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Multiple optical line traps using a single phase-only rectangular ridge

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ABSTRACT An optical line trap has the ability to simultaneously trap and align microparticles in line formation due to its intensity profile. In this paper, we demonstrate a straightforward means to generate multiple optical line traps by simply placing a phase-only rectangular ridge in the path of a laser beam. By carefully positioning the rectangular ridge, we were able to control the separation between the optical trapping lines, which were then used to create multiple line formations of trapped particles. The simplicity of the proposed technique lends itself to the realization of a highly efficient optical line trap converter for easy modification of existing optical microscopes.

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1 Introduction

Ashkin et al. reported the first experimental observation of a single beam gradient force optical trap in 1986 [1]. This optical trap relied on a tightly focused laser beam giving rise to a gradient force directed towards the region of highest intensity; hence, a dielectric transparent microparticle will be trapped three dimensionally by such an optical trap. Since Ashkin et al.'s discovery, this aptly named optical tweezers has been used in varied microbiological processes, e.g. to trap and move microscopic particles such as sorting bacteria [2], probe biological surfaces [3] and measure forces exerted by muscle fibers [4].

Perhaps one of the more significant improvements to the optical tweezers was to incorporate techniques that allowed optical rotation of trapped particles in a controlled manner. A trapped particle could be made to rotate by transferring the optical angular momentum of a laser beam to the particle that is either birefringent or absorptive in nature [5, 6]. Another approach was to shape the structure of microparticles to allow radiation pressure to be directed in different directions above and below the focus plane [7].

However, a more direct approach to spin particles already trapped by gradient force in optical beams is through the rotation of the beam's intensity pattern [8–12]. O'Neil and Padgett [8] have shown a simple technique whereby a 4-mm-wide rectangular aperture placed in the path of an incoming Gaussian beam results in the zero order having a line intensity pattern. Microparticles are trapped and aligned in the line intensity pattern. By rotating the aperture, the line pattern rotates and hence gives a direct rotation of the microparticles. However, the efficiency of this technique is low as the optical beam is highly attenuated after passing through the rectangular aperture. More recently, a single cylindrical lens has also been used to create an optical line trap [9] with a higher efficiency. Both of these methods allow for the generation of a single optical line trap and, by rotating the cylindrical lens or aperture, the microparticles can be made to rotate. The first demonstration of an optical trap that uses interference fringes for trapping and micromanipulation was shown by Chiou et al. [10], and to date interference fringes have been used for the manipulation of both high- and low-index microparticles [11].

On the other hand, techniques to generate multiple beam spots that simultaneously allow multiple microparticle rotation do exist; rotating Hermite–Gaussian (HG) modes from a spatially tuned laser beam were used to generate patterns of multiple rotating spots [12]. Macdonald et al. [13] made use of rotating spiral interference patterns generated from interfering a laser beam with a helical wavefront with a reference beam or its mirror image; the same group also utilized angular Doppler shifts to create continuous rotational interference patterns [11]. Such methods require the precise tuning of the laser's cavity or a large interferometric set-up.

In this paper, we propose to use a single phase-only rectangular ridge structure to split a Gaussian beam into a pattern of multiple line traps with high efficiency. By carefully positioning the structure in the path of the illuminating Gaussian beam, multiple light traps are generated that can be used for the optical translation of microparticles. The simplicity of such a technique lends itself to the realization of a highly efficient optical line trap converter for easy modification of existing optical microscopes. Fabrication of the 100-μm-wide and 4-mm-long phase-only ridge was done using commercially available AZ5214 positive photoresist spun on microscope cover slides; the 'top hat' phase profile is provided by a step change in the photoresist height. The refractive index (n) of the AZ5214 resist was measured using a prism coupler to be 1.641. With this value of n, the step height to achieve a π difference for 632.8 nm was calculated to be 0.494 μm. A spin coater set at

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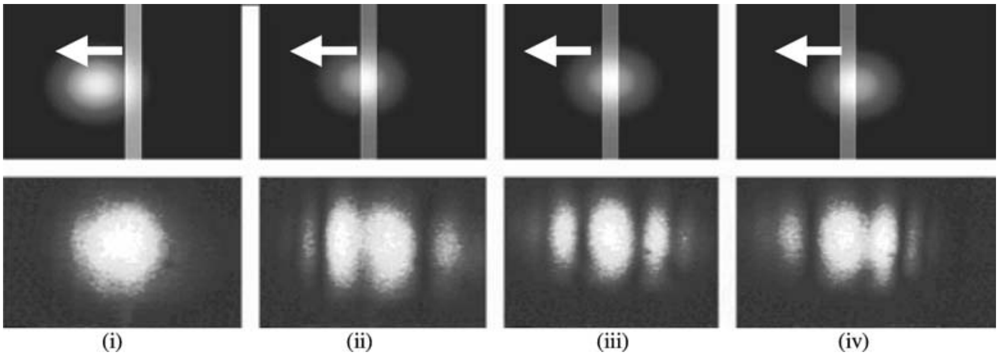

FIGURE 1 Evolution of fringe patterns when the rectangular phase structure was shifted into the path of an illuminating Gaussian beam. The *white arrow* indicates the scanning direction of the phase-only rectangular ridge

4000 rpm and a spin time of 35 s was used to achieve a resist height of about 1.5 μm. This corresponds to approximately a 3π phase difference. This odd multiple of π phase changes provides the necessary phase discontinuity for the formation of multiple line traps. Subsequently, it was a trivial matter of exposing the photoresist to UV radiation under a patterned mask followed by developing the resist to give the desired phase ridge.

The rectangular phase-only ridge can be treated like a phase plate that modulates the Gaussian beam into line intensity patterns. By translating the beam orthogonally across the rectangular phase-only ridge, we were able to achieve dual and triple line intensity patterns as compared to the adjustable binary diffractive optical element [14]. In Fig. 1, we present the patterns observed when the 100-μm rectangular ridge was shifted into the path of an illuminating Gaussian beam of $w_o = 0.6$ mm. As shown in Fig. 1, when the Gaussian beam illuminates the phase step, portions of the illuminating beam are phase shifted, thereby causing the output optical beam to result in a fringe pattern. Figure 1i shows the unmodulated beam when the rectangular ridge is at the edge of the beam waist. In Fig. 1ii and iv, when the Gaussian beam illuminates the start or end of the phase step, the line intensities will be approximately equal. When the illuminating Gaussian beam is fully centered on the rectangular slit, as shown in Fig. 1iii, we obtain a central maximum sandwiched between two fringes of equal intensity. Therefore, carefully positioning the phase ridge at different locations in the beam's cross section or alternatively scanning the beam across the phase-only rectangular ridge gives a range of useful fringe patterns. We used this evolution of the fringe patterns to form multiple optical line traps.

The multiple optical line traps were generated from a 30-mW linearly polarized 633-nm HeNe laser, which is used to illuminate the rectangular ridge. The optical traps were directed into an epi-fluorescence path of the upright optical tweezers configuration (Carl Zeiss Axiostar Plus), as shown in Fig. 2. The rectangular phase-only ridge structure is also mounted on a rotating x–y–z translation stage for precision alignment in the beam's path. The overall optical efficiency of the rectangular phase-only ridge was measured to be approximately 90%. This indicates an efficient conversion from a single Gaussian beam to multiple optical line traps. The laser was then directed into a $\times 100$ objective lens with a N.A. of 1.25 that focuses the beam and allows for viewing of the trapped object; a CCD camera attached to the system was used to monitor and capture the experimental observations that are shown in Figs. 3–6.

In Fig. 3, we show that five 0.97-μm silica microspheres with refractive index of 1.59 were initially trapped as a group by an unobstructed Gaussian beam. When the rectangular structure was slowly slid across the path of the laser

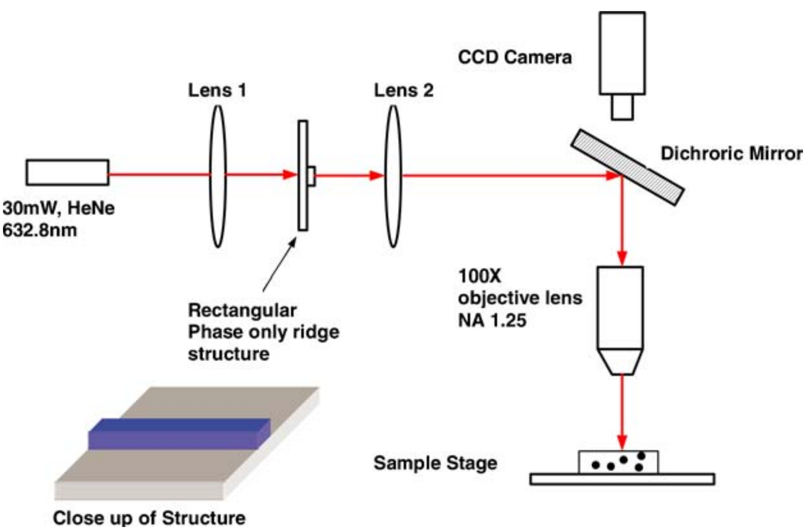

FIGURE 2 Schematic of an upright optical tweezers set-up with the phase-only rectangular ridge placed at the mid-point between two conjugate lenses

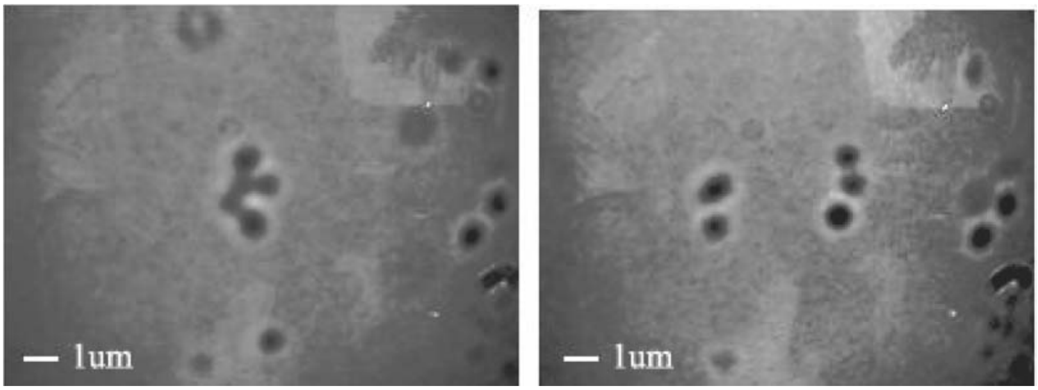

FIGURE 3 0.97-μm silica microspheres being tweezed apart by optical line tweezers generated from the phase-only rectangular ridge using the intensity gradient from Fig. 1ii

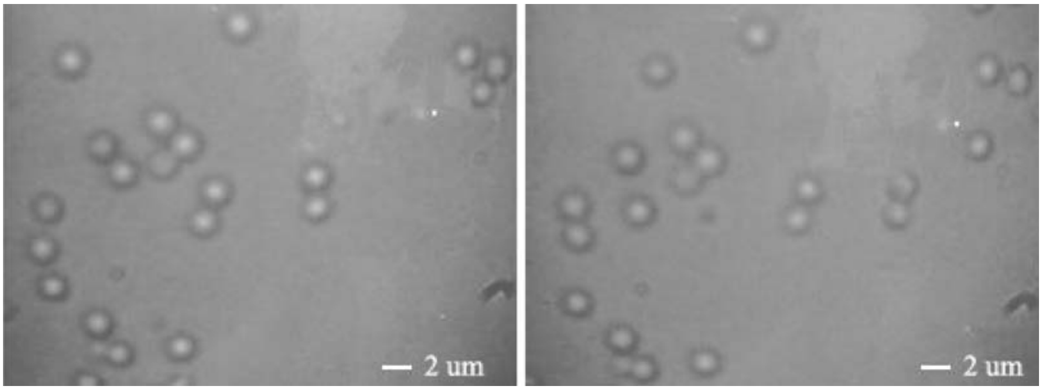

FIGURE 4 Translation of 2-μm silica microspheres trapped in double line formation using the intensity gradient from Fig. 1ii and iv

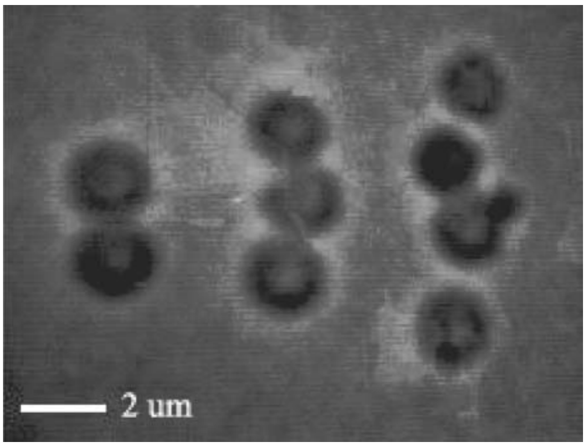

FIGURE 5 Triple line formation of 2-μm silica microspheres using the intensity gradient from Fig. 1iii

beam, the silica microspheres were tweezed apart into a formation of two separate lines. This corresponds to the intensity profile observed in Fig. 1ii or iv. The silica microspheres will be drawn into formations following the lines of high intensity when the beam's profile evolves. This emphasizes the point that it is possible to control the separation of particles by a straightforward motion of translating the phase-only ridge structure into the path of a beam. It is then possible to translate the microspheres while maintaining them in formation (Fig. 4); we demonstrate this using 2-μm silica microspheres that have been arranged in a double line using the technique.

Keeping the beam centered on the rectangular phase-only structure results in the triple line intensity profile observed in Fig. 1iii. We used this profile to demonstrate a triple optical line trap in Fig. 5. The number of particles in each line of Fig. 5 is not indicative of the pattern symmetry, but is due instead to the availability of particles near the trapping region. We note a reduction in the axial optical trapping efficiency due to the defocusing which is also seen in other line trap methods [10, 11]; however, this does not impair the usefulness of the technique to easily produce optical line traps. Compared to other methods of obtaining optical line traps, its advantage lies in its simplicity and straightforward insertion into an existing optical microscope.

We next demonstrate the capability of the simple phase-only structure to rotate particles while maintaining a double line formation. By revolving around the axis, we are able to perform an optically induced rotation for a double line formation of 2-μm silica microparticles. We illustrate our results in Fig. 6a i–iv, where the formation is tilted in steps of approximately 45°, while Fig. 6b i–iv shows the corresponding intensity pattern at each stage of the process.

In conclusion, we have shown a simple and efficient technique of generating multiple optical line traps by a single rectangular phase-only ridge structure. By just employing a simple rectangular ridge, configurable optical line traps can be easily generated that can tweeze apart, translate and rotate

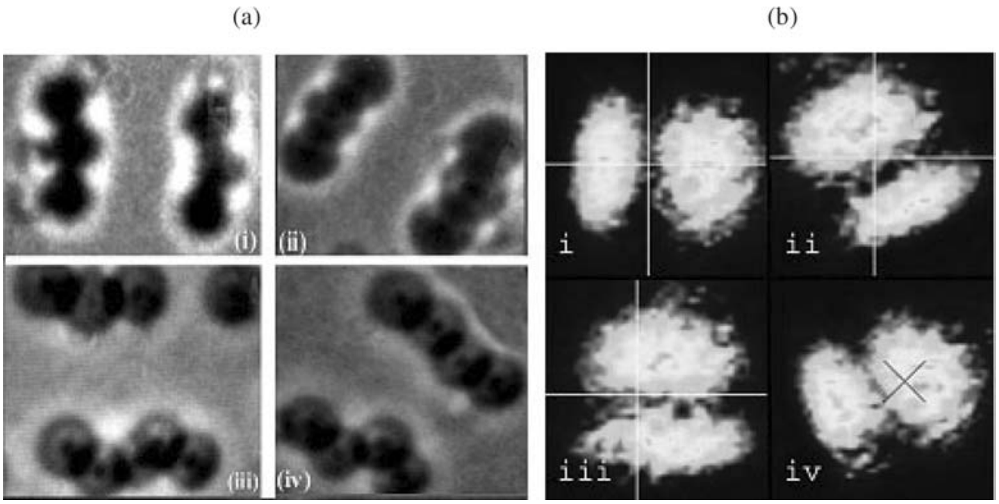

FIGURE 6 **a** i–iv Rotation of 2-μm silica microspheres trapped in double line formation. **b** i–iv Beam profile at each stage of the rotation

microparticles in formation. This method could find its use in aiding in the study of muscle contraction [15], stretching of DNA (without the need to physically anchor one end of the DNA) [16] or even in the fabrication of linear structures for microfluidic applications [17]. In addition, the rectangular phase-only ridge can be integrated with other microfabricated optical elements such as spiral phase plates [18] into a common platform. This would allow conversion to different types of optical traps efficiently and rapidly by simply sliding the illumination beam from one phase structure to another. To end-users without a background in optics, this would provide an easily accessible means of configuring the laser beam for any biological or chemical optical manipulation requirements.

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