Note: Toward multiple addressable optical trapping

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We describe a setup for addressable optical trapping in which a laser source is focused on a digital micromirror device and generates an optical trap in a microfluidic cell. In this paper, we report a proof-of-principle single beam/single micromirror/single three-dimensional trap arrangement that should serve as the basis for a multiple-trap instrument. © *2010 American Institute of Physics.* [doi:10.1063/1.3321535]

In the presence of an electromagnetic field gradient, a force is exerted onto objects with an index of refraction different from that of the medium in which they are immersed. In high-numerical aperture (NA) systems, the gradient force holds the object near the focus in three dimensions.[1] In low-NA systems, a scattering force overcomes the gradient force, so objects are trapped in only two dimensions.[2]

Parallel analysis on a set of microscopic objects is difficult but important. Arrays of beads can be used as multianalyte sensing platforms,[3] and arrays of cells can be used to study cell-to-cell differences[4,5] and cell-to-cell communication.[6] Parallel analysis also shortens the total analysis time and ensures that all particles are exposed to the same conditions.

Most arrays of trapped particles are not addressable—the particles cannot be captured or released individually. The ultimate goal of our study is to create an array of addressable, three-dimensional optical traps in a microfluidic device. Full addressability increases the control over and flexibility of sensing arrays.[7] For example, it would allow programmed assembly of particles in the array rather than the random approaches used for fixed arrays.[8,9] In random arrays, each particle type needs a different label, which places practical limits on the number of particle types that can be used. Programmed arrays are free from this limitation. The ability to selectively release particles is similarly beneficial, as it allows one to concentrate particles of interest, while releasing others or to selectively pass particles on for further analysis. In an array-based assay, cells could be sorted based on properties (such as morphology or time-based response[10]) not available in other cell-sorting techniques such as flow cytometry.

To achieve multiple trapping, one can use an array of microlenses.[11] Refractive microlenses alone; however, do not have high enough NAs to form three-dimensional traps. Merenda *et al.*[12] demonstrated three-dimensional trapping for a reflective type microlens array (MLA), but the pitch of this array was on the order of hundreds of microns, so the number of simultaneously observable traps was limited. The Talbot effect, in which a periodic structure is self imaged, can also be used to produce multiple optical traps.[13] These methods of multiple trapping, though successful, do not allow individual switching of traps.

The limitations of trap pitch and NA may be addressed by setting light sources elsewhere and optically relaying them into the area of interest. This approach was demonstrated for multiple laser sources—vertical cavity surface emitting lasers.[14] With a single laser source, the beam can be shared in time[15] or in space. To split the beam spatially, beam splitters,[16] MLAs,[11,17] fiber bundles,[18,19] and diffraction gratings have been used. The use of a dynamic holographic optical element,[17] as a diffraction grating has been the most successful approach and the only one of the aforementioned methods that demonstrates addressability.

An array of points formed by a low-NA MLA can be demagnified by a collimating lens and a high-NA objective, resulting in tightly focused spots usable for three-dimensional trapping.[20] Each beam will be either passed or blocked by one of a set of optical valves that are part of a digital micromirror device (DMD) (Texas Instruments).[19] Chiou *et al.*[21] also previously implemented a DMD for light-controlled dielectrophoretic trapping, but the relatively high light intensities needed for three-dimensional optical trapping were not used in that setup.

In this note, we describe an optical trapping setup in which a laser source is focused on a DMD and generates a three-dimensional optical trap in a microfluidic cell. We report a proof-of-principle single beam/single micromirror/single three-dimensional trap arrangement that should serve as the basis for a multiple-trap instrument in which each trap would be individually addressable.

The DMD we used is an array of 1024×768 micromirrors, each of which is 13.68×13.68 μm^2. When powered, each micromirror is bistable: it can tilt $\pm 12°$ relative to its resting position. To prevent interference effects, only one DMD mirror should be employed per trap. A stable three-dimensional trap typically requires several milliwatts of optical power.[22] To check the ability of an individual micromirror to withstand this power level, we focused a laser onto one DMD mirror. Initially, we used a HeNe (22 mW, 633 nm) with a $4\times/0.1$ NA Olympus microscope objective. No damage was observed even with the full power of the laser on a single micromirror for hours. We also tested a 1064 nm laser. The DMD tiles did not exhibit any visible (VIS) damage for input powers below 30 mW. For powers higher than 40 mW, the DMD tiles were permanently damaged. The dark areas in Fig. 1 are mirrors damaged due to exposure to high laser powers, the light areas are undamaged mirrors. The DMD's damage threshold made it suitable for optical trapping.

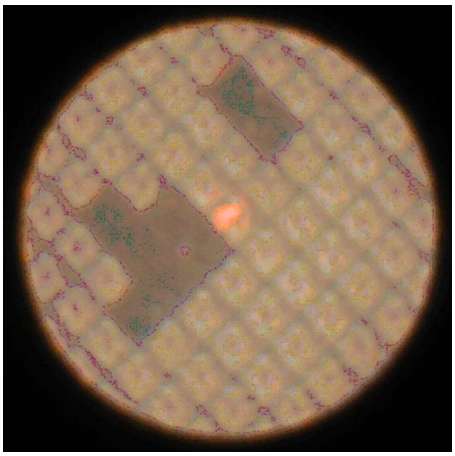

FIG. 1. (Color online) DMD surface viewed through a 400 mm lens and 40× eyepiece. Dark areas are mirrors damaged by high laser powers. Light areas are undamaged mirrors. The red spot is the HeNe laser reflecting off a single mirror.

The initial system uses a single lens in place of a MLA, but design was undertaken with the MLA in mind. The geometric constraints of the DMD and MLA were such that a direct coupling would not work. A relay was required so that light reflected from the DMD would not impinge on the MLA or lens. To create an array of traps in the same plane, the DMD had to be angled relative to the incoming light, which will also require the MLA to be angled so that the focal points it formed will land on the micromirrors. We needed a telecentric, achromatic, and diffraction-limited relay that presents a field of view comparable to the size of the active DMD area. We used an Offner triplet to meet these demands. The system is depicted in Fig. 2. The collimated laser beam will fall onto a tilted MLA and form a set of diffraction-limited focal spots. The spots will be relayed by the Offner triplet onto the DMD active area. Depending upon the illuminated micromirror position, the light will be either sent to a beam dump or collected by a collimator and passed to the high NA trapping objective.

The DMD places limits on the NA of the system. The NA cannot exceed $\sin(12°)=0.21$ due to illumination/reflection geometry, but it cannot be much less than 0.1 so that the spot formed by a 1064 nm laser is smaller than the micromirror size. We chose an NA of 0.1, partly because of the availability of optics.

For alignment, we simplified our setup by using the HeNe laser instead of the NIR laser, a $4\times/0.1$ NA microscope objective (Olympus) instead of a MLA, and a macromirror with a 3-mm-thick optical window instead of the DMD. Because the window was not perpendicular to the optical axis, there was a strong astigmatism. We compensated for this astigmatism by adding another tilted optical window between the Offner triplet and the DMD. The axis of the window's tilt was perpendicular to that of the DMD window. After alignment, we replaced the macromirror and plate with the DMD (Fig. 2).

We did not actuate the DMD chip with electric power. Instead, we focused the light onto permanently tilted micromirrors at the edges of the DMD active area. To make the mirrors visible, we used a Kohler-type illuminator based on two achromats (L1, L2), a 633 nm red bandpass filter (F1), and a gooseneck lamp (ILLUM1). The illuminator light reflected off the DMD surface, passed through the collimator, and formed an image of the DMD tiles by a 400 mm (L3) achromat in front of a 6 mm (40×) orthoscopic ocular. The individual micromirrors were clearly visible (Fig. 3), which allowed accurate laser spot positioning.

The 10-mm-diameter 22 mW HeNe beam was introduced into OBJ1 ($4\times/0.1$ NA Olympus PlanAchro). The Offner triplet relayed about 16 mW of laser power on the

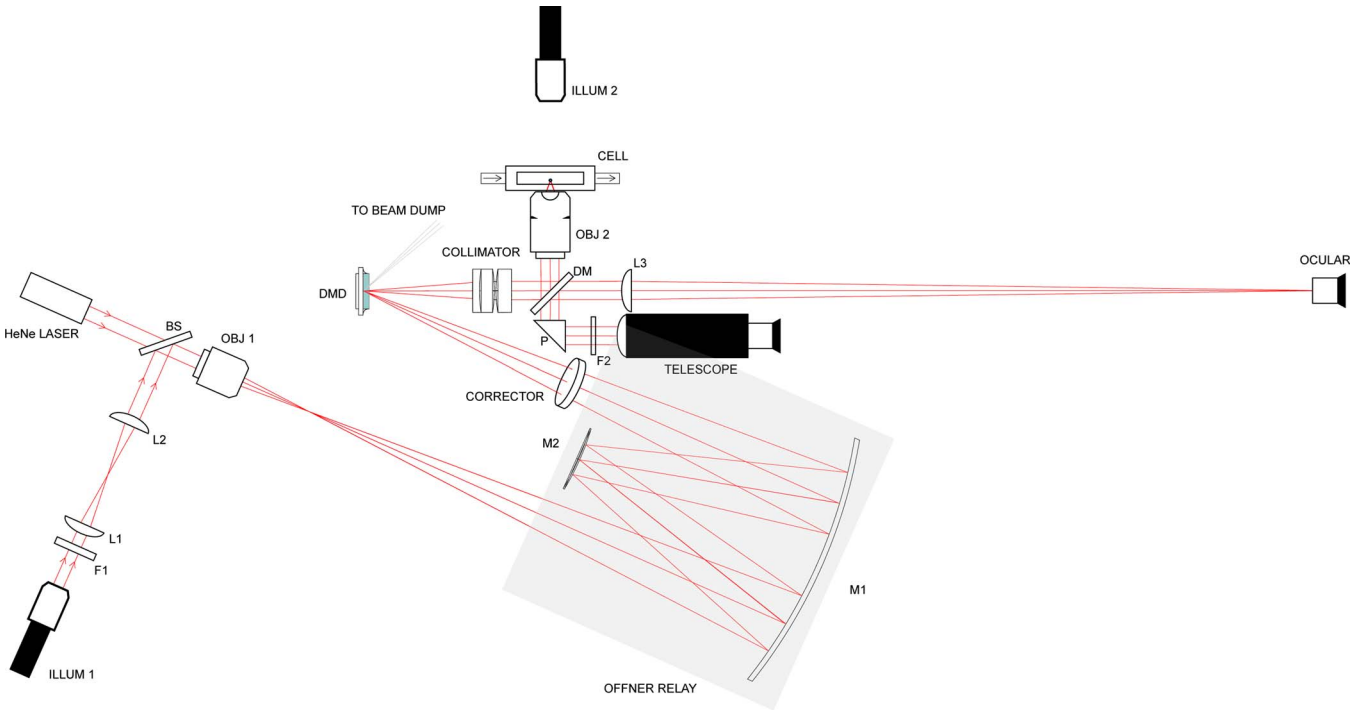

FIG. 2. (Color online) A system incorporating the DMD for creation and control of a single trap.

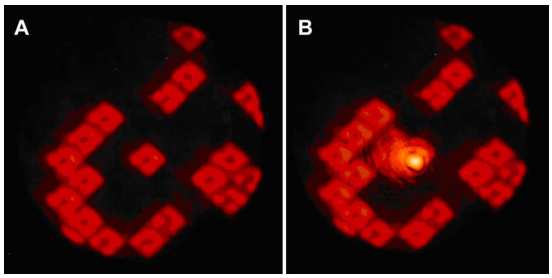

FIG. 3. (Color online) Images taken through the ocular shown in Fig. 2. (a) Micromirrors at the edges of the DMD active area illuminated with red light. (b) 633 nm laser focused on a single micromirror. Dark areas are micromirrors in the off position.

DMD, and the DMD micromirror reflected 7 mW toward the collimator. We attribute the loss to diffraction and to the 2×2 μm^2 aperture in the center of each micromirror. We verified the beam's collimation after the collimator with a shear interferometer. Finally, we directed the laser light toward the trapping objective OBJ2 ($40\times/1.3$ NA oil Olympus) with the help of a dichroic mirror. The trap was observed through a telescope and a green filter F2 that attenuated the HeNe reflection.

To test the trapping ability of this setup, we used a syringe pump to feed solution into a flow-through cell on a XYZ translation stage. Observation was through a 170-μm-thick glass coverslip on one side of the cell. To check the laser focus position (where the trap should occur), the microscope was focused on the surface of the coverslip, and the reflection was observed through the telescope. The focus was then moved vertically into the flow-through cell. A solution of 3-μm-diameter silica beads was introduced into the flow-through cell, and one bead was chosen for trapping. The cell was moved using the XYZ stage until the bead was near the trap and the gradient force pulled the bead into the trap. The bead was held for several minutes, while the flow-through cell was translated in all three dimensions to verify three-dimensional trapping. The trapped bead remained stationary while other beads moved with the cell. When the laser was striking an "off" mirror, no trapping occurred.

Trapping using a single micromirror has thus been verified with this optical setup. The arrangement will be expanded by incorporating a higher-powered NIR laser and an array of microlenses. This setup should enable multiple traps to be created and independently turned on and off.

We have built a system that demonstrates a proof-of-concept for multiple addressable trapping using a commercially available DMD as an optical switch. We demonstrated the concept using a single trap in the VIS range. Expanding the design to incorporate multiple traps will require the use of a higher-powered laser and a MLA.

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