Optical tweezer arrays and optical substrates created with diffractive optics

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We describe a simple method for creating multiple optical tweezers from a single laser beam using diffractive optical elements. As a demonstration of this technique, we have implemented a 4×4 square array of optical tweezers—the hexadeca tweezer. Not only will diffractively generated optical tweezers facilitate many new experiments in pure and applied physics, but they also will be useful for fabricating nanocomposite materials and devices, including photonic bandgap materials and optical circuit elements. [S0034-6748(98)02905-0]

I. INTRODUCTION

Since their introduction a decade ago,[1,2] optical tweezers have become indispensable tools for physical studies of macromolecular[3] and biological[4] systems. Formed by bringing a single laser beam to a tight focus, an optical tweezer exploits optical gradient forces to manipulate micrometer-sized particles. Optical tweezers have allowed scientists to probe the fantastically small forces which characterize the interactions of colloids,[5–9] polymers,[10–16] and membranes,[17–20] and to assemble small numbers of colloidal particles into mesoscopic structures.[21,22] These pioneering studies each required only one or two optical tweezers. Extending their techniques to larger and more complex systems will require larger and more complex arrays of optical tweezers.

We describe a simple and effective means to create multiple optical tweezers in arbitrary patterns from a single laser beam using diffractive optical elements. These tweezer arrays and their variants should have immediate applications for probing phenomena in biological systems and complex fluids, and in organizing soft matter into mesoscopically textured composite materials.

II. OPTICAL TWEEZER ARRAYS

The optical forces generated by a milliwatt of visible light are more than enough to overwhelm the random thermal forces which drive the dynamics of microparticles. The goal in creating an optical tweezer is to direct the optical forces from a single laser beam to trap a particle in all three dimensions. While quite general formulations of this problem have been developed,[23–26] a simplified discussion suffices to motivate the design of optical tweezer arrays. We will consider the forces exerted by monochromatic light of wavenumber k on a dielectric sphere of radius a in the Rayleigh limit, where $a \ll 2\pi/k$. The total optical force, $\mathbf{F}$, is the sum of two contributions:[27]

$$\mathbf{F} = \mathbf{F}_\nabla + \mathbf{F}_s, \tag{1}$$

the first of which arises from gradients in the light's intensity and the second of which is due to scattering of light by the particle. The gradient force on a particle of dielectric constant ϵ immersed in a medium of dielectric constant ϵ_0 and subjected to an optical field with Poynting vector $\mathbf{S}$,

$$\mathbf{F}_\nabla = 2\pi a^3 \frac{\sqrt{\epsilon_0}}{c} \left(\frac{\epsilon - \epsilon_0}{\epsilon + 2\epsilon_0} \right) \nabla |\mathbf{S}|, \tag{2}$$

tends to draw the particle toward the region of highest intensity. The scattering force,

$$\mathbf{F}_s = \frac{8}{3} \pi (ka)^4 a^2 \frac{\sqrt{\epsilon_0}}{c} \left(\frac{\epsilon - \epsilon_0}{\epsilon + 2\epsilon_0} \right)^2 \mathbf{S}, \tag{3}$$

drives the particle along the direction of propagation of the light.

An optical tweezer can be formed by focusing a laser beam to a diffraction limited spot with a high numerical aperture lens. The gradient force attracts the particle to the beam's focal point, while the scattering force drives the particle along the beam's axis. In order to form a full three dimensional trap, the axial intensity gradient must be large enough to overcome the scattering force.

In a typical experimental setup, a microscope objective lens focuses a Gaussian TEM_{00} laser beam into a tweezer while simultaneously imaging the trapped particles. In order to maximize the axial intensity gradient, the incident beam should be expanded to fill the objective's back aperture. An optical tweezer can be translated across the microscope's focal plane by adjusting the beam's angle of incidence at the back aperture and can be displaced along the optical axis by changing the curvature of its wavefront.

Similarly, if several collimated beams pass through the back aperture at different angles, they form separate tweezers at different locations in the focal plane. For instance, dual optical tweezer systems have been created by splitting and recombining a single laser beam with beamsplitters and refractive optics.[21,28] This approach, however, becomes cumbersome for more than a few traps. An elegant alternative for creating two-dimensional arrays of traps involves scanning a single tweezer rapidly among a number of positions to create

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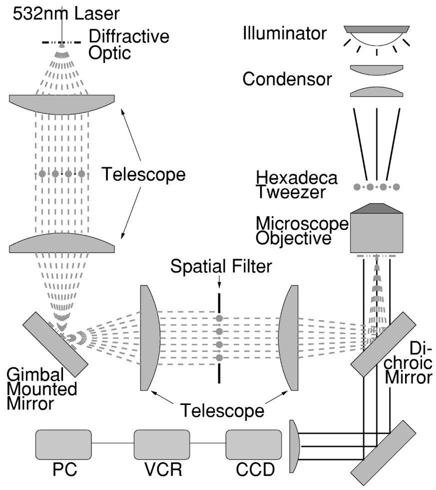

FIG. 1. Schematic diagram of a practical diffractively generated optical tweezer array.

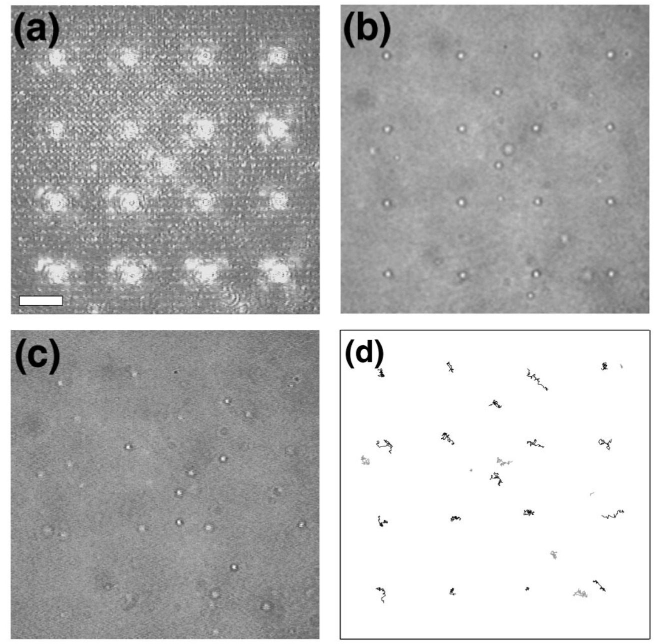

FIG. 2. 4×4 Optical tweezer array created from a single laser beam using a holographic array generator. (a) The tweezer array illuminates the $70\times70\ \mu m^2$ field of view with light backscattered from trapped silica particles. The scale bar represents 10 μm. (b) The particle array 1/30 s after being released. (c) The same field of view 3.1 s later. (d) Trajectories of the particles in the field of view after being released. Dark traces indicate particles initially trapped in the array. Shorter tracks indicate particles which diffused out of the ±200 nm depth of focus.

a time-averaged extended trapping pattern.[21,29–31] This approach has proved highly effective for shaping small colloidal assemblies.

Yet another alternative for creating two dimensional arrays of traps is to split and steer the light from a single beam with diffractive optical elements. As demonstrated in the next section, inexpensive commercially available diffractive pattern generators (e.g. MEMS Optical Inc., Huntsville AL) are ideally suited to this task. In addition, diffractive optics can be used to change the curvature of beam wavefronts, thereby facilitating the creation of three-dimensional arrays of traps. Additionally, diffractive optics can be used to modify beam profiles. For instance, computed holograms can convert a TEM_{00} Gaussian beam into multiple Gauss–Laguerre beams, otherwise known as optical vortices.[32–34] Tightly focused optical vortices can be used to trap low dielectric constant and reflective microparticles. Finally, the use of addressable liquid crystal phase shifting arrays allows for the dynamic reconfiguration of a tweezer array for active particle manipulation and assembly. Thus, diffractively generated optical fields can be used to configure arbitrary numbers of microscopic particles into useful and interesting arrangements. We will discuss some applications of these techniques after describing a practical demonstration of diffractively generated optical tweezer arrays.

III. THE HEXADECA TWEEZER

The schematic diagram in Fig. 1 shows one implementation of diffractively generated optical tweezer arrays. This design was used to create a 4×4 square array of tweezers—the hexadeca tweezer. The optical tweezer array is powered by a 100 mW diode-pumped frequency-doubled Nd:YAG laser operating at 532 nm. Two Keplerian telescopes arranged in series produce two planes conjugate to the back aperture of the microscope's objective lens (100×, N.A. 1.40). The laser beam passes through eyepoints in both planes to create a conventional single optical tweezer. Introducing a diffractive 4×4 square array generator (Edmund Scientific No. P53191, angular divergence 25 mrad at $\lambda=532$ nm) at the first eyepoint creates the pattern of rays desired for the hexadeca tweezer. A gimbal mounted mirror centered at the second eyepoint allows us to translate the entire tweezer array in the microscope's field of view and to dynamically stiffen the tweezers. A spatial filter placed in the inner focal plane of either telescope removes spurious rays created by imperfections in the low-cost diffractive optic. Conventional white-light illumination is used to form an image of the trapped particles. The image passes through a dichroic beam splitter and is captured with a video camera (NEC TI-324A) and recorded with a VCR (NEC PC-VCR) for later analysis.

For our demonstration, we used the hexadeca tweezer to trap silica spheres ($a=0.50\pm0.03\ \mu$m, $\epsilon=2.3$, Duke Scientific, Palo Alto CA, Cat. No. 8100) suspended in deionized water ($\epsilon_0=1.7$) at room temperature. The suspension was sandwiched between a microscope slide and cover glass separated by 40 μm. The tweezer array was focused 8 μm above the lower glass wall and left in place to acquire particles. Figure 2(a) shows all 16 of the primary optical traps filled with particles. Since the focal plane is several sphere diameters from the nearest wall, each sphere is trapped stably in three dimensions. Residence times in excess of 100 s, suggest a trapping potential deeper than $6k_BT$ per particle given the free spheres' self-diffusion coefficient of $0.4\ \mu m^2/s$. Comparable trapping efficiency would be expected for a single conventional optical tweezer operating at equivalent light intensity. Two additional spheres are trapped less strongly at spurious peaks in the diffraction pattern.

Figure 2(b) shows the same field of view 1/30 s after the laser was interrupted and before the spheres have had time to diffuse away. After 3.1 s [Fig. 2(c)], the pattern has completely dispersed with some of the spheres wandering out of the imaging volume altogether. Figure 2(d) shows two-dimensional projections of the particles' trajectories over this period.[6] Studying the dynamic relaxation of artificially structured colloidal crystals is just one application we foresee for manipulating soft matter with holographically patterned light.

IV. OPTICAL SUBSTRATES AND APPLICATIONS

Not all holographically generated optical fields will create arrays of traps. A large uniformly illuminated volume, for example, will not have the intensity gradients required for three-dimensional trapping. Such nontrapping patterns also have applications, however, and can be created in the same manner as the hexadeca tweezer, with diffractive optics. The resulting optical fields may be useful for forcing particles against a surface and into desired configurations.

Optically induced ordering has been demonstrated by intersecting several discrete beams.[35–42] The resulting periodic intensity patterns are observed to induce order in colloidal monolayers. In this respect, the pattern of light plays the role of a modulated substrate potential and affects the phase behavior of the illuminated two-dimensional system. This effect is believed to be closely analogous to the influence of atomic corrugation on the phase transitions of adsorbed atomic and molecular overlayers.[43,44] The optical substrate's symmetry, periodicity, and depth of modulation all can be adjusted experimentally. This system therefore has great promise for exploring the mechanisms of surface phase transitions. Diffractively generated optical substrates, moreover, need not be periodic. Quasiperiodic and aperiodic patterns will be useful for studies of the effect of pinning on monolayer dynamics, a potentially powerful analog for dynamics in superconducting vortex lattices and sliding charge density waves.

Beyond these applications to studies in fundamental condensed matter physics, optical substrates should be useful for assembling composite systems textured on the micron scale. In this case, the patterned illumination acts as a template for depositing particles directly or assisting self-assembly. The resulting mesoscopically arranged structures could be gelled in place and combined to create extended structures and devices. The fabrication of optical circuit elements might be based on such an approach.

Both tweezing arrays and optical substrates can be used to direct the self-assembly of three-dimensionally ordered colloidal crystals. These crystals recently have been shown to have a promising future as photonic circuit elements[45,46] and as quantitative chemical sensors.[47,48] Their full commercial exploitation will require the ability to fabricate large single crystals with desirable symmetry and lattice constants. Diffractive optical arrays can be used to organize the first layer of a growing colloidal crystal and register it with a desired substrate. Subsequent layers then grow epitaxially on the first, leading to much longer-ranged three-dimensional order than might be possible otherwise. This principle has been demonstrated with lithographically patterned substrates.[49] Optical substrates could be adjusted *in situ* to achieve optimal ordering.

Multilayer tweezer arrays could be used to directly form multilayer photonic crystals such as photonic bandgap materials,[50] with tuned defect states in the bandgap created with planned interstitials. The high-dielectric-constant materials required for realizing a full photonic bandgap most likely cannot be trapped with conventional tweezer arrays. Arrays of optical vortex tweezers, however, should be amenable to the task.

Finally, scanned and otherwise time-dependent optical substrates can provide the time-modulated spatially asymmetric potentials required for practical particle size fractionation through directed diffusion.[51] The optical ratchet principle required for practical directed diffusion has been demonstrated with a single scanned tweezer.[52–54] Extended optical substrates may turn this demonstration into a practical technique.

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[1] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, Opt. Lett. **11**, 288 (1986).
[2] A. Ashkin, Proc. Natl. Acad. Sci. USA **94**, 4853 (1997).
[3] D. G. Grier, Curr. Opin. Colloid Interface Sci. **2**, 264 (1997).
[4] K. Svoboda and S. M. Block, Annu. Rev. Biophys. Biomol. Struct. **23**, 247 (1994).
[5] J. C. Crocker and D. G. Grier, Phys. Rev. Lett. **73**, 352 (1994).
[6] J. C. Crocker and D. G. Grier, J. Colloid Interface Sci. **179**, 298 (1996).
[7] A. D. Dinsmore, A. G. Yodh, and D. J. Pine, Nature (London) **383**, 239 (1996).
[8] A. E. Larsen and D. G. Grier, Nature (London) **385**, 230 (1997).
[9] T. Sugimoto *et al.*, Langmuir **13**, 5528 (1997).
[10] S. B. Smith, L. Finzi, and C. Bustamante, Science **258**, 1122 (1992).
[11] C. Bustamante, J. F. Marko, E. D. Siggia, and S. Smith, Science **265**, 1599 (1994).
[12] H. Yin *et al.*, Science **270**, 1653 (1995).
[13] T. T. Perkins, D. E. Smith, R. G. Larson, and S. Chu, Science **268**, 83 (1995).
[14] S. B. Smith, Y. Cui, and C. Bustamante, Science **271**, 795 (1996).
[15] H. Felgner, R. Frank, and M. Schliwa, J. Cell. Sci. **109**, 509 (1996).
[16] M. D. Wang *et al.*, Biophys. J. **72**, 1335 (1997).
[17] R. Bar-Ziv, Phys. Rev. Lett. **73**, 1392 (1994).
[18] R. Bar-Ziv, R. Menes, E. Moses, and S. A. Safran, Phys. Rev. Lett. **75**, 3356 (1995).
[19] R. Bar-Ziv, T. Frisch, and E. Moses, Phys. Rev. Lett. **75**, 3481 (1995).
[20] J. D. Moroz, P. Nelson, R. Bar-Ziv, and E. Moses, Phys. Rev. Lett. **78**, 386 (1997).
[21] K. Sasaki *et al.*, Opt. Lett. **16**, 1463 (1991).
[22] H. Misawa *et al.*, Appl. Phys. Lett. **60**, 310 (1992).
[23] G. Gouesbet, B. Maheu, and G. Gréhan, J. Opt. Soc. Am. A **5**, 1427 (1988).
[24] A. Ashkin, Biophys. J. **61**, 569 (1992).
[25] K. F. Ren, G. Gréhan, and G. Gouesbet, Appl. Opt. **35**, 2702 (1996).
[26] Ø. Farsund and B. U. Felderhof, Physica A **227**, 108 (1996).
[27] Y. Harada and T. Asakura, Opt. Commun. **124**, 529 (1996).
[28] E. Fällman and O. Axner, Appl. Opt. **36**, 2107 (1997).
[29] L. P. Faucheux and A. J. Libchaber, Phys. Rev. E **49**, 5158 (1994).
[30] K. Visscher, S. P. Gross, and S. M. Block, IEEE J. Sel. Top. Quantum Electron. **2**, 1066 (1996).

[31] K. Sasaki *et al.*, Jpn. J. Appl. Phys. **30**, L907 (1997).
[32] N. R. Heckenberg *et al.*, Opt. Quantum Electron. **24**, S951 (1992).
[33] H. He, N. R. Heckenberg, and H. Rubinsztein-Dunlop, J. Mod. Opt. **42**, 217 (1995).
[34] K. T. Gahagan and J. G. A. Swartzlander, Opt. Lett. **21**, 827 (1996).
[35] A. Chowdhury, B. J. Ackerson, and N. A. Clark, Phys. Rev. Lett. **55**, 833 (1985).
[36] B. J. Ackerson and A. H. Chowdhury, Faraday Discuss. Chem. Soc. **83**, 1 (1987).
[37] K. Loudiyi and B. J. Ackerson, Physica A **184**, 1 (1992).
[38] K. Loudiyi and B. J. Ackerson, Physica A **184**, 26 (1992).
[39] M. M. Burns, J.-M. Fournier, and J. A. Golovchenko, Science **249**, 749 (1990).
[40] A. Chowdhury, B. J. Ackerson, and N. A. Clark, Science **252**, 1049 (1991).
[41] M. M. Burns, J.-M. Fournier, and J. A. Golovchenko, Science **252**, 1049 (1991).
[42] A. E. Chiou *et al.*, Opt. Commun. **133**, 7 (1997).
[43] J. Chakrabarti, H. R. Krishnamurthy, and A. K. Sood, Phys. Rev. Lett. **73**, 2923 (1994).
[44] J. Chakrabarti, H. R. Krishnamurthy, A. K. Sood, and S. Sengupta, Phys. Rev. Lett. **75**, 2232 (1995).
[45] G. Pan, R. Kesavamoorthy, and S. A. Asher, Phys. Rev. Lett. **78**, 3860 (1997).
[46] D. G. Grier, Phys. World **10**, 24 (1997).
[47] J. H. Holtz and S. A. Asher, Nature (London) **389**, 829 (1997).
[48] D. G. Grier, Nature (London) **389**, 784 (1997).
[49] A. van Blaaderen, R. Ruel, and P. Wiltzius, Nature (London) **385**, 321 (1997).
[50] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University Press, Princeton, 1995).
[51] M. Bier and R. D. Astumian, Phys. Rev. Lett. **76**, 4277 (1996).
[52] L. P. Faucheux, L. S. Bourdieu, P. D. Kaplan, and A. J. Libchaber, Phys. Rev. Lett. **74**, 1504 (1995).
[53] L. P. Faucheux, G. Stolovitzky, and A. Libchaber, Phys. Rev. E **51**, 5239 (1995).
[54] R. C. Gauthier, Appl. Phys. Lett. **67**, 2269 (1995).