Frontiers of Information Technology & Electronic Engineering
www.jzus.zju.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Review:

A review of optically induced rotation*

Qi ZHU[1], Nan LI[1], Heming SU[1], Wenqiang LI[1], Huizhu HU[†‡1,2]

[1] *State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China*

[2] *Zhejiang Lab, Hangzhou 311121, China*

[†] E-mail: huhuizhu2000@zju.edu.cn

Received July 10, 2020; Revision accepted Sept. 4, 2020; Crosschecked Sept. 2, 2021; Published online Jan. 24, 2022

Abstract: The optical rotation technique arose in the 1990s. Optical tweezer brought an ideal platform for research on the angular momentum of laser beams. For decades, the optical rotation technique has been widely applied in laboratory optical manipulation and the fields of biology and optofluidics. Recently, it has attracted much attention for its potential in the classical and quantum regimes. In this work, we review the progress of experiments and applications of optically induced rotation. First, we introduce the basic exploration of angular momentum. Then, we cover the development and application of optical rotation induced by orbital angular momentum, and the spin angular momentum is presented. Finally, we elaborate on recent applications of the optical rotation technique in high vacuum. As precise optical manipulation in a liquid medium enters its maturity, optical tweezers in high vacuum open a new path for the high-speed micro-rotor.

Key words: Optical tweezer; Optically induced rotation; Angular momentum; Micro-rotor
https://doi.org/10.1631/FITEE.2000338 **CLC number:** O436

1 Introduction

When Poynting first demonstrated that a photon carried an angular momentum of $\sigma\hbar$, where σ is +1 and −1 for left- and right-handed circularly polarized light, respectively, he did not expect that Beth (1936) set up an experiment to demonstrate that the angular momentum carried by a photon could be transferred to matter in the form of mechanical torque. A quartz wave plate was hung by a fine quartz fiber in Beth (1936)'s apparatus to enhance the torque and reduce the interference. Although the outcome showed that angular momentum brought by polarized light rotated the plate, further exploration of angular momentum was limited by the lack of appropriate experimental method.

Ashkin (1970) introduced the concept of "optical tweezers," which facilitated the use of laser beams to manipulate micro-scale particles. In a later experiment, the rotational motion of an optically trapped particle was observed (Ashkin and Dziedzic, 1977). Owing to a lack of detection methods, Ashkin and Dziedzic (1977) failed to give the exact rotational frequency, but they speculated that an optically levitated sphere in vacuum could reach a limited rotational frequency of 1500 MHz. Optically induced rotational motion of a particle trapped by optical tweezers was then observed and qualitatively discussed (Santamato et al., 1986; Sato et al., 1991). Allen et al. (1992) proposed that apart from spin angular momentum (SAM) carried by a photon, Laguerre-Gaussian (LG) mode light also carried orbital angular momentum (OAM). This was emblematic of the commencement of a new era of study on optically

‡ Corresponding author

* Project supported by the National Natural Science Foundation of China (Nos. 11304282 and 10947104), the National Program for Special Support of Top-Notch Young Professionals, China, the Fundamental Research Fund for the Central Universities, China (No. 2018XZZX001-08), and the Major Scientific Research Project of Zhejiang Lab, China (No. 2019MB0AD01)

ORCID: Qi ZHU, https://orcid.org/0000-0002-8632-6014; Huizhu HU, https://orcid.org/0000-0003-1690-9414

induced rotation. Rotational motion of nanoparticles of different shapes, liquid crystals, and gas molecules has been observed. Optically induced rotation was widely applied in several diverse areas, such as biophysics, nanotechnology, microrheology, microfluidics, and chiral resolution. With the latest breakthrough in cooling technique and the development of quantum optomechanics, optically induced rotation has rapidly become a vital instrument in microscopic particle manipulation and torque measurement.

2 Pioneering exploration of angular momentum: OAM and SAM

Following Poynting, Beth (1936) realized that angular momentum brought by light had a spin part associated with polarization. The angular momentum associated with circular polarization is a reflection of photon spin. According to the electromagnetic theory, light waves of a certain spatial distribution can carry angular momentum. Chang and Lee (1985) calculated the optical torque on an optically levitated weak absorbing sphere based on the classical electromagnetic theory. It is now generally considered that the angular momentum carried by light contains OAM and SAM. However, at that point, the discrimination between these two kinds was not well made. A further analytical study was required to interpret the experimental phenomenon.

OAM was first introduced in Allen et al. (1992), which showed that a laser beam could carry an orbital part associated with spatial distribution. The authors demonstrated that the photon of an LG mode laser beam with an azimuthal mode of exp($-il\gamma$), where l is the mode index and γ the azimuthal angle, carried an OAM of $l\gamma$ that could be delivered to trapped particles. The azimuthal phase determined the helical phase surface. When provided with an appropriate phase change, a Hermite-Gaussian (HG) mode beam could be transformed into a single LG mode beam. Astigmatic optical elements, such as cylindrical lenses, have been proved to be the perfect choices for mode converters in early experiments on laser transformation (Tamm and Weiss, 1990; Abramochkin and Volostnikov, 1991).

Based on Allen et al. (1992)'s analysis, it is feasible to produce laser beams carrying exactly defined amounts of OAM. The helical phase of the LG mode beam provides a helical structure and phase singularity, which was described by Friese et al. (1996) as a "doughnut laser beam." Three different kinds of mode converters could be applied to produce a helical laser beam. Spiral phase plates and computer-generated holographic converters can bring an azimuthal phase term to the classical $HG_{(0,0)}$ mode, while the cylindrical-lens mode converters employ changes in the Gouy phase to convert a higher-order HG mode laser beam. With the approximation in Allen et al. (1992), the angular momentum density per unit power on the z component of an LG mode beam is

$$M_z = \frac{l}{\omega}|\mu|^2 + \frac{\sigma r}{2\omega}\frac{\partial|\mu|^2}{\partial r}, \tag{1}$$

where ω is the angular frequency of light, r the union factor, μ the complex scalar function describing the amplitude of the light field, and $\sigma=\pm1$ for left- and right-handed circularly polarized light respectively, and 0 for linearly polarized light. The total angular momentum of the beam is given by

$$\tau=\left[l+\sigma+\sigma\left(\frac{2kz_\mathrm{r}}{2p+l+1}\right)^{-1}\right]\hbar, \tag{2}$$

where k is the wavenumber of the light, z_r the Rayleigh range, and p the mode index. For a collimated beam, $kz_\mathrm{r}\gg1$. Therefore, quantum mechanically, each photon carries $(l\mp\sigma)\hbar$ of angular momentum. The angular momentum carried by linearly polarized light with a spatial distribution is given by

$$\tau=\frac{P}{\omega}l, \tag{3}$$

where P is the laser power.

SAM was defined to describe the angular momentum determined by the polarization of light. Friese et al. (1998b) rotated a calcite fragment in water at a high frequency of 357 Hz, and proposed an incident polarized laser beam containing a circularly and linearly polarized component. Detailed analysis was presented in Nieminen et al. (2001a, 2001b, 2001c). The torque exerted on a material of thickness d and extraordinary and ordinary refraction indices of n_e and n_0 per unit, respectively, is given by

$$\tau = -\frac{c\varepsilon}{2\omega}E_0^2\sin\left[kd(n_0-n_e)\right]\cos(2\phi)\sin(2\theta) + \frac{c\varepsilon}{2\omega}E_0^2\left\{1-\cos\left[kd(n_0-n_e)\right]\right\}\sin(2\phi), \tag{4}$$

where E_0 represents the field intensity, ϕ the degree of ellipticity of light, k the free-space wavenumber, ε the permittivity, d the thickness of particle, and θ the angle between the fast axis of a quarter-wave plate and the optic axis of a birefringent particle. For linearly polarized light, ϕ=0 or 2π, and the torque is proportional to sin(2θ), which means that the linearly polarized light carries an alignment torque so long as θ is not 0. Trapped by a circularly polarized laser beam, a particle will experience constant torque brought by SAM. This was in line with the experimental results in Friese et al. (1998b).

Friese et al. (1998b)'s analysis brought a major revolution to momentum measurement. Before that, the observation on rotational motion was based mainly on charge-coupled device (CCD) and photodiodes (Sato et al., 1991; He et al., 1995; Sato and Inaba, 1996; Simpson et al., 1997; Friese et al., 1998a, 1998b; Rubinsztein-Dunlop et al., 1998). Verification experiments were carried out later by manipulating particles of different shapes by circularly and linearly polarized light (Bishop et al., 2003). Nieminen et al.'s work included measuring torque applied by decomposing the incident and outgoing light into left- and right-handed circularly polarized light, and applying a T-matrix on torque calculation (Nieminen et al., 2003, 2004a, 2004b). This method was proved to be efficient in later experiments (Rowe et al., 2003; Bishop et al., 2004; La Porta and Wang, 2004). Analysis on non-spherical particles also was proved to be the basis of measurement and detection of the transferred angular momentum (Friese et al., 2001). Theoretical studies of torque for particles of different shapes and beams of different spatial distributions were subsequently proposed (Bonin et al., 2002; Sheu et al., 2010; Liaw et al., 2015).

3 Rotation and application in liquid media

Many diverse factors can cause particles in optical tweezers to rotate at a certain speed. In dualbeam optical tweezers, a small rotational angle can be made by the rotation of one of the fibers (Kreysing et al., 2008) or misalignment along the radial axis (Li WQ et al., 2018), as shown in Fig. 1. It was proposed by O'Neil and Padgett (2002) that a rotating rectangular aperture can be inserted to change the front phase of the incident laser beam to achieve preferential rotational alignment. There are also some simplified methods to rotate particles. Friese et al. (2001) used two steerable circularly polarized beam traps, one to trap a $CaCO_3$ crystal and the other to trap a six-tooth SiO_2 structure, which by no means would rotate in the polarized laser beam, in the same plane. The SiO_2 structure would start to rotate when the two beams were brought close. The optical torque was transferred via the motion of the surrounding fluid.

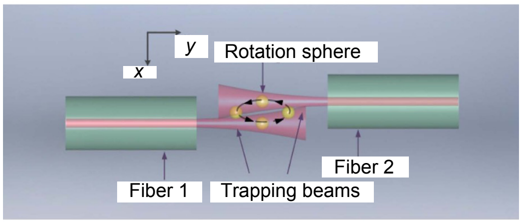


Fig. 1 Rotating particle by misalignment along the radial axis
Reprinted from Li WQ et al. (2018), Copyright 2018, with permission from OSA

Rotational motion of particles in optical tweezers can be divided into "spin" and "orbit" based on the rotating axis, but each type of rotational motion is not necessarily confined to the kind of angular moment corresponding to its name. OAM leads a particle to an optically induced rotation state due to the absorption of light, while SAM acts as counter torque on birefringent particles. Angular momentum of such kinds can be added or subtracted. In He et al. (1995)'s experiment, a CuO particle trapped by a linearly polarized LG03 mode was rotated in the same direction as the helicity of the beam. Friese et al. (1996) carried out further experiments to prove the coexistence of OAM and SAM. The angular velocity of a trapped CuO particle in a left-handed circularly, linearly, and right-handed circularly polarized LG03 mode donut beam was in the ratio of 2:3:4, and this corresponds to the result that the photon of such a beam had a total angular momentum of 2$\hbar$, 3$\hbar$, and 4$\hbar$. A similar experiment carried out by Simpson et al. (1997) applied a laser beam with l=1 mode. Trapped by a left-handed circularly polarized laser, a particle experienced no rotation, which verified the coupling of OAM and SAM. Furthermore, Friese et al. (1998a) used an elliptically polarized laser beam to achieve the control of rotation direction and frequency by controlling the degree of polarization.

Early experiments on angular momentum in the 1990s focused mostly on particles in liquid media, the viscosity of which damped the oscillation and helped form a stable trap. Most experiments focused on using polarized laser beams to manipulate birefringent particles and explore light with helical phase surfaces. Heating of absorbing particles is one of the main obstructions to enhancement of rotational frequency and further research. Rubinsztein-Dunlop et al. (1998) successfully captured and manipulated absorbing particles against a substrate, only to find that the energy transferred from the LG03 mode laser would cause the particle to heat up, and it might even reach the temperature above the boiling point of the surrounding liquid medium. On one hand, to obtain stable trapping and relatively high-speed rotation, using circularly polarized laser beams to trap transparent particles was suggested in Friese et al. (1998a). On the other hand, beams carrying OAM can be focused on certain shapes, such as an annular vortex and concentric circles. Such traps can confine particles of high absorption or low reflectivity. The special spatial distribution of light also makes it possible to trap and manipulate a large number of particles simultaneously.

After this pioneering stage, the focus of the research moved on from the abovementioned aspects. At that time, optical rotation was applied mainly to biology, micro-rotor, and micro-machine (Chang and Lee, 1985; Sato et al., 1991; Galajda and Ormos, 2001, 2002a, 2002b; Dharmadhikari et al., 2004). These required both precise control of movement in three dimensions and certain rotational frequency. It was referred to as an “optical spanner” for its ability to make non-contact manipulation of macro matter (Simpson et al., 1997). The shape and material of the trapped particle influenced the rotational motion. Rotational effects caused by altering shapes at the microscopic level also triggered much research. Galajda and Ormos (2001, 2002b) had been devoted to building shaped microscopic light-driven rotors. They also introduced the technique of using laser light-induced two-photon polymerization of light-curing resins to make sophisticated rotors and mode-converters. This pioneered a new field of sophisticated rotors (Jones et al., 2009; Asavei et al., 2010; Ukita and Kawashima, 2010).

3.1 Rotation induced by SAM

Essentially, the exchange of angular momentum in optical tweezers is the mechanical influence of light on matter. An optical process that involves a change of polarization means the exchange of SAM. Optical tweezers can trap and confine dielectric particles of micrometer size, or even nanometer size. This makes them the perfect platform for research on angular momentum. Santamato et al. (1986) demonstrated that although the transfer of angular momentum was insufficient to rotate a macroscopic body at that time, an elliptically polarized laser beam could induce time-dependent polarization rotation in a liquid-crystal medium. Although this experiment could not be regarded as particle manipulation, the outcome predicted that using micron-particles might be the solution to convert angular momentum.

The first attempt of using optical torque to rotate a micro-fabricated machine rotor was made by Higurashi et al. (1998). They found that a shape anisotropic micro-object, whose axis was perpendicular to the trapping laser beam, would follow the focal point of the laser beam when trapped. It would also rotate along an axis perpendicular to the laser beam axis after being trapped in three dimensions. In the early days, rod-shaped bacteria and ellipsoid blood cells had been observed to be fixed along the trapping axis of a laser beam (Sato et al., 1991). Controlled rotation was later managed (Bayoudh et al., 2003; Dasgupta et al., 2003; Rowe et al., 2003; Dharmadhikari et al., 2004; Mohanty et al., 2004; Singer et al., 2006).

Nieminen et al. (2001b)’s analysis showed that it is the alignment torque which exists in linearly polarized light that aligns particles at a certain angle in an optical trap, and that it is the rotational torque which exists in circularly polarized light, making particles rotate. A birefringent particle acts as a microscopic waveplate. A calcite crystal trapped by linearly polarized light will be aligned in a particular orientation, while the crystal’s fast axis coincides with the plane of polarization. Rotating the waveplate results in the rotation of the plane of polarization.

Therefore, it could rotate the crystal through a preset angle. A calcite crystal trapped in circularly polarized light would experience constant torque, which would be balanced by the drag torque brought by the surrounding medium (Friese et al., 1998b).

A linearly polarized laser was proved to be efficient at aligning non-spherical particles at certain positions and orientations (Yogesha et al., 2012), while the rotational speed could also be controlled by rotating the linear polarization with a half-waveplate or modulating the power of the component of the circularly polarized laser. Such rotational motion had not only been observed on a birefringent micron-object (Higurashi et al., 1998), but also been studied on blood cells, disc-shaped cells, and other ellipsoidal particles (Sato et al., 1991; Bayoudh et al., 2003; Oroszi et al., 2006; Arzola et al., 2014; Liaw et al., 2015), as shown in Fig. 2. When a rod-like particle was trapped by a linearly polarized laser, the equilibrium angle between the particle and the linear polarization was proved to be able to directly show the change of flow velocity (Lin et al., 2006). Rotating an inserted waveplate could result in direct rotation of the particle (Bishop et al., 2003), while the limitation of the rotation speed was obvious. It was proposed that an elliptically polarized laser beam could achieve feedback torque control by switching the handedness of the polarization and maintaining a constant rotational frequency to balance the effect caused by viscous drag or irregular shape (Zhong et al., 2009; Yu and She, 2014). Therefore, the rotation of an elliptically polarized trapping beam can rotate an elongated particle along its axis (O'Neil and Padgett, 2002).

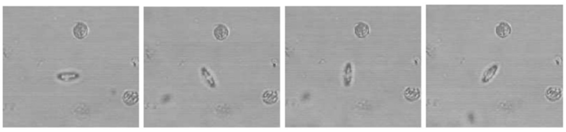


Fig. 2 Alignment of chloroplasts with linearly polarized laser beam

Reprinted from Bayoudh et al. (2003), Copyright 2003, with permission from Informa UK Limited

Left- and right-handed circularly polarized light is the perfect example of chiral entities. While conventional trapping and manipulating experiments could be defined as an interaction of chiral light with achiral objects, it also opened a route for chiral optomechanics. Chiral solid particles, for instance, chiral mirrors, yield a highly polarization-dependent optomechanical effect. Donato et al. (2014) discovered chirality-controlled photonic effects, while a specific ratio between the chiral particle radius and the helical pitch of the incoming light was set, as shown in Fig. 3. The inner Bragg structure of a trapped particle and the variation of the reflectivity allow only those SAM parallel to the particle handedness to be transferred. Tkachenko and Brasselet (2014) introduced an effective selective chiral particle trapping. Their results also showed that chiral particles of all types and sizes can be selectively 3D-trapped. Further experiments involving linearly polarized light and unpolarized light were made (Hernández et al., 2015).

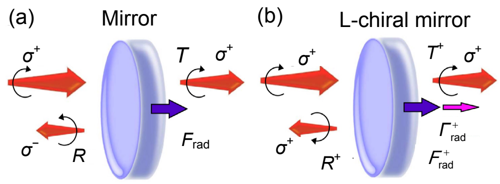


Fig. 3 Principle of chiral selection: (a) a traditional mirror with reflectance *R* experiences only a radiation force; (b) a left-handed chiral mirror experiences a radiation force and a torque

Reprinted from Donato et al. (2014), Copyright 2014, with permission from Springer Nature

The mathematical relation between the total amount of angular momentum transferred to a trapped particle and the detection of rotational frequency provides a feasible way to measure the viscous resistance of the liquid medium. It is also a vital factor in enhancing rotational frequency. Although Ashkin (1970) observed rotating motion of an optically levitated sphere in vacuum, most primary experiments on optical rotation were set in liquid media. Although there had been an explosive development of interest in optical rotation since the 1990s, the measurement of optical torque was first introduced by Nieminen et al. (2001c). By decomposing the incident and outgoing plane waves, they claimed that the variation of angular momentum could be given by the difference between the incident and outgoing angular momentum fluxes. This provided a means to measure the torque. Such a method was applied in later experiments and proved to be effective in torque measurement.

A stable rotating particle in optical tweezers experiences optical torque and counterpart drag torque. The quantization of torque makes it possible to calculate features of certain particles and certain media. Parkin et al. (2007) characterized a microviscometer using optically rotated particles to perform measurements over a large dynamic range of viscosities, as shown in Fig. 4. Efforts have been made to reduce the hydrodynamic coupling between the probe and the fluid. By observing the rotational Brownian motion, data on smaller samples and more highly nonhomogeneous fluids could be collected. The interaction between the trapped particles and the surrounding medium also provided a perfect platform for studying the adhesivity of certain surfaces (Vaippully et al., 2019; Vaipully, 2019). By pulling a rotating birefringent particle away from a surface, the shear force caused by rotating motion would break the bonds. Such an approach was expected to take the place of conventional techniques, while it could probe softly and sense interaction at a higher resolution.

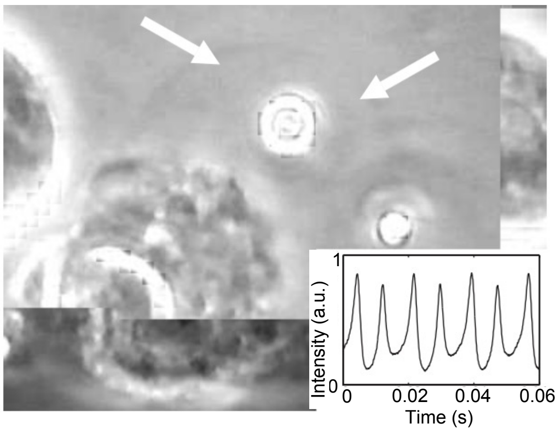


Fig. 4 A phase-contrast image of a vaterite rotating inside a cell as a microviscometer

The left arrow points to the cell membrane. The right arrow points to the vaterite within the cell membrane. The inset picture shows the normalized intensity that is used to determine the rotation rate of the vaterite. Reprinted from Parkin et al. (2007), Copyright 2007, with permission from American Physical Society

Mason and Weitz (1995) pioneered the idea that small particle Brownian motion excited by thermal stochastic force could reflect the viscoelasticity of the medium. This might make it possible to obtain quantitative information that was not accessible by conventional means about the rheological properties of a polymer matrix. Experimental verifications of applying optical tweezers in the field of microrheology were presented (Leach et al., 2006; Sriram et al., 2010; Bennett et al., 2013). Such passive microrheological characterization has been widely applied because of the simplicity of experimental setup and data analysis. The limitation caused by the thermal motion of the probe particles that decreased the measurement to a linear response regime can be eliminated by actively driving the particle. Bishop et al. (2004) demonstrated a microrheology system with a nearly perfectly spherical crystal probe to measure the viscosity in a cellular structure.

Rotating motion induced by SAM has greatly impacted many fields, including chiral optomechanics, microrheology, and biology. While linearly polarized light was suitable for position and orientation control, the spin of a birefringent particle trapped in circularly polarized light pioneered a new branch of optical manipulation. Transmission of SAM, which can be simply interpreted as the transfer of the polarization state, has been proved to be an efficient way to circumrotate micro-particles.

3.2 Rotation induced by OAM

Allen et al. (1992) introduced that a single photon could carry multiple units of $\hbar$, and used a combination of cylindrical lenses to transform the beam and successfully produced laser-carrying OAM in a laboratory, which laid the foundation for an "optical spanner." While polarized light could trap and rotate transparent particles, the absorption of the OAM of light could achieve a stable trap and rotation of absorbing particles. Sato et al. (1991) took the lead on optically rotating particles by trapping and manipulating a blood cell; his group used a higher-order HG mode laser beam to achieve a 360° rotation of the blood cell. They also found that the axis of blood cells coincided with the elongated direction of beam intensity, and this predicted the feasibility of optical manipulation by OAM.

The use of annular beams was first brought up by Ashkin (1992), who used the LG mode beam to create annulus and trapped absorbing particles in the high-intensity region. A transparent low-index particle would be pushed away from the beam, but could stay in the dark region of an annular beam because of the scattering force (Garcés-Chávez et al., 2002b).

Hollow glass spheres could be imprisoned in the dark region and carry certain drugs (Prentice et al., 2004). Further experiments of trapping low-index particles using laser beam carrying zero average angular momentum have been made (O'Neil et al., 2002; Santamato et al., 2002; Nieminen et al., 2008; Ran et al., 2012; Mitri, 2016a, 2016b; Chen MS et al., 2018).

The special spatial distribution of beam-carrying OAM not only provided the opportunity to trap and manipulate particles in three dimensions, but also broke the limit on the population of particles. Experiments involving a polarized "doughnut beam" were performed to elaborate the possibility of rotating and manipulating a large number of absorbing particles made by different materials (He et al., 1995; Garcés-Chávez et al., 2002a; Arzola et al., 2014; Ivanov and Hanstorp, 2018). It was also noted that a birefringent particle was observed simultaneously spinning and orbiting around the optic axis (O'Neil et al., 2002; Garcés-Chávez et al., 2003). Calculation and derivation results showed that both OAM and SAM could trigger intrinsic rotation, while extrinsic rotation could be caused only by the OAM of light (O'Neil et al., 2002).

It is natural to speculate that by altering the spatial distribution, precise rotation control can be achieved. Paterson et al. (2001) generated a rotating beam by interfering with an annular-shaped laser beam (LG03 mode) and with a reference beam (plane wave) to make an attempt to confine a very large number of particles within the interference pattern. Although it was the first demonstration of manipulating multiple objects simultaneously, the large quantity of particles collapsed in a short time. MacDonald et al. (2002a) trapped a cubic structure of eight particles in the interference pattern of two counter-propagating LG beams, and rotated the cube at a frequency of 2 Hz by simply changing the path length of one of the beams. MacDonald et al. (2002b) also presented different cross-sections of LG laser beams at different azimuthal numbers. The spiral interference pattern could be tailored to fit the shape of the cluster and be used to trap and rotate structures of silica micro-spheres. Setting a frequency shift between the interfering modes could create a continuous rotating pattern, which allowed rotating control (Arzola et al., 2014; Mitri, 2016a, 2016b; Li RX et al., 2017a, 2017b). Further research also showed that such a method could lower only the rotational speed of particles. To set the rotational speed of an interference pattern higher than a critical value would cause trapped particles to rotate at periodic angular velocities (Arzola et al., 2014).

Experimental results showed that the azimuthal phase brought transverse manipulation along the axis, and that several groups were also seeking the perfect beam for radial manipulation. Bessel beams are propagation-invariant. The arbitrary transmission cross-section is a series of concentric circles. Illuminating a Gaussian beam on a conical shaped optical element is the simplest way to generate a beam that is a close approximation of a Bessel beam over a characteristic propagation distance. It can create an optical trap that extends for millimeters of confining force. The two-dimensional optical tweezers formed by the Bessel beam can push a particle precisely over a certain distance, as shown in Fig. 5. Garcés-Chávez et al. (2002a) constructed Bessel beam tweezers that could manipulate particles of large spatial separation along the optical axis. Then they used circularly polarized high-order Bessel beam tweezers to capture and rotate a birefringent particle (Garcés-Chávez et al., 2003). Apart from rotating around its own axis because of the SAM, it also rotates around the beam's axis. This is consistent with Allen et al. (1992)'s and Friese et al. (1998b)'s analysis. Simulations and experiments of torque on different sizes of absorbing particles were also made (Nieminen et al., 2001a; Mitri, 2016a, 2016b).

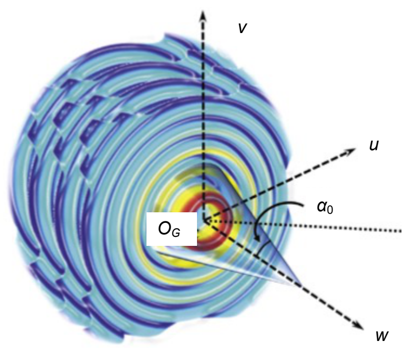


Fig. 5 Wavefront of Bessel beam

Reprinted from Li RX et al. (2017a), Copyright 2017, with permission from Elsevier Ltd.

Non-contact manipulation had been one of the optical tweezers' dominant advantages. It is favored for trapping and manipulating cells and bacteria, and even intracellular objects, thanks to the noninvasive operation and relatively precise control. Many groups had applied optical rotation techniques in biology since a blood cell was successfully trapped and rotated in Sato et al. (1991). With gradual maturity of the technique, the applications of optical tweezers in biology developed rapidly (Oroszi et al., 2006). The interferometric approach introduced by Paterson et al. (2001) avoided the trapping object's thermal effect induced by the laser, and this could efficiently avoid the damage of the heating generated from the energy transferred to trapped absorbing objects. This made it possible to achieve prolonged trapping (MacDonald et al., 2002b). Most trapped objects in the biological field lack spherical symmetry, and thus alignment can be handy (Bayoudh et al., 2003; Hörner et al., 2010; Liang et al., 2010; Xie et al., 2016; Cao et al., 2017).

As well as the abovementioned ways of manipulating particles, other innovative ways have been applied. Hörner et al. (2010) used two position-adjustable optical traps focusing on both ends of a rod-shaped bacterium to achieve rotation. Wu et al. (2012a, 2012b) tried using a laser-driven birefringent sphere to guide the behavior of the growth cone at the tip of a growing nerve axion. Specific detection of certain particles, e.g., DNA, was made (Oroszi et al., 2006; Deufel et al., 2007). It is convenient to control particles rotating at a low speed by the application of a rotating beam. Particles of different materials and larger sizes were used in laboratory experiments and theoretical studies (Starr et al., 2005; Raghu et al., 2010; Arzola et al., 2014; Liaw et al., 2015, 2016; Tanaka, 2018; Chen XT et al., 2019).

4 Up to date optical rotation in high vacuum

The unwanted axial forces, viscous resistance, and heating of absorbing particles are the main obstructions for the enhancement of rotational frequency. The fastest rotating speed in an aqueous solution can reach 1000 Hz. It is beneficial to choose transparent articles as research subjects, to avoid thermal deformation caused by absorbing particles and consequent boiling of the surrounding medium. To further increase the rotation rate, reducing the viscous drag force and stabilizing the trapped particles are the burning issues. An obvious solution is to suspend and manipulate particles in air. It becomes the focus of recent research (Manjavacas and García de Abajo, 2010; Roy et al., 2014; Arita et al., 2016; Rodríguez-Sevilla et al., 2018; Diniz et al., 2019). The rotational frequency of a particle with ultra-high mechanical quality attributes and low viscoelasticity environment was predicted to reach the order of GHz (Monteiro et al., 2018).

A micro-particle suspended in a fluid colliding with surrounding molecules experiences random Brownian motion. The dynamics and effect of a homogeneous, rotating birefringent particle levitated in high vacuum generated heated debate. Friese et al. (1998b) predicted that the lack of mechanical friction in the optical tweezer system in high vacuum can eliminate environmental decoherence. The method of feedback cooling, which was first introduced in cavity optomechanics that trapped particles in an optical cavity, could be stabilized by modulating the trapping frequency, and this led to cooling of the center-of-mass (COM) motion. Based on their previous apparatus to measure the Brownian motion, LI TC et al. (2011) successfully cooled an optically levitated glass microsphere's COM motion from room temperature to 1.5 mK. Their research was an important step toward quantum cooling, and showed that optical tweezers could be the perfect platform to study issues concerning the quantum ground state.

The increment of rotational frequency became a hot topic, for certain phenomenon occurred only on high-speed rotating particles. Arita et al. (2013) made a revolutionary leap in optical rotation. A rotation rate of 2.45 MHz was realized at a pressure of 1 Pa. By decreasing the pressure in the trapping regime, a rotation rate of 10 MHz was achieved, which was the highest rotation rate measured at that time. They also discovered that when the rotational frequency coincided with the oscillation frequency of the trapped particle while decreasing the pressure, resonance occurred, which led to enhancement of the detection signal. The effect brought by high rotation rates was similar to that of a micro gyroscope's intrinsic stabilization. According to Arita et al.'s experiments and simulations, the rotational motion of the particle could play a crucial role in cooling the COM of the particle while no active feedback cooling was applied, for the distribution width of transversal angular velocity decreased. The positional stabilization in the experiment showed an effective cooling to 40 K. This experiment opened a new route to explore new directions in optical rotation. The realization of stabilized high rotation rate presented the possibility for the study of the performance of rotors at the micronscale, while the cooling effect provided a potential mean for measuring quantum rotational effects.

The coupling of rotational motion and translational motion is a result of hydrodynamic interaction, and thus contains useful information about the nature of interactions and Brownian motion. The crucial sticking point of discrimination between the abovementioned motion types was solved by Roy et al. (2014) by setting a coupled Langevin equation for rotational Brownian motion and translational motion, allowing the detection of each motion, along with the coupling effect. Such a method has been proved to be efficient in measuring the rotational motion of asymmetric particles with high sensitivity, and independent of birefringence, polarization, and effective width of the particle.

Ahn et al. (2018) and Reimann et al. (2018) detected particles rotating at frequencies exceeding 1 GHz, as shown in Fig. 6, at almost the same time. The major difference laid on the shape of the trapped objects. Ahn et al. (2018) trapped a nano-dumbbell in linearly polarized optical tweezers, as shown in Fig. 7, while Reimann et al. (2018) chose a silica nanoparticle with a diameter of 100 nm.

One of the prominent obstacles for maintaining particles at a steady-state high rotational speed is the perturbation caused by precession and laser heating. Dumbbell-shaped particles had been proposed as suitable for studying multi-body systems isolated from the environment (Lechner et al., 2013), and thus became Ahn et al. (2018)'s ideal choice. Particles of such shape also showed excellent stiffness in their experiments and appeared to be less easy in escaping the trap than particles of other typical shapes (Hoang et al., 2016), e.g., nanosphere and nanorod. An ultrasonic nebulizer was used to deliver the dumbbell in Ahn et al. (2018)'s experiment. Their vacuum chamber would be set below 0.001 33 Pa after successful trapping and then retained at the desired pressure level. A new method of measurement by detecting the damping rate of the particle was applied. The dumbbell acted as an ultrasensitive nanoscale torsion balance in linearly polarized optical tweezers and became an ultrafast nanomechanical rotor when captured in circularly polarized light. A dumbbell rotating at a frequency of 1.1 GHz was detected on a position sensitive detector (PSD). The increase of rotational frequency would lead to the disassembly of the dumbbell because of centrifugal force. Not only could such a nano-dumbbell detect the Casimir torque, but might it be able to sustain a frequency beyond 10 GHz (Ahn et al., 2018).

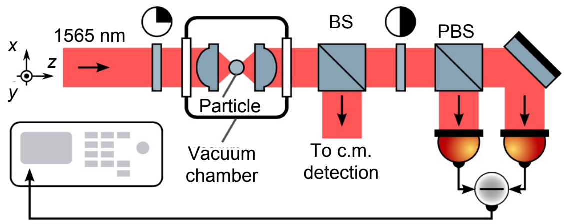


Fig. 6 Experimental setup in Reimann et al. (2018)'s research

Reprinted from Reimann et al. (2018), Copyright 2018, with permission from American Physical Society

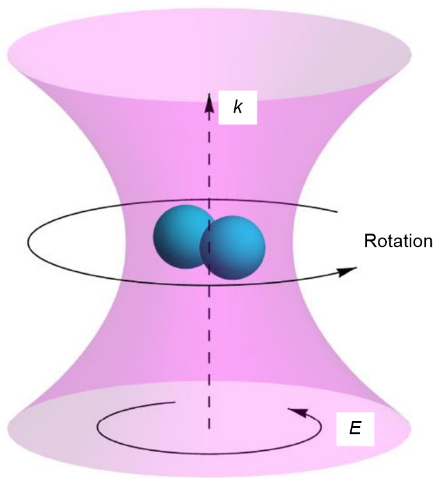


Fig. 7 Scheme of a nano-dumbbell rotating in optical tweezers

Reprinted from Ahn et al. (2018), Copyright 2018, with permission from American Physical Society

A similar experimental setup was applied in Reimann et al. (2018). The detected rotational frequency reached above 1 GHz, while the pressure in the vacuum chamber was decreased to below 10^{-5} Pa. Reimann et al. (2018)'s work involved the analysis of torques on particles and corresponding laboratory data. The coupling of COM and rotational degrees of freedom was not observed (Reimann et al., 2018).

The precise control of rotational frequency has always been a prominent topic. Kuhn et al. (2017b) designed a system that set the rotational frequency locked at a certain frequency, as shown in Fig. 8. The introduction of an external clock, which switched the laser polarization between linear polarization and circular polarization, could tune the rotational frequency over a range of 1012 linewidths. By modulating a certain ratio between the driving frequency and the rotational frequency to a certain region, locking of rotation rate could happen. Although there were proposals that a more stable clock might further stabilize the rotor, no further research has yet been carried out.

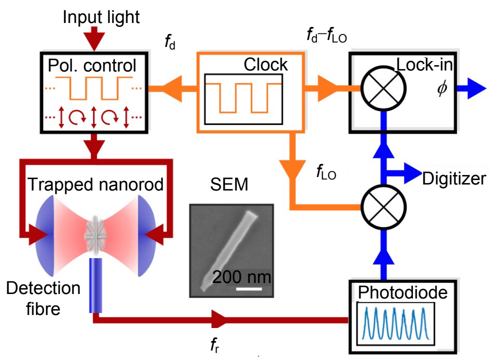


Fig. 8 Scheme of frequency locking experiment

Quantum optomechanics is an emerging field that has its roots in the study of mechanical action of light. A breakthrough of quantum ground state cooling of mechanical oscillators was first proposed by Li TC et al. (2011). Later, several groups successfully showed the effect in experiments (Chan et al., 2011; Kuhn et al., 2015, 2017a; Stickler et al., 2016). The combination of optical tweezers and optomechanical systems has attracted great attention. An optically levitated particle experiences no mechanical contact, so the decoherence of the system is negligible. This makes it the ideal carrier for research on macroscopic quantum mechanics. Research on quantum optomechanics has undoubtedly become a current hotspot topic.

Optomechanical systems are usually employed to solve quantum mechanical issues such as superposition, decoherence, and entanglement. By cooling the COM of the optically levitated particle to the quantum ground state with sideband cooling, such systems can achieve ultrasensitive detection for Casimir force, non-Newtonian force, gravitational wave, single molecule collisions, and so on. An initial experiment involving an optical cavity and angular momentum was carried out by Kuhn et al. (2015). They used an intense intra-cavity field to capture nanorods launched from laser-induced mechanical cleavage, and cooled the rotational motion and torsional optomechanics by optical torque. The cavity field could also induce coupling between rotational degree and motion degree. The influence of the optical potential was so sufficiently prominent that the exchange of motion and rotational degree was observed (Stickler et al., 2016). The full rotation of nanorods in a cavity was realized by setting elliptically polarized light with particular degree of polarization (Kuhn et al., 2017a). By modifying the optical potential, the rotational frequency can be tuned, which opens the route to rotational ground cooling and further research.

5 Conclusions and outlook

For research on optically induced rotation, optical tweezers created opportunities. The technique of trapping and manipulating particles made significant progress since first proposed. Controllable rotation and precise alignment made the optical trap the most suitable tool for manipulating biological cells and obtaining liquid character. Owing to the successful trapping of a particle in high vacuum with optical tweezers, the optically induced rotation had entered into a brand-new phase. With extremely low drag force, the rotation rate increased dramatically. In this review, we explored the development process of optical rotation. Experiments and multiple methods to impart rotating motion on trapped particles and applications of such techniques were introduced.

We also presented recent advances in laboratory optical rotation and progress in the quantum regime, as shown in Fig. 9. While the COM motion was agreed with an avalanche of publicity, ultrafast rotors optically levitated became a new platform, not only for their interaction with COM motion, but also for their own prospects to explore friction and precise measurement. Furthermore, particles rotating at GHz frequency might provide a path to cosmology.

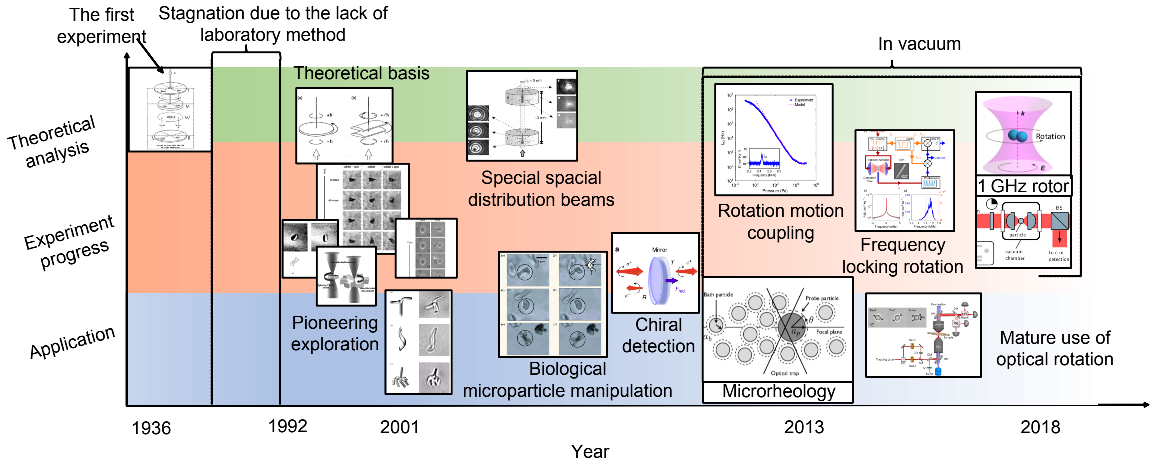


Fig. 9 Development history of optical rotation
This figure is derived from the literature and published with permission from the authors or publishers

In addition to wide application in biophysics, nanotechnology, microrheology, microfluidics, and chiral resolution, optical rotation made its way to become the research hotspot for its potential in researching ground-state cooling, material properties, precise measurement, thermodynamics, and so on. Challenges remain, such as thorough dynamic analysis, improvement of detection method, and realization of ground-state rotation, but their potential encourages researchers to continue exploration.

Contributors

Qi ZHU and Huizhu HU designed the research. Qi ZHU collected the data and drafted the paper. Nan LI, Heming SU, Wenqiang LI, and Huizhu HU helped organize the paper. Qi ZHU and Huizhu HU revised and finalized the paper.

Compliance with ethics guidelines

Qi ZHU, Nan LI, Heming SU, Wenqiang LI, and Huizhu HU declare that they have no conflict of interest.

References

Abramochkin E, Volostnikov V, 1991. Beam transformations and nontransformed beams. *Opt Commun*, 83(1-2):123-135. https://doi.org/10.1016/0030-4018(91)90534-K

Ahn J, Xu ZJ, Bang J, et al., 2018. Optically levitated nanodumbbell torsion balance and GHz nanomechanical rotor. *Phys Rev Lett*, 121(3):033603. https://doi.org/10.1103/PhysRevLett.121.033603

Allen L, Beijersbergen MW, Spreeuw RJC, et al., 1992. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. *Phys Rev A*, 45(11):8185-8189. https://doi.org/10.1103/PhysRevA.45.8185

Arita Y, Mazilu M, Dholakia K, 2013. Laser-induced rotation and cooling of a trapped microgyroscope in vacuum. *Nat Commun*, 4:2374. https://doi.org/10.1038/ncomms3374

Arita Y, Richards JM, Mazilu M, et al., 2016. Rotational dynamics and heating of trapped nanovaterite particles. *ACS Nano*, 10(12):11505-11510. https://doi.org/10.1021/acsnano.6b07290

Arzola AV, Jákl P, Chvátal L, et al., 2014. Rotation, oscillation and hydrodynamic synchronization of optically trapped oblate spheroidal microparticles. *Opt Expr*, 22(13):16207-16221. https://doi.org/10.1364/OE.22.016207

Asavei T, Nieminen TA, Heckenberg NR, et al., 2010. Use of shape induced birefringence for rotation in optical tweezers. Optical Trapping and Optical Micromanipulation VII, p.77621C. https://doi.org/10.1117/12.861793

Ashkin A, 1970. Acceleration and trapping of particles by radiation pressure. *Phys Rev Lett*, 24(4):156-159. https://doi.org/10.1103/PhysRevLett.24.156

Ashkin A, 1992. Forces of a single-beam gradient laser trap on a dielectric sphere in the ray optics regime. *Biophys J*, 61(2):569-582. https://doi.org/10.1016/S0006-3495(92)81860-X

Ashkin A, Dziedzic JM, 1977. Feedback stabilization of optically levitated particles. *Appl Phys Lett*, 30(4):202-204. https://doi.org/10.1063/1.89335

Bayoudh S, Nieminen TA, Heckenberg NR, et al., 2003. Orientation of biological cells using plane-polarized Gaussian beam optical tweezers. *J Mod Opt*, 50(10):1581-1590. https://doi.org/10.1080/09500340308235232

Bennett JS, Gibson LJ, Kelly RM, et al., 2013. Spatially-resolved rotational microrheology with an optically-trapped sphere. *Sci Rep*, 3:1759. https://doi.org/10.1038/srep01759

Beth RA, 1936. Mechanical detection and measurement of the angular momentum of light. *Phys Rev*, 50(2):115-125. https://doi.org/10.1103/PhysRev.50.115

Bishop AI, Nieminen TA, Heckenberg NR, et al., 2003. Optical application and measurement of torque on microparticles of isotropic nonabsorbing material. *Phys Rev A*, 68(3):033802.

https://doi.org/10.1103/PhysRevA.68.033802

Bishop AI, Nieminen TA, Heckenberg NR, et al., 2004. Optical microrheology using rotating laser-trapped particles. *Phys Rev Lett*, 92(19):198104. https://doi.org/10.1103/PhysRevLett.92.198104

Bonin KD, Kourmanov B, Walker TG, 2002. Light torque nanocontrol, nanomotors and nanorockers. *Opt Expr*, 10(19):984-989. https://doi.org/10.1364/OE.10.000984

Cao B, Kelbauskas L, Chan S, et al., 2017. Rotation of single live mammalian cells using dynamic holographic optical tweezers. *Opt Lasers Eng*, 92:70-75. https://doi.org/10.1016/j.optlaseng.2016.12.019

Chan J, Alegre TPM, Safavi-Naeini AH, et al., 2011. Laser cooling of a nanomechanical oscillator into its quantum ground state. *Nature*, 478(7367):89-92. https://doi.org/10.1038/nature10461

Chang S, Lee SS, 1985. Optical torque exerted on a homogeneous sphere levitated in the circularly polarized fundamental-mode laser beam. *J Opt Soc Am B*, 2(11): 1853-1860. https://doi.org/10.1364/JOSAB.2.001853

Chen MS, Huang SJ, Shao W, et al., 2018. Optical force and torque on a dielectric Rayleigh particle by a circular Airy vortex beam. *J Quant Spectrosc Radiat Trans*, 208:101-107. https://doi.org/10.1016/j.jqsrt.2018.01.018

Chen XT, Cheng WZ, Xie MY, et al., 2019. Optical rotational self-assembly at air-water surface by a single vortex beam. *Result Phys*, 12:1172-1176. https://doi.org/10.1016/j.rinp.2018.11.070

Dasgupta R, Mohanty SK, Gupta PK, 2003. Controlled rotation of biological microscopic objects using optical line tweezers. *Biotechnol Lett*, 25(19):1625-1628. https://doi.org/10.1023/A:1025678320136

Deufel C, Forth S, Simmons CR, et al., 2007. Nanofabricated quartz cylinders for angular trapping: DNA supercoiling torque detection. *Nat Methods*, 4(3):223-225. https://doi.org/10.1038/nmeth1013

Dharmadhikari JA, Roy S, Dharmadhikari AK, et al., 2004. Torque-generating malaria-infected red blood cells in an optical trap. *Opt Expr*, 12(6):1179-1184. https://doi.org/10.1364/OPEX.12.001179

Diniz K, Dutra RS, Pires LB, et al., 2019. Negative optical torque on a microsphere in optical tweezers. *Opt Expr*, 27(5):5905-5917. https://doi.org/10.1364/OE.27.005905

Donato MG, Hernandez J, Mazzulla A, et al., 2014. Polarization-dependent optomechanics mediated by chiral microresonators. *Nat Commun*, 5:3656. https://doi.org/10.1038/ncomms4656

Friese MEJ, Enger J, Rubinsztein-Dunlop H, et al., 1996. Optical angular-momentum transfer to trapped absorbing particles. *Phys Rev A*, 54(2):1593-1596. https://doi.org/10.1103/PhysRevA.54.1593

Friese MEJ, Nieminen TA, Heckenberg NR, et al., 1998a. Optical alignment and spinning of laser-trapped microscopic particles. *Nature*, 394(6691):348-350. https://doi.org/10.1038/28566

Friese MEJ, Nieminen TA, Heckenberg NR, et al., 1998b. Optical torque controlled by elliptical polarization. *Opt Lett*, 23(1):1-3. https://doi.org/10.1364/OL.23.000001

Friese MEJ, Rubinsztein-Dunlop H, Gold J, et al., 2001. Optically driven micromachine elements. *Appl Phys Lett*, 78(4):547-549. https://doi.org/10.1063/1.1339995

Galajda P, Ormos P, 2001. Complex micromachines produced and driven by light. *Appl Phys Lett*, 78(2):249-251. https://doi.org/10.1063/1.1339258

Galajda P, Ormos P, 2002a. Rotation of microscopic propellers in laser tweezers. *J Opt B*, 4(2):S78-S81. https://doi.org/10.1088/1464-4266/4/2/372

Galajda P, Ormos P, 2002b. Rotors produced and driven in laser tweezers with reversed direction of rotation. *Appl Phys Lett*, 80(24):4653-4655. https://doi.org/10.1063/1.1480885

Garcés-Chávez V, McGloin D, Melville H, et al., 2002a. Simultaneous micromanipulation in multiple planes using a self-reconstructing light beam. *Nature*, 419(6903):145-147. https://doi.org/10.1038/nature01007

Garcés-Chávez V, Volke-Sepulveda K, Chávez-Cerda S, et al., 2002b. Transfer of orbital angular momentum to an optically trapped low-index particle. *Phys Rev A*, 66(6): 063402. https://doi.org/10.1103/PhysRevA.66.063402

Garcés-Chávez V, McGloin D, Padgett MJ, et al., 2003. Observation of the transfer of the local angular momentum density of a multiringed light beam to an optically trapped particle. *Phys Rev Lett*, 91(9):093602. https://doi.org/10.1103/PhysRevLett.91.093602

He H, Friese MEJ, Heckenberg NR, et al., 1995. Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity. *Phys Rev Lett*, 75(5):826-829. https://doi.org/10.1103/PhysRevLett.75.826

Hernández RJ, Mazzulla A, Provenzano C, et al., 2015. Chiral resolution of spin angular momentum in linearly polarized and unpolarized light. *Sci Rep*, 5:16926. https://doi.org/10.1038/srep16926

Higurashi E, Sawada R, Ito T, 1998. Optically induced angular alignment of trapped birefringent micro-objects by linearly polarized light. *Phys Rev E*, 59(3):3676-3681. https://doi.org/10.1103/PhysRevE.59.3676

Hoang TM, Ma Y, Ahn J, et al., 2016. Torsional optomechanics of a levitated nonspherical nanoparticle. *Phys Rev Lett*, 117(12):123604. https://doi.org/10.1103/PhysRevLett.117.123604

Hörner F, Woerdemann M, Müller S, et al., 2010. Full 3D translational and rotational optical control of multiple rod-shaped bacteria. *J Biophoton*, 3(7):468-475. https://doi.org/10.1002/jbio.201000033

Ivanov M, Hanstorp D, 2018. Controlled spin of a nonbirefringent droplet trapped in an optical vortex beam. *Opt Commun*, 427:152-157. https://doi.org/10.1016/j.optcom.2018.06.021

Jones PH, Palmisano F, Bonaccorso F, et al., 2009. Rotation detection in light-driven nanorotors. *ACS Nano*, 3(10): 3077-3084. https://doi.org/10.1021/nn900818n

Kreysing MK, Kiessling T, Fritsch A, et al., 2008. The optical cell rotator. *Opt Expr*, 16(21):16984-16992. https://doi.org/10.1364/OE.16.016984

Kuhn S, Asenbaum P, Kosloff A, et al., 2015. Cavity-assisted manipulation of freely rotating silicon nanorods in high vacuum. *Nano Lett*, 15(8):5604-5608. https://doi.org/10.1021/acs.nanolett.5b02302

Kuhn S, Kosloff A, Stickler BA, et al., 2017a. Full rotational control of levitated silicon nanorods. https://arxiv.org/abs/1608.07315

Kuhn S, Stickler BA, Kosloff A, et al., 2017b. Optically driven ultra-stable nanomechanical rotor. *Nat Commun*, 8(1): 1670. https://doi.org/10.1038/s41467-017-01902-9

La Porta A, Wang MD, 2004. Optical torque wrench: angular trapping, rotation, and torque detection of quartz microparticles. *Phys Rev Lett*, 92(19):190801. https://doi.org/10.1103/PhysRevLett.92.190801

Leach J, Mushfique H, di Leonardo R, et al., 2006. An optically driven pump for microfluidics. *Lab Chip*, 6(6): 735-739. https://doi.org/10.1039/B601886F

Lechner W, Habraken SJ, Kiesel N, et al., 2013. Cavity optomechanics of levitated nanodumbbells: nonequilibrium phases and self-assembly. *Phys Rev Lett*, 110(14):143604.

Li RX, Yang RP, Ding CY, et al., 2017a. Optical torque on a magneto-dielectric Rayleigh absorptive sphere by a vector Bessel (vortex) beam. *J Quant Spectrosc Radiat Trans*, 191:96-115. https://doi.org/10.1016/j.jqsrt.2017.02.003

Li RX, Ding CY, Mitri FG, 2017b. Optical spin torque induced by vector Bessel (vortex) beams with selective polarizations on a light-absorptive sphere of arbitrary size. *J Quant Spectrosc Radiat Trans*, 196:53-68. https://doi.org/10.1016/j.jqsrt.2017.03.035

Li TC, Kheifets S, Raizen MG, 2011. Millikelvin cooling of an optically trapped microsphere in vacuum. *Nat Phys*, 7(7):527-530. https://doi.org/10.1038/nphys1952

Li WQ, Li N, Shen Y, et al., 2018. Dynamic analysis and rotation experiment of an optical-trapped microsphere in air. *Appl Opt*, 57(4):823-828. https://doi.org/10.1364/AO.57.000823

Liang YL, Huang YP, Lu YS, et al., 2010. Cell rotation using optoelectronic tweezers. *Biomicrofluidics*, 4(4):43003. https://doi.org/10.1063/1.3496357

Liaw JW, Lo WJ, Lin WC, et al., 2015. Theoretical study of optical torques for aligning Ag nanorods and nanowires. *J Quant Spectrosc Radiat Trans*, 162:133-142. https://doi.org/10.1016/j.jqsrt.2015.03.030

Liaw JW, Chen YS, Kuo KM, 2016. Spinning gold nanoparticles driven by circularly polarized light. *J Quant Spectrosc Radiat Trans*, 175:46-53. https://doi.org/10.1016/j.jqsrt.2016.01.012

Lin CL, Wang I, Dollet B, et al., 2006. Velocimetry microsensors driven by linearly polarized optical tweezers. *Opt Lett*, 31(3):329-331. https://doi.org/10.1364/OL.31.000329

MacDonald MP, Paterson L, Volke-Sepulveda K, et al., 2002a. Creation and manipulation of three-dimensional optically trapped structures. *Science*, 296(5570):1101-1103. https://doi.org/10.1126/science.1069571

MacDonald MP, Volke-Sepulveda K, Paterson L, et al., 2002b. Revolving interference patterns for the rotation of optically trapped particles. *Opt Commun*, 201(1-3):21-28. https://doi.org/10.1016/S0030-4018(01)01652-2

Manjavacas A, García de Abajo FJ, 2010. Vacuum friction in rotating particles. *Phys Rev Lett*, 105(11):113601. https://doi.org/10.1103/PhysRevLett.105.113601

Mason TG, Weitz DA, 1995. Optical measurements of frequency-dependent linear viscoelastic moduli of complex fluids. *Phys Rev Lett*, 74(7):1250-1253. https://doi.org/10.1103/PhysRevLett.74.1250

Mitri FG, 2016a. Negative optical spin torque wrench of a non-diffracting non-paraxial fractional Bessel vortex beam. *J Quant Spectrosc Radiat Trans*, 182:172-179. https://doi.org/10.1016/j.jqsrt.2016.05.033

Mitri FG, 2016b. Spin reversal and orbital torques on a viscous fluid Rayleigh sphere located arbitrarily in acoustical Bessel vortex (spiraling) beams. *Ultrasonics*, 72:57-65. https://doi.org/10.1016/j.ultras.2016.07.007

Mohanty SK, Uppal A, Gupta PK, 2004. Self-rotation of red blood cells in optical tweezers: prospects for high throughput malaria diagnosis. *Biotechnol Lett*, 26(12): 971-974. https://doi.org/10.1023/B:BILE.0000030041.94322.71

Monteiro F, Ghosh S, van Assendelft EC, et al., 2018. Optical rotation of levitated spheres in high vacuum. *Phys Rev A*, 97(5):051802. https://doi.org/10.1103/PhysRevA.97.051802

Nieminen TA, Rubinsztein-Dunlop H, Heckenberg NR, 2001a. Calculation and optical measurement of laser trapping forces on non-spherical particles. *J Quant Spectrosc Radiat Trans*, 70(4-6):627-637. https://doi.org/10.1016/S0022-4073(01)00034-6

Nieminen TA, Rubinsztein-Dunlop H, Heckenberg NR, et al., 2001b. Numerical modelling of optical trapping. *Comput Phys Commun*, 142(1-3):468-471. https://doi.org/10.1016/S0010-4655(01)00391-5

Nieminen TA, Heckenberg NR, Rubinsztein-dunlop H, 2001c. Optical measurement of microscopic torques. *J Mod Opt*, 48(3):405-413. https://doi.org/10.1080/09500340108230922

Nieminen TA, Bishop AI, Heckenberg NR, et al., 2003. Polarimetric measurement of optical torque. Proc 7th Conf on Electromagnetic and Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications, p.267-270.

Nieminen TA, Parkin SJW, Heckenberg NR, et al., 2004a. Optical torque and symmetry. Optical Trapping and Optical Micromanipulation, p.254-263. https://doi.org/10.1117/12.557070

Nieminen TA, Heckenberg NR, Rubinsztein-Dunlop H, 2004b. Computational modeling of optical tweezers. Optical Trapping and Optical Micromanipulation, p.514-523. https://doi.org/10.1117/12.557090

Nieminen TA, Heckenberg NR, Rubinsztein-Dunlop H, 2008. Forces in optical tweezers with radially and azimuthally polarized trapping beams. *Opt Lett*, 33(2):122-124. https://doi.org/10.1364/OL.33.000122

O'Neil AT, Padgett MJ, 2002. Rotational control within optical tweezers by use of a rotating aperture. *Opt Lett*, 27(9): 743-745. https://doi.org/10.1364/OL.27.000743

O'Neil AT, MacVicar I, Allen L, et al., 2002. Intrinsic and extrinsic nature of the orbital angular momentum of a light beam. *Phys Rev Lett*, 88(5):053601. https://doi.org/10.1103/PhysRevLett.88.053601

Oroszi L, Galajda P, Kirei H, et al., 2006. Direct measurement of torque in an optical trap and its application to double-strand DNA. *Phys Rev Lett*, 97(5):058301. https://doi.org/10.1103/PhysRevLett.97.058301

Parkin SJ, Knöner G, Nieminen TA, et al., 2007. Picoliter viscometry using optically rotated particles. *Phys Rev E*, 76(4):041507. https://doi.org/10.1103/PhysRevE.76.041507

Paterson L, MacDonald MP, Arlt J, et al., 2001. Controlled rotation of optically trapped microscopic particles. *Science*, 292(5518):912-914. https://doi.org/10.1126/science.1058591

Prentice PA, MacDonald MP, Frank TG, et al., 2004. Manipulation and filtration of low index particles with holographic Laguerre-Gaussian optical trap arrays. *Opt Expr*, 12(4):593-600. https://doi.org/10.1364/OPEX.12.000593

Raghu A, Yogesha, Ananthamurthy S, 2010. Optical tweezer for micro and nano scale rheology of biomaterials. *Indian J Phys*, 84(8):1051-1061. https://doi.org/10.1007/s12648-010-0099-7

Ran LL, Guo ZY, Qu SL, 2012. Rotational motions of optically trapped microscopic particles by a vortex femtosecond laser. *Chin Phys B*, 21(10):104206. https://doi.org/10.1088/1674-1056/21/10/104206

Reimann R, Doderer M, Hebestreit E, et al., 2018. GHz rotation of an optically trapped nanoparticle in vacuum. *Phys Rev Lett*, 121(3):033602. https://doi.org/10.1103/PhysRevLett.121.033602

Rodríguez-Sevilla P, Arita Y, Liu XG, et al., 2018. The temperature of an optically trapped, rotating microparticle. *ACS Photon*, 5(9):3772-3778. https://doi.org/10.1021/acsphotonics.8b00822

Rowe AD, Leake MC, Morgan H, et al., 2003. Rapid rotation of micron and submicron dielectric particles measured using optical tweezers. *J Mod Opt*, 50(10):1539-1554. https://doi.org/10.1080/09500340308235228

Roy B, Bera SK, Banerjee A, 2014. Simultaneous detection of rotational and translational motion in optical tweezers by measurement of backscattered intensity. *Opt Lett*, 39(11): 3316-3319. https://doi.org/10.1364/OL.39.003316

Rubinsztein-Dunlop H, Nieminen TA, Friese MEJ, et al., 1998. Optical trapping of absorbing particles. *Adv Quant Chem*, 30:469-492. https://doi.org/10.1016/S0065-3276(08)60523-7

Santamato E, Daino B, Romagnoli M, et al., 1986. Collective rotation of molecules driven by the angular momentum of light in a nematic film. *Phys Rev Lett*, 57(19):2423-2426. https://doi.org/10.1103/PhysRevLett.57.2423

Santamato E, Sasso A, Piccirillo B, et al., 2002. Optical angular momentum transfer to transparent isotropic particles using laser beam carrying zero average angular momentum. *Opt Expr*, 10(17):871-878. https://doi.org/10.1364/OE.10.000871

Sato S, Inaba H, 1996. Optical trapping and manipulation of microscopic particles and biological cells by laser beams. *Opt Quant Electron*, 28(1):1-16. https://doi.org/10.1007/BF00578546

Sato S, Ishigure M, Inaba H, 1991. Optical trapping and rotational manipulation of microscopic particles and biological cells using higher-order mode Nd:YAG laser beams. *Electron Lett*, 27(20):1831-1832. https://doi.org/10.1049/el:19911138

Sheu FW, Lan TK, Lin YC, et al., 2010. Stable trapping and manually controlled rotation of an asymmetric or birefringent microparticle using dual-mode split-beam optical tweezers. *Opt Expr*, 18(14):14724-14729. https://doi.org/10.1364/OE.18.014724

Simpson NB, Dholakia K, Allen L, et al., 1997. Mechanical equivalence of spin and orbital angular momentum of light: an optical spanner. *Opt Lett*, 22(1):52-54. https://doi.org/10.1364/OL.22.000052

Singer W, Nieminen TA, Gibson UJ, et al., 2006. Orientation of optically trapped nonspherical birefringent particles. *Phys Rev E,* 73(2):021911. https://doi.org/10.1103/PhysRevE.73.021911

Sriram I, Meyer A, Furst EM, 2010. Active microrheology of a colloidal suspension in the direct collision limit. *Phys Fluids*, 22(6):062003. https://doi.org/10.1063/1.3450319

Starr C, Dultz W, Wagner HP, et al., 2005. Optically controlled rotation of PTCDA crystals in optical tweezers. 27th Int Conf on Physics of Semiconductor, p.1099-1100. https://doi.org/10.1063/1.1994496

Stickler BA, Nimmrichter S, Martinetz L, et al., 2016. Ro-translational cavity cooling of dielectric rods and disks. *Phys Rev A*, 94(3):033818. https://doi.org/10.1103/PhysRevA.94.033818

Tamm C, Weiss CO, 1990. Bistability and optical switching of spatial patterns in a laser. *J Opt Soc Am B*, 7(6):1034-1038. https://doi.org/10.1364/JOSAB.7.001034

Tanaka Y, 2018. Double-arm optical tweezer system for precise and dexterous handling of micro-objects in 3D workspace. *Opt Lasers Eng*, 111:65-70. https://doi.org/10.1016/j.optlaseng.2018.07.019

Tkachenko G, Brasselet E, 2014. Helicity-dependent three-dimensional optical trapping of chiral microparticles. *Nat Commun*, 5:4491. https://doi.org/10.1038/ncomms5491

Ukita H, Kawashima H, 2010. Optical rotor capable of controlling clockwise and counterclockwise rotation in optical tweezers by displacing the trapping position. *Appl Opt*, 49(10):1991-1996.

https://doi.org/10.1364/AO.49.001991

Vaippully R, Bhatt D, dev Ranjan A, et al., 2019. Study of adhesivity of surfaces using rotational optical tweezers. *Phys Scr*, 94(10):105008. https://doi.org/10.1088/1402-4896/ab292d

Vaipully R, Bhatt D, dev Ranjan A, et al., 2019. Determination of surface binding properties using rotational optical tweezers. Optics in the Life Sciences Congress, Article AW1E.2. https://doi.org/10.1364/OMA.2019.AW1E.2

Wu T, Nieminen TA, Mohanty S, et al., 2012a. Directing growth cones of optic axons growing with laser scissors and laser tweezers. Optical Trapping and Optical Micromanipulation IX, p.84580P. https://doi.org/10.1117/12.930411

Wu T, Nieminen TA, Mohanty S, et al., 2012b. A photon-driven micromotor can direct nerve fibre growth. *Nat Photon*, 6(1):62-67. https://doi.org/10.1038/nphoton.2011.287

Xie MY, Chen SX, Mills JK, et al., 2016. Cell out-of-plane rotation control using a cell surgery robotic system equipped with optical tweezers manipulators. Proc IEEE Int Conf on Information and Automation, p.103-108. https://doi.org/10.1109/ICInfA.2016.7831804

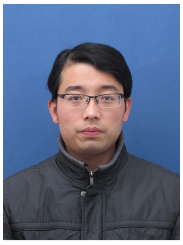
Yogesha, Bhattacharya S, Ananthamurthy S, 2012. Characterizing the rotation of non symmetric objects in an optical tweezer. *Opt Commun*, 285(10-11):2530-2535. https://doi.org/10.1016/j.optcom.2012.01.055

Yu HC, She WL, 2014. Rotation dynamics of a uniaxial birefringent cylinder in an optical tweezer with a rotating polarization ellipse. *J Opt Soc Am B*, 31(11):2864-2870. https://doi.org/10.1364/JOSAB.31.002864

Zhong MC, Zhou JH, Ren YX, et al., 2009. Rotation of birefringent particles in optical tweezers with spherical aberration. *Appl Opt*, 48(22):4397-4402. https://doi.org/10.1364/AO.48.004397

Zhong MC, Zhou JH, Ren YX, et al., 2009. Rotation of birefringent particles in optical tweezers with spherical aberration. *Appl Opt*, 48(22):4397-4402. https://doi.org/10.1364/AO.48.004397

Qi ZHU, first author of this invited paper, received her BS degree in Optical Engineering from Zhejiang University, China. She is now a PhD candidate at Zhejiang University. Her current research interests include optical tweezers and optical rotation.



Huizhu HU, corresponding author of this invited paper, received his BS degree from the Department of Applied Physics, Xi'an Jiaotong University in 1999, and his PhD degree from the Department of Optical Engineering, Zhejiang University in 2004. He is now a professor at Zhejiang University. Prof. HU is a corresponding expert for the *Front Inform Technol Electron Eng*. He has been engaged in the research of inertial technology, optical sensing, and precision measurement technology for a long time, and undertaken and participated in a number of major national key projects. He won the provincial and ministerial science and technology progress award and various other provincial and national commendations.