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Abstract: We have experimentally observed the steady rotation of a mesoscopic size metallic particle trimer that is optically trapped by tightly focused circularly polarized optical vortex. Our theoretical analysis suggests that a large proportion of the radial scattering force pushes the metallic particles together, whilst the remaining portion provides the centripetal force necessary for the rotation. Furthermore we have achieved optical trapping and rotation of four dielectric particles with optical vortex. We found that, different from the metallic particles, instead of being pushed together by the radial scattering force, the dielectric particles are trapped just outside the maximum intensity ring of the focused field. The radial gradient force attracting the dielectric particles towards the maximum intensity ring provides the centripetal force for the rotation. The achieved steady rotation of the metallic particle trimer reported here may open up applications such as micro-rotor.

Invented by Ashkin three decades ago, optical tweezers has been widely used in manipulating objects in the micro world¹. Rotating objects, as a special form of object manipulation, has been studied intensively because it could have a range of applications such as biological cell orientation², photonics devices³, optical spanner⁴⁻⁶ and micro-rotor⁷⁻¹². Generally, torque induced by angular momentum of light can be used to rotate an object, and it has two distinct forms: Spin Angular Momentum¹³ (SAM) and Orbital Angular Momentum¹⁴ (OAM). SAM is associated with circular polarization. Each photon in a circularly polarized light carries a basic unit of SAM $\pm\hbar$. The sign of the SAM depends on whether the light is left or right circularly polarized ¹⁶. OAM is associated with helical wavefront. Beam with helical phase $\varphi = l\phi$ (*l* is positive or negative topological charge and ϕ is the polar angle) possesses well-defined OAM with $l\hbar$ ¹⁴. SAM rotation has been applied to birefringence materials¹⁶⁻¹⁸, irregular objects⁹, ¹⁹, ²⁰, turbine type structures⁸, ¹¹, ²¹ and non-uniform coated spheres¹². However, the torque changes with the orientation of the objects. In addition, the photothermal effect and photodamage are challenges for high absorption objects and biological samples²². OAM provides an alternative method for optical rotation of particles without special requirement of the shape and/or material composition of particles. Optical vortex is a typical beam

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Publishing that possesses OAM^{4, 23}. Compared with laser beam being focused directly to the particle, optical vortex with doughnut-Publishing tensity distribution leads to less instant heating and photodamage because of its relatively large illumination area²². Therefore optical vortex is an attractive candidate for trapping and rotating particles.

Trapping and rotating of metallic particles with optical vortex has indeed attracted much attention. Zhao *et al* demonstrated the rotation of three individual metallic particles by using strongly focused circularly polarized Laguerre-Gaussian beam²⁴. K. Dholakia 's group reported the trapping and rotation of two individual nanoparticles in the dark core of optical vortex²⁵. We previously demonstrated the rotation of single metallic particle on a metal-thin-film with plasmonic vortex²⁶. However, in all previous studies the rotation of metallic particles is not steady in terms of rotation path and speed. In addition, the trapped metallic particles in the experiments of all previous studies were individual particles rather than an integrated system, which is highly desirable for practical applications such as micro-rotor. Furthermore, as for theoretical analysis, previous work only studied the force of dielectric particle in optical vortex and there is no detailed quantitative analysis of the force of metallic particle in optical vortex.

In this paper, we experimentally demonstrated the stable trapping and steady rotation of a metallic particle trimer with optical vortex. We have derived and calculated three-dimensional electric field distribution of a focused radially polarized optical vortex beam, by using angular spectrum representative method and Debye vector diffraction method^{27, 28}. Through morphological analysis, we found that the metallic particles are confined within the maximum intensity ring of the focused field. Moreover, in order to investigate the mechanism of the interaction between metallic particle and optical vortex, we used Finite-Difference Time-Domain (FDTD) simulation and Maxwell Stress Tensor (MST) method for quantitative force analysis. The theoretical results agree with the experimental results.

Figure 1 shows the schematic diagram of our experimental set up. After passing through a half-waveplate and a quarterwaveplate, the 1064 nm Nd YAG laser beam was converted to a circular polarized beam. The spiral phase plate was used to give a helical wavefront to the beam. In a full cycle, the spiral phase plate with topological charge of 1 can introduce $0~2\pi$ phase change to the beam with its continuously increasing step thickness. The step thickness is typical in the order of the laser wavelength. The obtained circularly polarized optical vortex was finally focused to the sample on glass slide by using an oil immersion high Numerical Aperture (NA) objective. Particles were suspended in water. The sample of particles solution was held in a homemade well (fabricated on an electric insulating tape) to minimize the motion of water. Note that the use of insulation tape is not essential; any other waterproof material of thickness 100~200 micrometres can be used here. The CCD camera (Point Grey Chameleon CMLN-13S2M) was used to record the movement of the particles. Since the

debroic mirror has a high transmission coefficient but a low reflection coefficient at 1064 nm, most of the reflected 1064 nm blisching 1 not be collected on the CCD camera. Nevertheless a band-stop infrared filter was further used to prevent the

remaining 1064 nm stray light from entering into the CCD camera.



FIG. 1. Optical tweezers system with focused circularly polarized optical vortex. The incident wavelength is 1064 nm. The incident laser power is about 100 mW. HWP: half-waveplate. QWP: quarter-waveplate. The topological charge of the spiral phase plate is 1. The NA of the oil immersion objective lens is 1.49.

First, we performed the optical tweezers experiment using $0.8 \sim 1.5 \mu m$ diameter gold particles (ALFA AESAR). The gold particles will not be trapped automatically by the focused optical vortex because of the repulsion force from the bright ring of the focused optical vortex. We used following five steps in order to achieve stable trapping of a gold particle trimer. (1) The spiral phase plate in the experimental setup (Fig. 1) was removed. The focused optical vortex now became a conventional focused beam. (2) The focused circularly polarized beam was then used to push/move selected gold particles to a desired position. (3) In total three gold particles were moved to the same position and they were placed close to each other by repeating step 2. (4) The laser was then switched off, and a motorized stage was used to move the sample plate so that the center position of the three gold particles was at the focus position of the optical beam. (5) Finally, the spiral phase plate was reloaded and the laser beam was re-launched. The three gold particles were automatically pushed together into the center of the focused optical vortex. The gold particle trimer was now trapped stably inside the bright ring of the focused optical vortex where they started rotating. Note that we have repeated this experiment many times and stable trapping and rotating of metallic particle trimers can always be reproduced using this 5-step experimental procedure. Typical results are shown in Fig. 2 (Multimedia view) where three gold particles with similar size were trapped. We found that the speed of the rotation could vary because of the variation of the gold particles size (0.8~1.5 μ m).





FIG. 2 (Multimedia view). Successive frames of a video recording that show the movement of gold particle trimer in the focused circularly polarized optical vortex. The time interval is 0.2 s. The gold particle in the red dotted circle is to indicate the clockwise rotation. The panel at the bottom right corner shows the force analysis graph. The dotted circle indicates the maximum intensity ring. The solid circle indicates the rotation path of gold particles. F_A and F_c is the angular force and centripetal force of the dotted circle indicating particle, respectively.

The number of the gold particles trapped stably here is three, as the size of gold particle trimer matches the size of the bright ring of the focused optical vortex (with topological charge 1). If the laser is switched off, the trapped and rotating gold particle trimer will not be able to continue rotating. Rather the gold particles will follow a centrifugal motion afterwards, and the gold particle trimer will eventually break apart because the optical force no longer exists. The three gold particles will return to Brownian movements, and they will diffuse away.

Gold particles rotate approximately 21 cycles in 20 seconds [Fig. 2 (Multimedia view)], so their angular velocity is $21 \times 2\pi/20s \approx 6.6rad/s$. Since the trimer particles are touching each other and the diameter of each particle is around 1.15 μ m, their radius of rotation is $1.15/\sqrt{3} \mu m \approx 0.664 \mu m$. The volume of the gold particle is $7.96 \times 10^{-19} m^3$ and the mass of each particle is $1.54 \times 10^{-14} kg$, assuming that the mass density of gold is $19320 kg / m^3$. According to Newton's second law of motion ($F_c = mrw^2$), we can calculate the centripetal force F_c of gold particles to be $4.45 \times 10^{-19} N$. The angular force F_A of gold particles experienced in this experiment approximately equals to the hydrodynamic drag force, which is influenced by both the interaction between particles and the wall effect²⁹. Here we used a simplified model where the trimer was treated as three isolated particles thus only the effect of wall (e.g., glass slide substrate) on a rotating particle was considered to estimate the hydrodynamic drag force. Under these assumptions, we can get the following equation according to Stokes's law with the Faxen correction to fifth order³⁰,

$$F = \mu_{drag} v = 6\pi\eta R v \left\{ \left[1 - \frac{9}{16} \frac{R}{h} + \frac{1}{8} \left(\frac{R}{h} \right)^3 - \frac{45}{256} \left(\frac{R}{h} \right)^4 - \frac{1}{16} \left(\frac{R}{h} \right)^5 \right]^{-1} \right\},\tag{1}$$

where μ_{rag} is the drag coefficient, v is the angular velocity and R is the particle radius. The viscous coefficient η in water blishing is about $3.9 \times 10^{-4} Pa \cdot s$ at $25^{\circ}C$. h is the distance between the center of trapped particle and the glass slide. Therefore, the angular force F_A of gold particles can be calculated as about $4.37 \times 10^{-14} N$, assuming $h = 10 \mu m$. It should be pointed out that a complex model considering both particle-particle and particle-wall interactions is necessary in order to precisely calculate the hydrodynamic drag force related to the rotation of the particle trimer.

In addition, by using the following equation in the paraxial limit^{14, 31}, the torque of a rotating particle can be calculated as

(2)

$$\mu_{drag} vr = \tau = \alpha p(l + \sigma_z) / \omega,$$

where *r* is the rotation radius, τ is the torque of a rotating particle, α is the absorption coefficient, *p* is the incident laser power, ω is the frequency of the light, *l* is the topological charge, $\sigma_z = \mp 1$ for right-handed or left-handed circularly polarized light and $\sigma_z = 0$ for linearly polarized light. The rotation speed *v* of the metallic particle trimer is proportional to the incident power, thus the rotation speed of the metallic particle trimer can be controlled by adjusting the laser power. Note that the topological charge of the spiral phase plate used here is 1. Higher topological charge could also be used but this would lead to a larger rotation radius, as shown in Eq. 2. Higher topological charge would thus be more suitable for trapping and rotating larger size metallic particles.

Having obtained the experimental parameters in the metallic particles rotation, here we will perform theoretical estimation of the particle position trajectory. Fig. 3 shows the calculated field distributions of the focal plane (see supplementary material for the derivation of the electric field of the focused circularly polarized optical vortex beam). The radius of the maximum intensity ring (r_{ring}) is calculated to be about 0.76 µm, which is larger than the rotation radius of gold particles of 0.664 µm. Thus the gold particle trimer is confined within the maximum intensity ring, which is consistent with our experimental observation.



FIG. 3. Electric field strength of a tightly focused left-hand polarized optical vortex (topological charge l = 1) in the focal plane. $n_1 = 1.515$; $n_2 = 1.33$; Other parameters are same as experiment in Fig. 1. (a)(b)(c) The cross sections of the *x*, *y* and *z* polarized components in the transverse plane respectively. (d) The total electric field strength distribution.

Figure 4(a) shows the calculated force distributions of a gold particle in three directions at different radiuses (see supplementary **Publicities** or MST optical force calculation method). We used a commercial software Rsoft (Fullwave v8.1) for the numerical calculations. In the simulation, the diameter of gold particles was set to be 1 µm and the refractive index of gold is 0.26+6.97i at a wavelength of 1064 nm³². The *x* direction force (F_x) represents the radial force. When the radius is less than 2.2 µm, the force is pulling the particles to the center because of the radiation pressure from the bright ring of the focused optical vortex. For the same reason, when the radius is between 2.2 µm and 4 µm, F_x is pushing the particles away from the center, as shown in the insert of Fig. 4(a). The *y* direction force (F_y) represents the angular force. The negative F_y provides the angular torque of the particle in the clockwise rotation. The *z* direction force (F_z) is always negative and it can balance the gravity, buoyancy and the force of the thermal conversion (usually from bottom to top). At the position of the rotation radius, the radial force F_x is calculated to be $5.4 \times 10^{-14} N$, which is larger than $4.45 \times 10^{-19} N$ thus the radial force can provide sufficient centripetal force for the rotation. The angular force is calculated to be about $4.3 \times 10^{-14} N$ which is in the same order of magnitude to the estimated experimental angular force of $4.37 \times 10^{-14} N$.



FIG. 4. (a) The force distributions in x, y and z directions of a 1-µm-gold particle in the focused optical vortex field. x represents the distance between particle and the focus center. The insert shows the forces at the radius 2.2~4 µm. (b) The calculated trapping potential distribution for the gold particle along x direction. The solid green circles indicate gold particles and the black arrows indicate the potential movement directions.

Publishpipes horder to study the stability of the trap, we further calculated the trapping potential of a gold particle in the optical vortex (see **Publishpipes** have material for the trapping potential calculation method), as shown in Fig. 4(b). When x is around 1.2 μm, the trapping potential barrier is sufficient for the confinement of gold particles because the trapping potential at this position is larger than 10 k_BT. Since the largest depth of trapping potential is located at the center, the gold particles have the tendency to move towards the center. Thus all three particles were pushed towards the center of the optical vortex and form a stable gold particle trimer.

Finally, we also investigated the optical trapping and rotation of 1 µm silica particles using the same experimental system. In contrast to gold particles, silica particles can be automatically trapped to the bright ring of the focused optical vortex when the particle is close to the ring. By moving the motorized stage, up to four silica particles can be trapped near the bright ring of the focused optical vortex, forming a silica particle tetramer that starts rotating spontaneously. The number of the silica particles trapped here is four since the size of silica particle tetramer matches the size of the ring of the focused optical vortex (with topological charge 1). Following this experimental procedure, we have repeated this experiment many times. Similar experimental result as those shown in Fig. 5 (Multimedia view) could consistently be reproduced. Silica particles rotate at a much slower pace of approximately 4 cycles in 15 s [Fig. 5 (Multimedia view)], corresponding to an angular velocity of $4 \times 2\pi/15s \approx 1.68rad^4 s$. The radius of rotation is about 1 µm, which is larger than the rotation radius of 0.667 µm for a gold trimer. Given that the density of silica particle is $2650kg / m^3$, the centripetal force of a dielectric particle is mainly due to the varying gradient of the intensity of a facused optical vortex in the radial direction. The gradient force of a dielectric particle is not the spressed in terms of its polarizability α and the gradient of the electric field intensity as $F_{grad} = -(1/2)n\alpha\nabla E^2$, where *n* is the refractive index of water where the particle is suspended¹. As shown in the bottom-right of Fig. 5 (Multimedia view), the centers of the silica particles are slightly outside the maximum intensity ring, indicating that the direction of the gradient force is towards the center, thus providing the centripetal force for the rotation.



Publicitized (Multimedia view). Successive frames of a video recording that show the movement of a silica particle tetramer in the focused **Publicitized** polarized optical vortex. The time interval is 0.2 s. One of the silica particles is marked with dotted circle to indicate the clockwise rotation. The panel at the bottom right corner shows the force analysis graph. The dotted circle indicates maximum intensity ring. The solid circle indicates the rotation path of silica particles. F_A and F_c is the angular force and centripetal force of the dotted circle indicated particle, respectively.

The rotation status relies on the forces exerted on the particles. The angular force is $1.02 \times 10^{-14} N$ and $4.37 \times 10^{-14} N$ for the silica particle and the gold particle, respectively. Because of the smaller angular force, the silica particle tetramer rotates at a slower speed than the metallic trimer. This agrees with our experimental observations. The centripetal force is $3.89 \times 10^{-21} N$ and $4.45 \times 10^{-19} N$ for the silica particle and gold particles, respectively. For silica particles, the thermal motion will slightly change the particle position related to the bright ring in radical direction. This will cause changes to the gradient force on the silica particles, leading to a fluctuating centripetal force. In addition, as the gradient force is associated with the field intensity distribution, the bright ring of the focused beam may not be uniform and this will cause change of the centripetal force. In contrast, the gold particles are more strongly trapped because of the much larger angular force and centripetal force. In addition, all three gold particle are trapped inside the bright ring of the focused optical vortex, the rotation will thus not be affected by the non-uniform field distribution of the bright ring, making the rotation of metallic particles in the metallic particles is not steady of the gold particle trimer can be controlled by the incident light power (Eq. 2). Therefore the metallic particles trimer rotation speed of the gold particle trimer can be controlled by the incident light power (Eq. 2).

In conclusion, we observed the stable trapping and the steady rotation of a gold particle trimer in the tightly focused circularly polarized optical vortex. The gold particles are found to be confined inside the maximum intensity ring of the focused field. The rotation of the gold particle trimer is steady at a speed of 6.6rad / s, which can be adjusted according to the incident laser power. Different from individual metallic particles being manipulated with optical vortex reported in previous studies, a gold particle trimer reported here is trapped and rotated as an integrated system. In addition, our experimental observation of the stable trapping and steady rotation of the gold particle trimer can be explained by quantitative theoretical modelling using vector diffraction theory and MST method. We believe that the trapping and rotating of a metallic particle trimer with optical vortex provides an alternative method for micro-rotor, which may find potential applications in micro-fluidics devices. The obtained metallic particle trimer may also be useful in Surface Enhanced Raman Scattering (SERS), where the trimer gap can be used as a hot spot for electric field enhancement.

SUPPLEMENTARY MATERIAL

see supplementary material for the focusing field calculation derivation of circularly polarized optical vortex, MST optical force

Publication method and trapping potential calculation method.

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