Nanofabrication with Holographic Optical Tweezers

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An optical tweezer uses forces exerted by a focused beam of light to trap particles and manipulate mesoscopic volumes of matter[1]. Recently, we introduced methods for creating[2–4] large arrays of optical tweezers in arbitrary arrangements by using computer-designed diffractive optical elements to configure the necessary pattern of laser beams. Such holographic optical tweezer (HOT) arrays can be used to assemble large numbers of colloidal particles into complex three-dimensional structures for photonic, optoelectronic and sensor applications. Achieving this potential requires a technique for filling large arrays of traps efficiently. This Letter presents a particularly simple and effective method whose generalizations suggest still further applications.

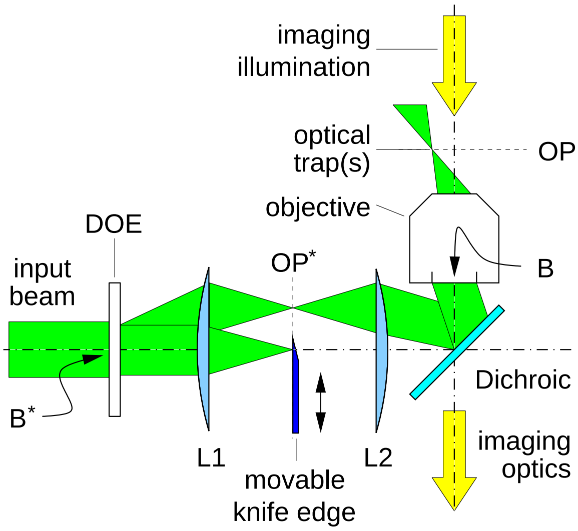

FIG. 1. Schematic diagram of holographic optical tweezers. A diffractive optical element (DOE) splits a collimated laser beam into several beams, each of which is transferred to the back aperture (B) of an objective lens by the telescope formed by lenses L1 and L2. The objective lens focuses each beam into a separate optical trap in the object plane (OP). Corresponding focii occur at the conjugate to the optical plane (OP*). The dichroic mirror separates imaging illumination from trapping light, allowing images to be formed of the trapped particles.

As shown schematically in Fig. 1, an optical tweezer forms when an intense beam of light is brought to a tight focus by a strongly converging lens, typically a microscope objective. Any collimated beam passing through the objective's back aperture, labeled B in Fig. 1, comes to a focus in its object plane (OP) and forms a trap. Beams passing obliquely through B form traps displaced from the center of the object plane.n The telescope and dichroic mirror shown in Fig. 1 create a conjugate point to B at a convenient location (B*). Beams passing through B* also pass through B and thus form traps. A computer-generated diffractive optical element centered at B* splits a single collimated beam into the pattern required for a particular arrangement of traps. Because each trap requires only a few hundred microwatts of light, quite large trapping patterns can be implemented with modest laser power.

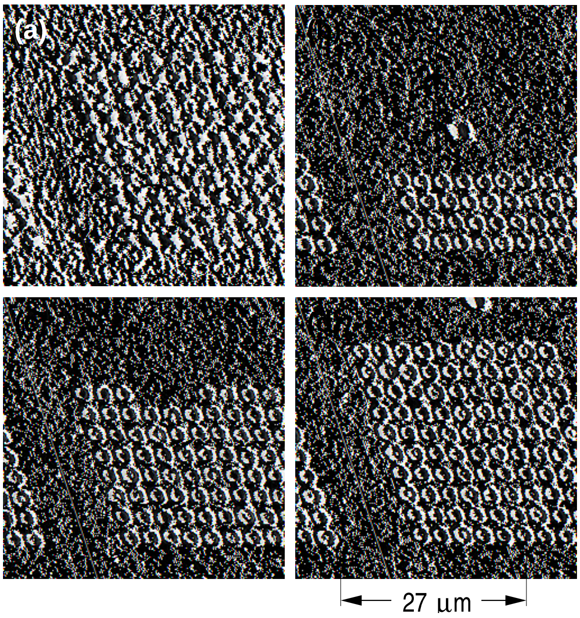

FIG. 2. Systematically filling holographic optical tweezers with 1.5 μm-diameter silica spheres suspended in water. (a) The 10×10 array of tweezers focused on a glass-water interface. (b) Now focused 2 μm above the glass, the fifth row of tweezers is exposed to a flow of particles, as indicated by the arrow. (c) Filling the eighth row. (d) The completely filled pattern.

However, this very efficacy leads to a problem. Particles tend to occupy the outer regions of HOT patterns first, blocking access to the inner traps and preventing them from filling. Fortunately, a convenient solution presents itself.

The object lens, L2, of the telescope forms a conjugate (OP^*) to OP in which each trapping beam comes to a separate focus. Their separation in OP^*, moreover, is magnified by the ratio of L2's focal length to the objective's. Blocking an individual beam in OP^* extinguishes the corresponding trap in OP. A simple knife edge can block all but one row of a trapping pattern, exposing those tweezers to the population of particles until they are full. Retracting the knife edge systematically exposes more of the pattern until the entire array is filled, as shown in Fig. 2. The process can be hastened by flowing particles past the exposed traps with a pressure differential, through electrophoresis or electro-osmosis, using a temperature gradient, or by translating the entire pattern through the suspension like a fishing net. Starting from a particle concentration on the order of 10^{-4} μm^{-3}, a reasonable flow rate of 100 μm/sec reliably fills one line of a pattern such as that in Fig. 2 in less than a minute. Comparably good results can be achieved with larger, aperiodic, and three-dimensional HOT arrays.

A completed pattern can be made permanent by transferring it onto a substrate, or by gelling the suspending fluid. Each tweezer then can be used to optically interrogate its particle, for instance to implement optical transport or microrheological measurements. Blocking patterns of beams in OP^* then would make possible an entire array of N-body measurements. Local-scale gelling or deposition can be repeated to build up larger, more complex arrangements of particles.

Cycling a pattern of beam blocks in OP^* also can convert a static HOT array into a dynamic particle manipulator, suitable for pumping or sorting particles in the nanometre to micrometre size range. A liquid-crystal spatial light modulator could be used to create a changing pattern of beam blocks, although quite sophisticated effects can be obtained with mechanical shutters.

Matthew Dearing and Steven Sheets fabricated the holographic beam splitter for this study using techniques described in Ref. [3]. This work was supported by the NSF, by a Fellowship from the David and Lucile Packard Foundation, and by an award from the Research Corporation.

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