Appl. Phys. B 78, 705–709 (2004)
DOI: 10.1007/s00340-004-1425-6

Applied Physics B
Lasers and Optics

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Multiple-spot optical tweezers created with microlens arrays fabricated by proton beam writing

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Received: 19 November 2003/
Revised version: 21 January 2004
Published online: 26 March 2004 •

ABSTRACT We report two different applications for using arrays of microlenses on glass substrate to facilitate multiple-spot optical trapping of colloidal microbeads. The array of microlenses was made of SU8 or PMMA resist and created by a combination of Proton-Beam writing followed by thermal reflow processes. Firstly, similar to previous reports [8–10], the lenses were utilized as an optical element in generating multiple laser spot arrays that were subsequently focused down to impose a microbead array. In addition, we demonstrated the feasibility of a novel approach of integrating the microlens array into a sample chamber to provide localized optical trapping.

PACS 07.60.Pb; 41.75.Ak; 42.15.Eq; 42.65.Jx; 42.79.Bh

1 Introduction

The technique of optical trapping, pioneered by Ashkin et al. [1–3], is an active area of research. A wide variety of experiments were made possible with the access and control optical traps provided [4–7]. In addition, rapid advances are also being made in the technical development of novel methods for creating optical traps [7]. In particular, progress has been made in the development of holographic [8, 9] multiple-spot tweezer arrays, either diffractively generated [10] or time-sharing trap [11–13], where an array of microparticles can be trapped and manipulated simultaneously. In this work, we report on two different applications of using an array of microlenses on a glass substrate to achieve multiple-beam optical tweezing. Firstly, similar to the earlier reports by Dufresne et al. [8, 10] and Korda et al. [9], the array of microlenses was used as a diffractive optical element to generate an array of laser spots that was focused down to trap microbeads. Note that in these techniques, the laser spots were generated by optical elements external to the sample system. In a novel second application, the array of microlenses was incorporated into the sample chamber itself. With a powerful incident laser beam, each of the individual microlenses created a corresponding focused light cone. This resulted in the formation of a corresponding array of optically trapped microbeads.

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2 Thermal reflow microlens array

The periodic array of microlenses was created by a combination of Proton-Beam writing [14] followed by thermal reflow processes [15]. Figure 1 shows the schematic of the processing steps for the fabrication of the thermal reflow microlens array. Firstly, a thin layer of SU-8 resist with a uniform thickness of 25 μm was spin-coated on a glass substrate. Using the technique of Proton-Beam writing [14], a periodic array of circles with uniform diameter was irradiated with a scanning focused proton beam (Fig. 1a). The dosage used was 30 nC/mm^2. With an energy of 2.0 MeV, the proton has a long range of 62 μm in the SU-8 resist with very little scattering except when the proton beam is at the end of its range. This range was determined from both simulation using the commercial software SRIM and from the imaging of the edge of a bulk sample that has been irradiated. In this way, a periodic array of uniformly sized cylinders was left behind on glass after chemical development. The diameter of the cylinders was controlled by limiting the region exposed to the incoming focused scanning proton beam. The sample was then heated to 285 °C for 1 hour to allow the SU-8 to reflow under surface tension. This process creates an array of micro plano-convex lenses.

Figure 1b shows an optical micrograph of the fabricated square array of microlenses used in this work. The diameter of the lens is 180 μm and the spatial period is 250 μm. The refractive index of the resist SU-8 used in this work is $n = 1.596$@632.8 nm. The thickness of the lens was found to be 24 μm with quantitative phase microscopy. The width of the lens is the same as the diameter of the cylinders before the heat treatment. On the other hand, the thickness of the lens is related to the original length of the cylinders before heat treatment. Thus, with a combination of controlling the scanning proton irradiated dimensions and the thickness of the resist used, one can tailor the pattern and dimensions of the microlenses for various applications. The array of microlenses on glass resembles a diffractive optical element comprising of

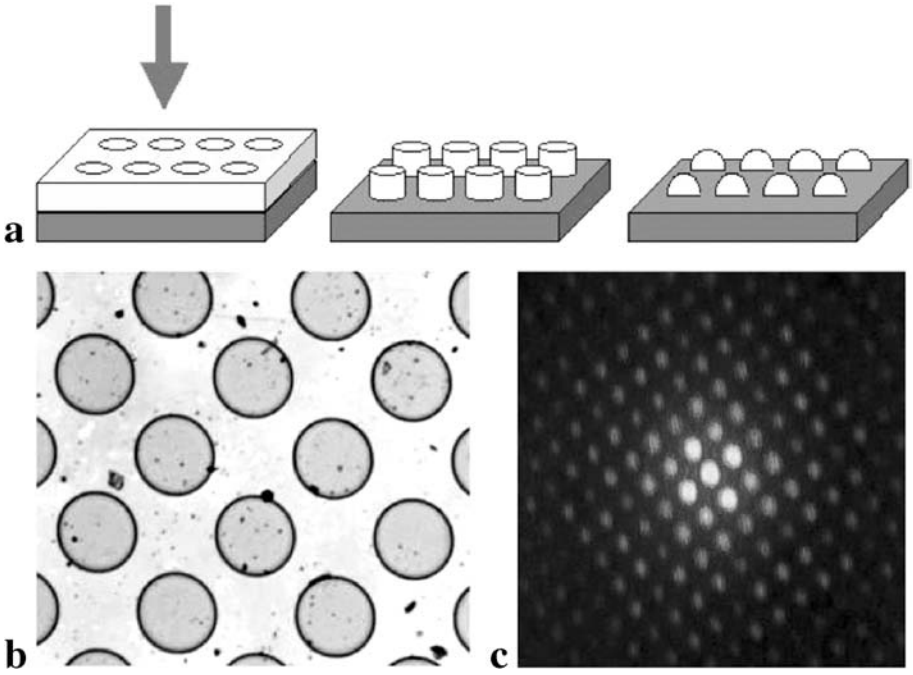

FIGURE 1 **a** Schematic of the processing steps for the fabrication of the thermal reflow microlens array. **b** Optical microscope image of a top view of a square array of microlenses. The diameter of the lens is about 180 μm and the spatial period is 250 μm. **c** Diffractive laser spot pattern generated after a He-Ne laser (wavelength 632 nm) beam passes through the microlenses array

the substrate with a periodic variation of refractive index that is commonly used for generating interesting laser beam pattern [10]. Figure 1c shows a square array of laser spots pattern generated after a single beam from a He-Ne laser (wavelength 632 nm) passes normally through the glass substrate with the microlenses array. As reported by Dufresne et al. [8, 10], Korda et al. [9] and Hoogenboom et al. [13] an array of laser spots can be utilized in realization of multiple spots optical tweezers. In this work, we report two separate applications of the microlens array for facilitating the realization of a multiple-spots optical tweezers array.

In the first application, the array of microlenses served as a diffractive optical element that is inserted into the path of the laser beam in a typical optical tweezer setup. Simple rotation of the microlens array resulted in rotating multiple-spot optical tweezers. These approaches are again similar to earlier works by Dufresne et al. [8, 10], Korda et al. [9] and Ogura et al. [16]. In the novel second application, the array of microlenses was integrated into a sample chamber. When the lenses were illuminated by an external laser beam, they produced individual converging light cones that in turn exhibit optical trapping ability. The resulting system is very compact and easy to align. This result could potentially be useful in the development of lab-in-chip by providing a means to trap and manipulate microparticles or biological cells without direct contact.

3 Experimental setup

Figure 2 shows the schematics of the experimental setup used in the first application of the microlenses to achieve multiple-spot optical tweezers. Dilute aqueous suspensions of polystyrene microbeads with a diameter of 1.2 μm or 1.9 μm sandwiched in between a glass slide and a coverglass were used as test samples. The separation of the two confining walls is about 3 μm. As a result, the microbeads were tightly confined in a two dimensional system. Once assembled, the sample was placed on a sample stage of an inverted Nikon TE300 microscope that is equipped with an oil-immersion objective lens (100X, N.A. = 1.3). The microscope is also equipped with a side port and an 80/20-beam splitter. The beam splitter reflects 80% of the laser beam that enters through the side port towards the objective lens. A SUWTech LDC-2500 Diode Laser emitting laser beam with a wavelength of 1064 nm and a maximum power of 500 mW was utilized. As shown in Fig. 2, the laser beam was split into two separate paths (paths A and B) by a beam splitter. The two beams were reflected by adjustable mirrors and recombined by a second beam splitter before entering the side port of the microscope.

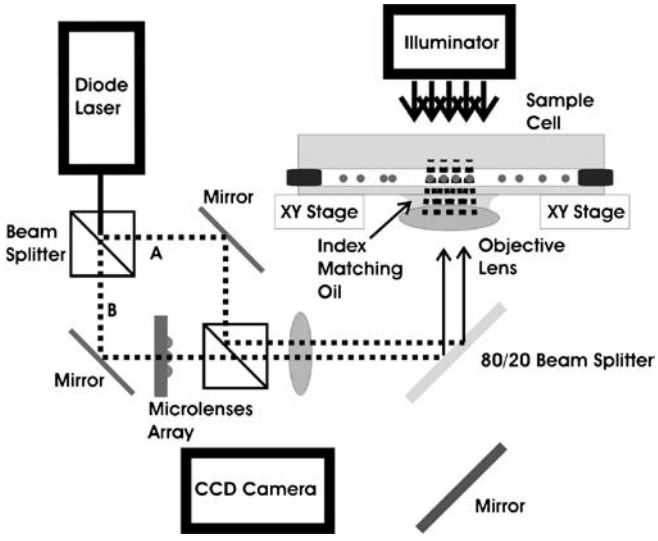

FIGURE 2 Schematics of the experimental setup showing the interior of an inverted microscope. A laser beam passes through a microlens array and the resultant light pattern is focused onto a sample chamber consisting of aqueous suspension of polystyrene microbeads

In this way, we generated two independent optical tweezers. A glass substrate with the array of microlenses was inserted in the path B as shown. The resultant laser pattern diverges slightly from the glass substrate and a convex lens was used to focus the laser beam pattern towards the objective lens that in turn focused the laser beam pattern onto the sample cell. The transparent sample was illuminated in transmission mode with a Halogen light source from the top. 20% of the illumination light passes through the 80/20 beam splitter and the image was captured by a Hamamatsu CCD camera. The images were then recorded onto videotapes or fed directly to the computer.

4 Results and discussions

Even though Fig. 2 shows the laser pattern being focused beyond the sample, the two-dimensional nature of the system and the intensity profile of each individual spots resulted in effective trapping of the microbeads. Figure 3 shows optical micrographs of different assemblies of microbeads made possible with the multiple-spot optical tweezer array. Note that Fig. 1c shows that the intensities of the different laser spots are not uniform and this will naturally lead to optical tweezers spots of different trapping strength. Typically, optical trappings start with the brightest spots and are followed by the weaker ones. With the additional independent tweezing spot from path A, we used that optical tweezers to trap a microbead and release it at the desired location. In this way, we can selectively fill the array of tweezing spots with microbeads. Figure 3b shows our best effort in simultaneously trapping 25 microbeads at maximum laser power. The spacing of the microbeads is about 3.2 μm. In addition, we can also form an interesting array of microbeads configuration. Figure 3c shows a mosaic of alphabetic letters formation by the optically trapped microbeads. A video clip of the microbeads assembly process can be found at [17].

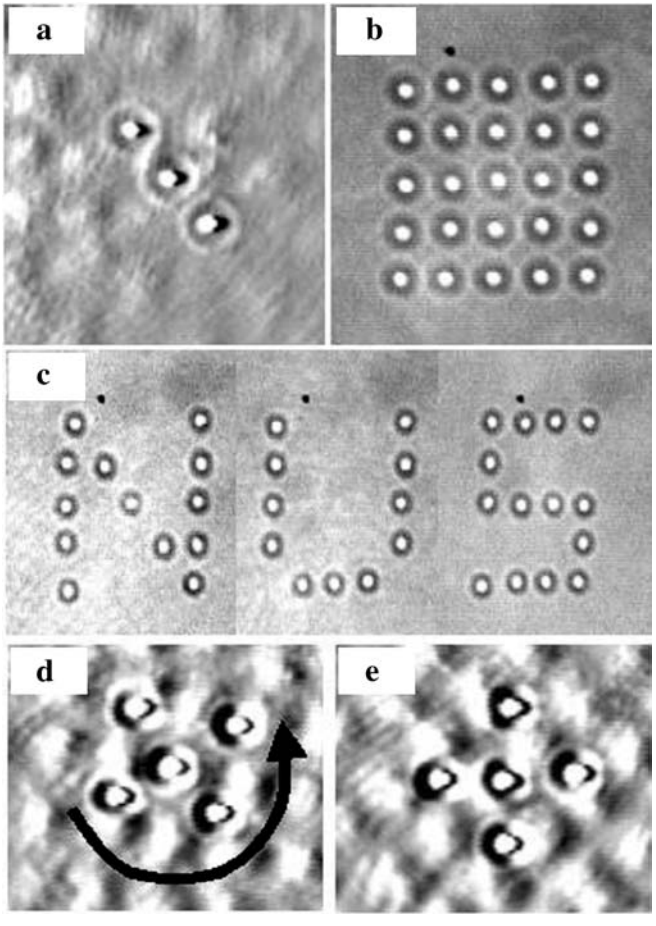

FIGURE 3 **a**,**b** Optical microscope images of different assemblies of the microbeads achieved via multiple-spots optical tweezers array. The spatial period of the microbeads array is about 3.2 μm. **c** A mosaic of letters formation by trapped microbeads. **d**,**e** Two snapshots of a microbead configuration during an anti-clockwise rotation. The diameters of the microbeads shown are: **a**,**d**,**e** 1.9 μm and **b**,**c** 1.2 μm. Video clips of the formation and rotation of the microbead assembly can be found at [17]

In addition to multiple trapping, one can easily rotate the trapped microbeads' configuration as a single entity. This was achieved as follows. The glass substrate with an array of microlenses as shown in Fig. 2 was mounted on a rotating optical mount. Rotating the aligned and centered glass substrate resulted in the rotation of the laser pattern. As a result, the optically trapped microbead array rotated accordingly. Figure 3d and e shows two snapshots of a microbead configuration during an counterclockwise rotation. The rotation can be executed manually or by using a motor that was coupled to the optical mount. A video clip of the rotation process can be found at [17].

5 Integration of optical tweezers array

A typical optical tweezer setup involves a laser system coupled into an optical microscope system. This type of system setup could be cumbersome. Therefore, it is worthwhile to develop a portable optical tweezer system, and it is even better, if the optical tweezers can be integrated into the sample systems or devices. In this way, the built-in optical tweezers provide potentially useful functions like trapping, manipulation and possibly particle or cell sorting without direct contact.

In this section, we report a novel second application of the glass substrate with the array of microlenses. Here we utilized the light focusing ability of each individual microlens. The relationship between the various dimensions of the microlens and the focal length of the lens as illustrated in Fig. 4a is given by

$$n_2 R_c = (n_1 - n_2) f = n_2 \frac{D^2/4 + L^2}{2L} , \quad (1)$$

where R_c (= 16.0 μm) is radius of curvature of the lens, n_1 (= 1.477) is the refractive index of the PMMA resist that makes the lens, n_2 (= 1.33) is the refractive index of medium (water in our case), D (= 20 μm) is the diameter of the lens, and L (= 3.5 μm) is the thickness of the lens. The PMMA microlenses were fabricated using the same method as mentioned before. In this case, the dosage of the proton beam used was 100 nC/mm^2. Using (1), f turns out to be 145 μm in water. This is similar to the thickness of a typical coverglass that is used as a spacer in our sample chamber. A hexagonal array of microlenses with a lattice spacing of 25 μm was utilized (Fig. 4b). The glass substrate is incorporated into the sample chamber. The schematic of the sample chamber is shown in

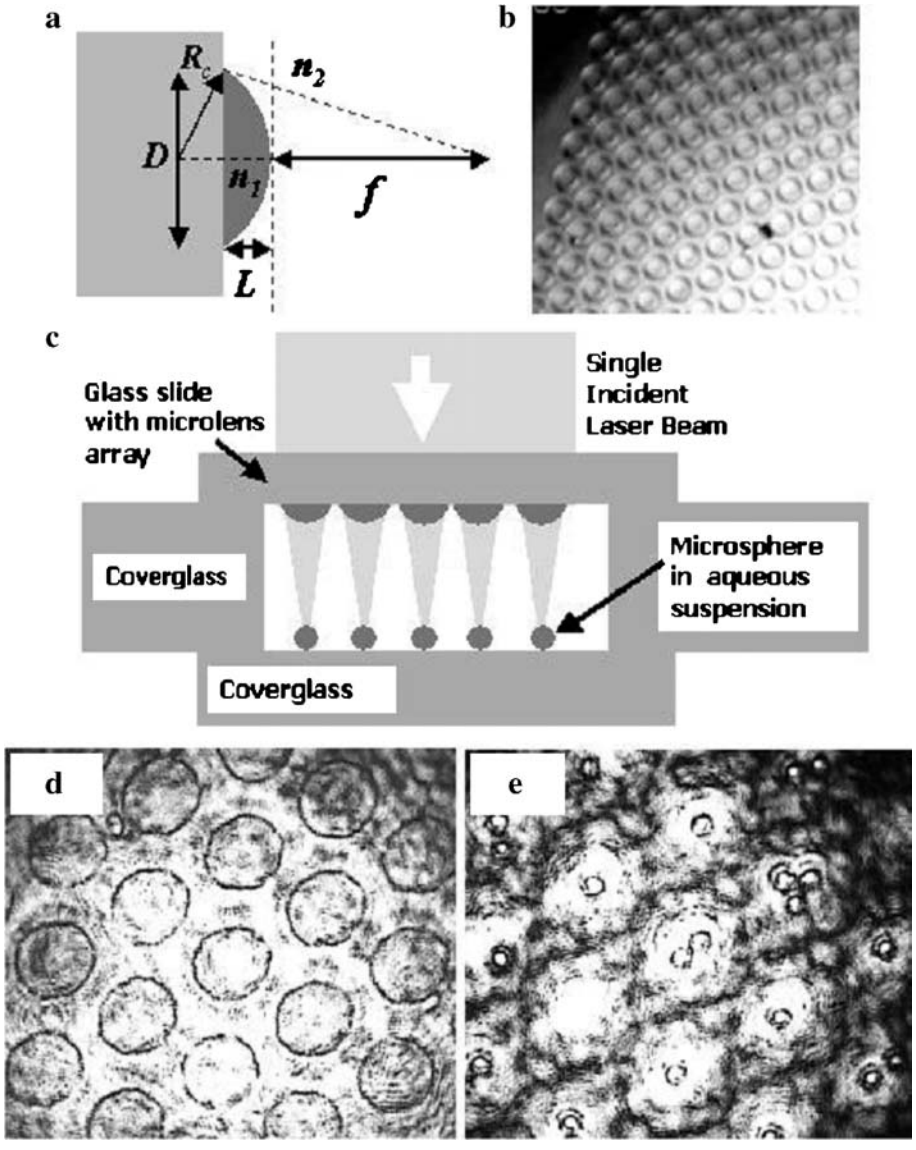

FIGURE 4 **a** Schematic diagram labeling various parameters associated with the microlens. **b** Optical Micrograph of array of microlenses used in this application. The lenses form a hexagonal array with a lattice spacing of 25 μm. **c** Schematic (not to scale) of a sample cell where the array of microlenses is built into the sample chamber. **d** Optical microscope image of a close-up view of the array of microlenses. **e** Viewing plane about 150 μm from (**d**) showing the bright focused laser spots. Microbeads can be found trapped at the local beam intensity maxima. The diameter of the microbeads is 5.1 μm. Video clip of the trapping of the microbeads by this built-in optical tweezer array can be found at [17]

Fig. 4c. In this sample chamber, an aqueous suspension of microbeads was sandwiched between the glass substrate with an array of microlenses and a cover-glass. An additional four pieces of the cover-glasses (two of which shown in Fig. 4c) were used as spacers.

Once assembled, a laser beam was normally directed towards the upper wall of the sample chamber as shown in Fig. 4c. Individual microlenses focused the part of the laser beam incident upon them and modified the incident beam into corresponding individual converging light cones. With sufficient power, each of these focused light cones provided sufficient trapping power to hold the microparticles that were suspended in the aqueous medium. To capture the operation of the integrated microlens array, we placed the sample chamber on an inverted microscope for imaging purposes only. Figure 4d provides a close-up view of the lens array. Figure 4e shows the view of the optical microscope focused at a plane about 150 μm away from the microlenses with the laser turned on. One can clearly see the bright focused laser spots with 1 to 3 trapped microbeads. The diameter of the polystyrene microbeads used in this case is 5.1 μm. In this experiment, we used a SUWTech LCD-2500 diode laser emitting light with a wavelength of 532 nm and a maximum power of 120 mW. Video clips of the integrated optical tweezers in action can be found at [17]. In the video clips, one can see that microbeads readily moved into the focused spots.

The advantages of integrating an optical tweezer array into the system include the ease of optical alignment and compactness of the system. It also makes the device simple to use. The diameter of the incident laser beam is about 1.5 mm, and thus a large number of microlenses can be engaged in optical trapping simultaneously. Since the laser power is essentially divided into individual spots, relatively large laser power is required for effective multiple trapping. With sufficient incident laser beam power, an extended array of optically trapped microbeads can be achieved. In this experiment, the laser beam passed through a moderately converging lens before it is incident upon the sample. Moreover, we have intentionally positioned the lower wall of the sample chamber approximately at the focal plane of the microlenses. In this way, the lower wall served as additional barrier to hold the microbeads at that level and the optical tweezers array would arrange the

microbeads into the desired pattern. In this way, lesser laser power is required. Future experiments include directing the incident laser beam from different oblique angles. By changing the incident angle, the converging light cones would be directed to focus at different positions. This will in principle allow a certain degree of local manipulation of the trapped particles.

6 Conclusion

We have demonstrated two applications of proton-beam micromachined array of microlenses for the simultaneous optical trapping of multiple microbeads. The first application illustrated the function of the lens array as an optical element in generating multiple laser spots for optical tweezing. Capturing an array of particles with a unique configuration is useful for the micro-assembly of colloidal particles. The ability to both trap and rotate tiny objects could be useful in pulling and twisting polymer-like objects. The second application demonstrated the feasibility of integrating the microlens array into a device to provide localized optical trapping. This suggests a potentially useful development in facilitating a few additional functions on a "lab-on-a-chip' microfluidic device. It can be used to hold microspheres or biological cells in predetermined locations for testing and analysis. In addition, if the particles are moving, the array of spots can be used as a guide to direct the particles towards a desired direction [9]. For future work, it is worthwhile to incorporate the laser source into the device and also to improve the efficiency of the optical trapping.

ACKNOWLEDGEMENTS CHS acknowledges the support of Academic Research Fund from the National University of Singapore. AAB acknowledges the support of a Defence Innovative Research Programme (DIRP) grant from the Defence Science and Technology Agency (DSTA), Singapore.

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17 Video clips of the colloidal assembly using the multiple-spots laser tweezing, rotation of colloidal spheres array and on-board multiple spots optical tweezers trapping can be found from the following website http://www.physics.nus.edu.sg/∼physowch/multi_optw/multi_optw.html