiency in our apparatus \[11\].

Coordinated counter-rotation of the two ranks of optically-trapped spheres drives a steady flow from right to left in our images, through the 5 \( \mu \)m wide clear channel between the rows, with a return flow outside the pattern. Particles that are not trapped in the optical vortices serve as passive tracers of the fluid flow. Figure 2 shows a multiply exposed image of colloidal spheres’ interaction with the optical vortex array. The majority of spheres drawn into the pump’s inlet on the right become trapped in the
FIG. 3: (a) Circulation rate in revolutions per minute (rpm) and (b) axial flow speed, as a function of laser power.
into self-healing diffractionless Bessel beams [20, 21].

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