Rotational motions of optically trapped microscopic particles by a vortex femtosecond laser*

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The rotational motions of the optically trapped microscopic particles by the vortex femtosecond laser beam are investigated in this paper. Black particles can be trapped and rotated by a vortex femtosecond laser beam very effectively because the vortex beam carries orbital angular momentum due to the helical wave-front structure in assoication with the central phase singularity. Trapped black particles rotate in the vortex beam due to the absorption of the angular momentum transferred from the vortex beam. The rotating directions of the trapped particles can be modulated by reversing the topological charge of the optical vortex in the vortex femtosecond beam. And the rotating speeds of the trapped microscopic particles greatly depend on the topological charges of the vortex tweezer and the used pulse energies.

Keywords: vortex femtosecond laser, rotation, particles

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1. Introduction

In recent years, optical tweezers have become a powerful tool in fields manipulating the living cell and big molecules in biological experiments because of their ability to manipulate microscopic particles since the demonstration by Arthur Ashkin.[1−3] Optical tweezers can make use of the light scattering and gradient forces due to the interaction of the particle with the light. For particles of higher refractive index than their surrounding medium, the laser beam induces a force attracting the trapped particle to the region of the highest light intensity. Various forms of optical traps, single-beam and levitating, have been used to manipulate a wide range of small particles including cells, polymers, spores, viruses, bacteria, biological motors, and motor proteins.[4,5] With the development of laser technology, the femtosecond laser has become a powerful tool for ultrafast and ultrahigh applications. There are some groups[6−8] focusing on the application of optical tweezers using the femtosecond laser as the light source. Compared with CW tweezers, the femtosecond tweezer has a prominent advantage in that the high peak power of the femtosecond pulse is able to induce a nonlinear optical process within the trapped particle such as multiphoton absorption and second harmonic generation. It was reported that the dynamics of optical trapping with a femtosecond laser was dominated by the average power, not the peak power of the pulse.[6] A femtosecond laser is able to provide us with not only optical trapping but also information about these nonlinear optical phenomena.

It has been proved that photons can carry both spin angular momentum (SAM)[9] and orbital angular momentum (OAM).[10] Both the SAM and the OAM can result in the rotation of the microparticles in light by transferring the angular momentum from beams to particles, which offers a new manipulating method to microparticles or biological molecules. The SAM is associated with polarized states of the light and was observed more than 70 years ago.[9] However, the OAM is associated with the azimuthal phase of the complex electric field, in which a laser light with a Laguerre–Gaussian amplitude distribution is thought to have a well-defined OAM because it has an azimuthal angular

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dependence of $\exp(\mathrm{i}l\phi)$, and the corresponding helical phase fronts carry an orbit angular momentum of $l\hbar$ per photon.[10−13] Furthermore, this OAM of the photons has also been proved experimentally to be able to transfer partially absorbing particles held in optical vortex tweezers.[10,11] However, there are few investigations focusing on optical vortex tweezers with a famtosecond laser as a light source.

In this paper, we investigate the controllable rotations of the trapped microparticles (micro-sized copper–oxide (CuO) particles) by the femtosecond vortex tweezers in experiments. The experimental results show that the OAM of the photons in femtosecond vortex pulses could transfer to the absorptive particles and result in the rotation of the microscopic particles in the femtosecond vortex beam. The concrete rotational motions of the microscopic particles are recorded using a video camera and could be analysed in a timing sequence. Our experimental results show that this technique is very effective for manipulating the microscopic particles and may offer an important application in optical tweezers.

2. Experiment

The experimental setup for a femtosecond optical vortex tweezers system is constructed by ourselves as shown in Fig. 1. A Ti:sapphire laser system (Coherent Inc) with a pulse width of 120 fs, wavelength of 800 nm, and repetition rate of 76 MHz is used as a trapping light source. In order to obtain the vortex beam for the vortex tweezers, firstly we need to obtain the computer-generated hologram (CGH) of the optical vortex. The CGH of optical vortex can be obtained by numerically calculating the interferogram of two waves: a planar reference wave and an object wave containing the desired optical vortex. The binary CGH is directly fabricated inside glass by femtosecond laser pulses,[14] the experimental progress used in this work is similar to the one used in Ref. [15]. The pulse energy of the femtosecond laser can be adjusted by a variable neutral-density filter, and the number of used laser pulses can be chosen by a mechanical shutter system controlled by the PC. Then, the femtosecond laser beam is incidental to the fabricated CGH of an optical vortex for generating the femtosecond optical vortex pulses. The $+1^{\mathrm{st}}$ order diffraction with the topological charger of $l = 1$ is chosen by a special mask to be incident to the objective lens through a dichroic mirror in a modified optical microscope, which could be strongly focused by the objective lens (NA = 0.9) and then was used to trap and manipulate particles. The image of the trapped particles is monitored by a charge coupled device (CCD) monitor through the optical microscope. All experiments are performed in ambient air conditions under atmospheric pressure. The sample of the microparticles (absorbing particles of black CuO) dispersed in distilled water are placed between a glass slide and a cover slip. Sizes of the particles that can be trapped are around 1 μm–3 μm. The particles are illuminated by a lamp below. A video camera placed vertically on the top of the microscope is used to record the motions of the trapped particles in femtosecond vortex tweezers. The sample was mounted on a computer-controlled XYZ-translation stage, and the trap depth could be changed by stage for observing and manipulating the particles.

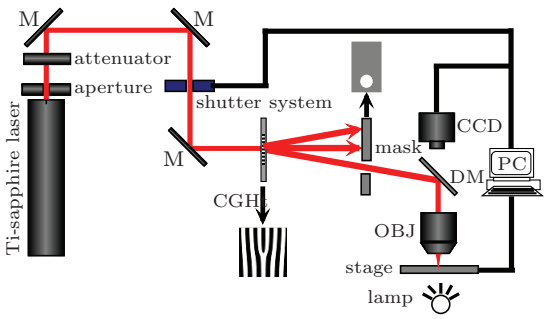


Fig. 1. (color online) Experimental setup. M: mirror; CGH: computer generated hologram; OBJ: objective lens; DM: dichroic mirror.

3. Results and discussion

A vortex beam is described by its azimuthal mode index l that can also be called its topological charge, and its azimuthal mode index denotes the number of complete cycles of phase (2π) upon going around the circumference of the mode. Here, we fabricate the CGH of the optical vortex with a topological charge of $l = 1$ by the CGH method, and the fabricating process is similar to that in Ref. [15]. Then, the vortex beam can be reconstructed by the continuous He–Ne laser and femtosecond laser pulses respectively as depicted in Fig. 2. The analytical results of the reconstructed results show that the intensity distributions in the cross section of the generated vortex beam have a higher fidelity to the original characteristics of the optical vortex.

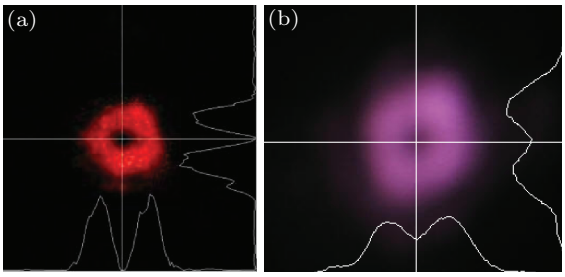


Fig. 2. (color online) Intensity distribution in a cross section of the generated optical vortex by the He–Ne laser (a), and femtosecond laser pulses (b) respectively.

In order to trap the microscopic CuO particles, the generated femtosecond vortex pulses with a topological charge of $l = 1$ are introduced into the optical objective as shown in Fig. 1. The experimental results show that the properly chosen CuO particles can be moved from one place to another in the sample cell with a proper moving speed by the femtosecond vortex tweezer system with the method of moving the three-dimensional stage, and at the same time, the trapped particles also rotate around the centre of the optical spot. From the video camera, we can clearly observe that the trapped microscopic CuO particle always rotates in one direction, which could be interpreted by the determined OAM of the specific femtosecond vortex pulses relating to the spiral phase distribution of the wavefront. As shown in Fig. 3, a fairly symmetric CuO particle with a size of about 3 μm denoted by a circle is trapped in the femtosecond vortex tweezer and spun at a rate of about 0.125 Hz, under an incident pulse power of 15 mW. And the particle also keeps rotating in the same direction while being moved to other place relative to its surroundings by the femtosecond vortex tweezer. The rotation of a trapped particle can be easily maintained for long period of time. The particle can be trapped again in the same rotational direction after having been freed from the vortex tweezers. When the power of the incident beam increases from 15 mW to 18 mW, the rotating speed of the trapped particle (the same nanoparticle) will increase too, and the rotating frequency increases to about 0.167 Hz. However, if the incident power continues to be increased to 20 mW, the microstructure of CGH will be destroyed very swiftly (in several seconds). If the femtosecond vortex beam reaches a power of 20 mW in the first order of the CGH, the femtosecond laser power incident to the CGH should be higher than 250 mW. Therefore, if the CGH structure is destroyed by the incident laser, the femtosecond vortex beam will also vanish. In order to obtain a femtosecond vortex beam with a higher power in future experiments, we intend to enhance the diffractive efficiency of the fabricated CGH by reducing the period (Λ) or increasing the depth (d) of the CGH according to the grating parameter $Q = 2\pi\lambda d/(n\Lambda^2)$ defined by Kogelnik.[16]

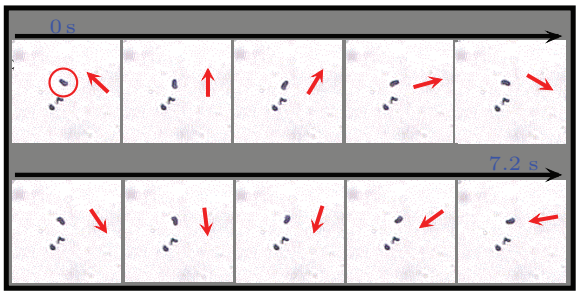


Fig. 3. (color online) Image sequence showing the controlled rotation of a laser-trapped black CuO particle. The trapped particle is denoted by a circle; the arrows show the direction of the trapped particle modulated by the femtosecond vortex tweezer; other objects in the field are stationary.

We also observe that the femtosecond vortex tweezers can also trap some microscopic CuO particles with very irregular shapes, instead of steady rotational particles like the regular particles, these irregular particles tumble acutely in the vortex tweezers and occasionally rotate in the opposite direction because the irregular morphology of the particle could obtain a different directional momentum from the interaction between the particle, the femtosecond laser pulse, and the solution. Figure 4 shows ten successive frames of a video recording of the tumble and rotation of the irregular particles in the manipulation by the femtosecond vortex tweezers. The rotating speed of the trapped particle changes at different stages, which is dependent on its shape and size. Particles with different shapes and sizes are observed to rotate at different speeds and in different directions in the same femtosecond vortex tweezers with the same incident pulse energy.

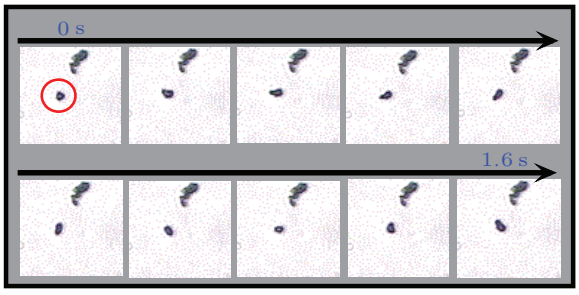


Fig. 4. (color online) Ten successive frames of a video recording of an asymmetric particle of black CuO. The particle trapped is marked with a circle; other objects in the field are stationary.

When we turn the CGH 180 degrees in the CGH's plane, we will obtain a vortex beam with a topological charger of $l = -1$ in the same selected diffraction order by the special mask as shown in Fig. 1. We repeat the above procedures in our experiment using this vortex beam with the toplogical charger of $l = -1$ as a source of the tweezers. The particles can also be manipulated in the vortex tweezers, however, the rotating direction of the manipulated particles is reversed into an anticlockwise direction. We also try to increase the energy of the incident pulses to a higher level, and we observe that the rotating speed can be enlarged compared with the used smaller pulse energy. In addition, we try to manipulate the microscopic particles using the femtosecond vortex tweezers generated from the CGH with a higher topological charge of $l = 3$, and we observe that the manipulating rotation of the particle is easier than that of the vortex with a topological charge of $l = 1$ in the same pulse energy and a similar particle.

The observed rotation of the trapped particle could be attributed to the absorption of the orbital angular momentum from the used femtosecond vortex pulses, and some kinds of unbalanced forces, such as a thermal force, or a scattering force, which may produce a torque acting on a nonsymmetric particle, have been proposed for explaining the non-equilibrium motion of the trapped particle by He *et al.*[10] Among these forces, the scattering force is regarded as the most important one, and since the direction of the scattering force is predominantly downward, the direction of the torque produced by the scattering force is therefore perpendicular to the beam axis.[10] The torque is presumed to be responsible for the irregular tumbling exhibited by asymmetric particles. Of course, asymmetric particles will tend to rotate unbalanced as a result.

The fact that we do not see any rotation when we use the linearly polarized CW and femtosecond Gaussian beams without the optical vortex as the radiation sources for trapping regular particles also strongly suggests that the rotation of the trapped particles is a direct consequence of the transfer of the orbit angular momentum carried by the vortex beam to the trapped particles. The trapped particle CuO is one kind of absorbing particle. Our experimental results show that not only the used laser parameter, but also the nature, shape, and size of the particles can influence the speed and direction of femtosecond vortex tweezer manipulation. This technique offers important applications in the fields of micro-optics and micro-machines. Further experiments on the rotation of the particle are now in progress in our laboratory.

4. Conclusions

In this work, we demonstrated that the absorptive particles can be trapped in the dark core of the femtosecond vortex tweezers made steady in the experiment by the generated vortex femtosecond laser pulses. The rotational motion of the particle is attributed to the transfer of orbit angular momentum carried by the vortex femtosecond laser to the trapped particle. The direction of the rotational motion is determined by the chirality of the vortex femtosecond laser beam. Such a controllable technique offers important applications in micro-optics and micromachines. Further experiments on the rotation of the particle are now in progress in our laboratory.

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