Optical vortex beam shaping by use of highly efficient irregular spiral phase plates for optical micromanipulation

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Optical dark traps such as Laguerre–Gaussian beams, modulated optical vortices, and high-order Bessel beams have been used in the micromanipulation of microparticles. Such optical traps are highly versatile, as they are able to trap both high- and low-index microparticles as well as to set them into rotation by use of the orbital angular momentum of light. Holography has been widely used to modulate the shape of an optical vortex for new optical traps. We show that, by designing the shape of a spiral phase plate and using electron-beam lithography for fabrication, one can modulate the amplitude and the phase of an optical vortex with respect to the specific shape of the spiral phase plate as required. Furthermore, to the best of our knowledge this is the first report of transferring orbital angular momentum from a spiral phase plate to an absorptive microparticle in an experiment. Hence, with this technique, optical dark traps can easily be designed and fabricated.

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In recent years, optical dark traps have generated much interest in the field of optical trapping. High-order Bessel beams[1] have been shown to be able to trap and rotate both high- and low-index microparticles. Another optical dark trap, the Laguerre–Gaussian (LG) beams, or optical vortex, was demonstrated to be more versatile than Gaussian beams[2] in optical trapping. It has been shown to be capable of simultaneously manipulating low- and high-index microparticles[3,4] as well as of setting absorptive microparticles into rotation.[5] Furthermore, LG beams are able to provide more stable axial trapping than can fundamental Gaussian beams on microparticles of larger size than the focused beam spot.[6] The LG beam has also been observed to possess the ability to stack microspheres about its intensity ring, thus forming a three-dimensional structure.[7] The highly efficient optical elements used to generate optical dark traps are spiral phase plates,[8–10] liquid-crystal cells,[11] and diffractive optics.[12] These optical elements have conversion efficiencies of as much as 90–99%. However, to create more variations of optical dark traps, holograms have frequently been employed. Both Zhang and Yuan[13] and Curtis and Grier[14] modified the azimuthal phase variation of an optical beam mathematically and encoded the phase information into a hologram to create variations of optical dark traps. They then reconstructed the phase profile by directing a reference beam onto a spatial light modulator. Such a method of optically designing an optical dark trap is versatile but has its limitations. This is so because the spatial light modulator, which is a dynamic diffractive optical element, is of high cost and moderate efficiency. The holographic method is one of many ways to achieve azimuthal phase variation in an optical beam.

In this Letter we introduce a technique in which shaping the spiral phase plate directly shapes the area of the azimuthal phase variation. This technique will result in direct shaping of the optical vortex beam. In our technique we specify the area in which the spiral phase ramps from 0 to 2π. Subsequently we make use of electron-beam lithography for direct writing upon an SU8 negative resist.[15] By varying the electron-beam energy dosage at different parts of a specific area we can easily fabricate a spiral phase plate of the desired optical shape. After fabrication, we incorporated the designed spiral phase plate into an upright optical trapping system. We subsequently directed the optical dark traps into collections of rainwater, silica, or latex microspheres.

The spiral phase plate structure was directly based on the mathematical expression[8–10] $\exp(il\phi)$. By insertion of the phase element along the propagation axis of the Gaussian beam, the output optical beam will have the function

$$\mathrm{LG}(r, \phi, z) = G(r, \phi, z)\exp(il\phi), \tag{1}$$

where l is the azimuthal phase variation of the optical beam and $G(r, \phi, z)$ is the expression of a Gaussian amplitude distribution. Such a spiral phase plate creates a 2π phase shift at the beam axis that results in an intensity pattern comparable to that of the LG beam, which is a phase singularity at the central axis of the optical beam. Hence the output optical beam will possess well-defined azimuthal phase variations in the central axis of the optical beam because of the presence of the spiral phase plate. Thus the optical beam will also possess a defined orbital angular momentum,[16] which can be observed by optical rotation of absorptive microparticles[5] or by interference.[9,11]

In the research reported here we designed an elliptical area to fabricate the irregular-shaped spiral phase plate by electron-beam lithography. The spiral phase plate results in an output optical vortex that took the shape of a closed-loop ellipse. It was shown by Zhang and Yuan[13] that directing the path and the area of

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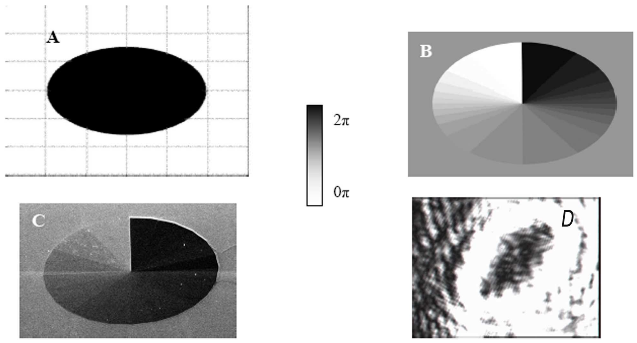

Fig. 1. A, Mathematical plot of the elliptical area. B, Elliptical spiral phase distribution from the mathematical plot and C, elliptical spiral phase plate (500 μm by 250 μm), both in the counterclockwise direction. D, Elliptical optical vortex propagated to the far field.

azimuthal phase variables $\phi(x,y)$ as the phase changes from 0 to 2π will cause the vortex beam to shape the optical path as follows:

$$\mathrm{LG}(r,\phi,z) = G(r,\phi,z)\exp[il\phi(x,y)]\,. \tag{2}$$

Here an elliptical path is specified; the azimuthal phase variation follows an elliptical path as the phase changes from 0 to 2π, as shown in Fig. 1. The elliptical spiral phase still possesses charge $l = 1$, where the overall winding path of the spiral phase plate is 1.

To design the elliptical vortex, we first mathematically plotted the elliptical vortex area, as shown in Fig. 1A. Subsequently we specified the phase distribution from 0 to 2π to comprise 24 sectors. The direction of the phase increment was counterclockwise within the elliptical vortex area, as shown in Fig. 1B. In the fabrication, this phase distribution directly represents the amount of exposure at the various sectors within the elliptical area. Once the mask, which is a phase distribution within the designed shape, is exposed to electron-beam illumination, the elliptical phase plate will be constructed as shown in Fig. 1C. The elliptical spiral phase plate is then placed in the path of the optical beam, Gaussian mode. The output optical beam will take the shape of an elliptical optical vortex when it propagates to the far field, as shown in Fig. 1D. The elliptical optical vortex is directed at 45° from the horizontal onto the sample plate.

In the trapping setup, the elliptical spiral phase plate is incorporated into our existing upright optical trapping setup by use of a Carl Zeiss Axiostar Plus upright microscope, as shown in Fig. 2. Figure 2 shows an elliptical spiral phase plate mounted onto a rotating $x-y-z$ stage in the propagation path of a 30-mW linearly polarized 632.8-nm He–Ne laser. The efficiency of the elliptical spiral phase plate as measured with a powermeter is approximately 85–90%. The average power incident onto the sample is approximately 24–25 mW.

Figure 3 shows a set of silica microspheres trapped within the lower half of the intensity ring of an elliptical vortex beam. In Fig. 4 we show that the elliptical vortex is able to transfer orbital angular momentum onto an absorptive particle from a collected sample of rainwater at the rotational rate of ~0.8 Hz. The rotation of the microparticles was counterclockwise, the same as the helicity of the spiral phase plates. The rotation lasted for an hour after the spiral phase plate was removed from the optical path after which the rotation stopped. This demonstrates the existence of

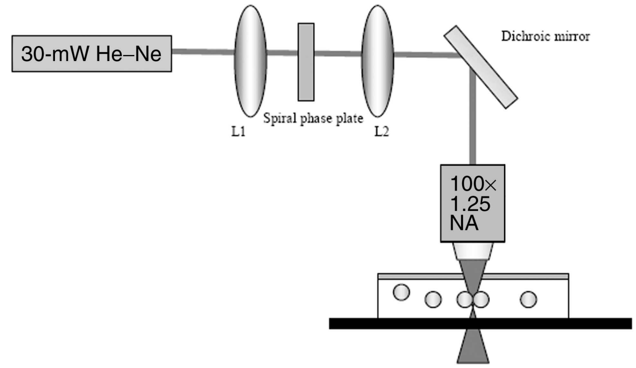

Fig. 2. Linearly polarized 30-mW He–Ne laser is directed onto an optical tool kit. The single optical tool kit is mounted onto a rotating $x-y-z$ stage inserted between optical lenses. Lens L1 is used to focus the optical beam onto the phase elements; lens L2 focuses the optical trap into the 100× objective of N.A. 1.25.

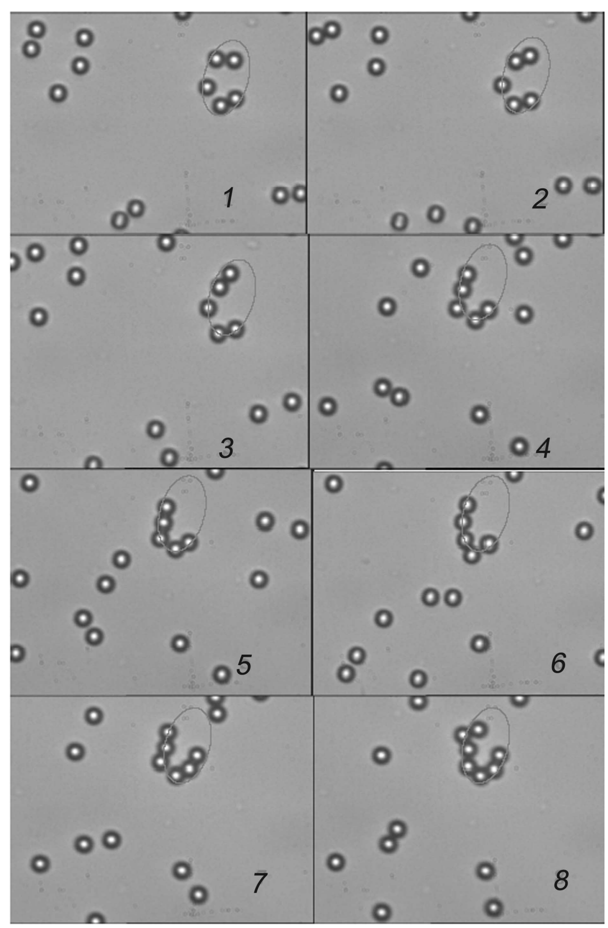

Fig. 3. Silica microspheres of 3 μm, each with a refractive index of 1.4 trapped at the intensity rings of the elliptical vortex beam. (The elliptical beam is oriented 45° from the horizontal.)

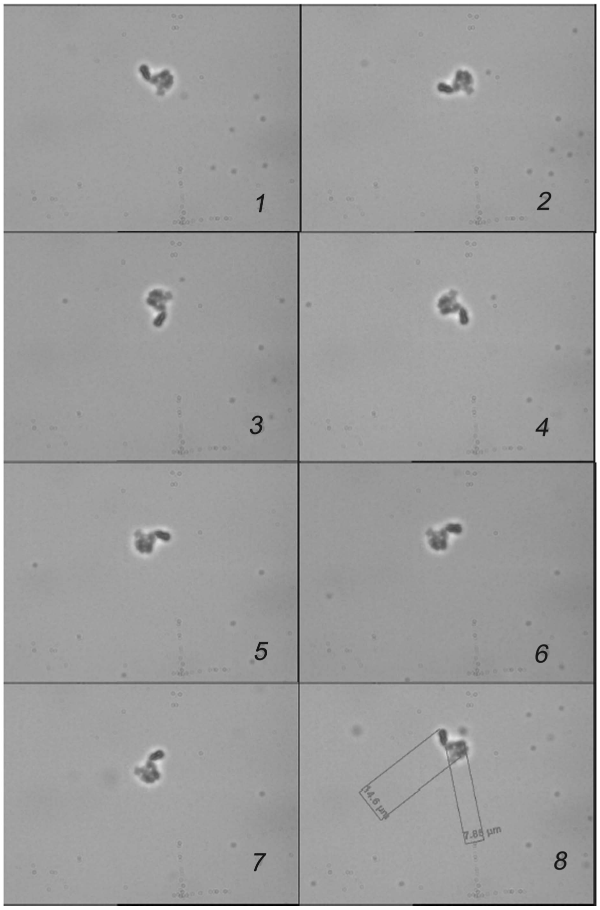

Fig. 4. Orbital angular momentum transferred onto an absorptive irregular microparticle of ~5-μm width and 14-μm length in the collected sample of rainwater. The microparticle was stably rotating at a relatively low rate because of the size of the microparticle, which creates a high drag force, for an hour before the optical beam was released, after which the particle rotation stopped.

well-defined orbital angular momentum of the elliptical vortex trap. The same rate of optical rotation was observed for ~20 other absorptive microparticles of sizes from 8 to 10 μm. The optical forces within the Mie regime are involved in the trapping, and rotations are the gradient forces of high intensity.[2] Because the total orbital angular momentum of a linearly polarized elliptical vortex beam remains directly proportional to the azimuthal phase variation, the optical torque can be calculated[5] as follows:

$$\Gamma_z = \frac{P}{2\pi\nu} l, \tag{3}$$

where P is the laser power, l is the azimuthal mode index, and ν is the frequency of light.

In conclusion, we have demonstrated a new technique whereby modulation of the shape of a spiral plate results in modulation of the shape of the optical vortex. This technique will be important for the trapping of irregularly shaped micro-organisms whose microbiological cellular structures[17,18] have mostly irregular shapes. Furthermore, we also report, for the first time to our knowledge, that optical rotation of absorptive microparticles by use of a designed spiral phase plate has been achieved with high efficiency. Such an optical technique can be extended to the generation of new optical dark traps for atomic-physics studies.[19,20]

In addition, Lee and Yuan previously demonstrated optical stacking of a Laguerre–Gaussian beam[7] in an inverted optical trapping setup. Using this optical vortex beam shaping technique and directing the beam into an inverted optical trapping setup can easily organize microparticles into a specific three-dimensional crystalline structure determined by the shape of the optical vortex beam. We are using the techniques presented in this Letter to explore more optical vortex shapes.

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