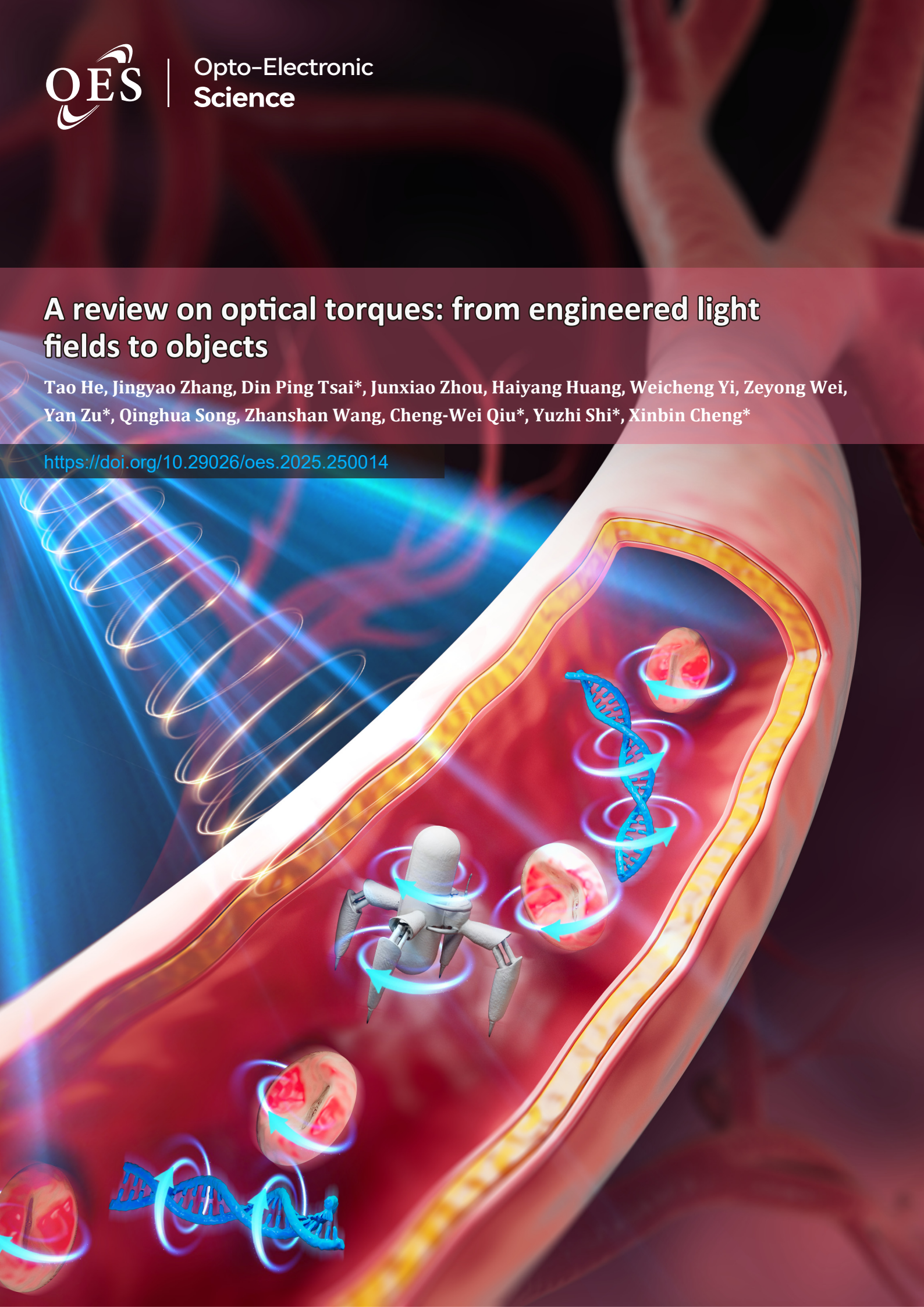


A review on optical torques: from engineered light fields to objects

Tao He, Jingyao Zhang, Din Ping Tsai*, Junxiao Zhou, Haiyang Huang, Weicheng Yi, Zeyong Wei, Yan Zu*, Qinghua Song, Zhanshan Wang, Cheng-Wei Qiu*, Yuzhi Shi*, Xinbin Cheng*

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A review on optical torques: from engineered light fields to objects

Tao He^{1,2,3,4,5}, Jingyao Zhang^{1,2,3,4,5}, Din Ping Tsai^{6*}, Junxiao Zhou⁶, Haiyang Huang^{1,2,3,4,5}, Weicheng Yi^{1,2,3,4,5}, Zeyong Wei^{1,2,3,4,5}, Yan Zu^{7*}, Qinghua Song⁸, Zhanshan Wang^{1,2,3,4,5}, Cheng-Wei Qiu^{9*}, Yuzhi Shi^{1,2,3,4,5*} and Xinbin Cheng^{1,2,3,4,5*}

In recent decades, optical micro/nano manipulation has made remarkable strides in the fields of biology and the physical sciences, benefiting from both theoretical and experimental advances in optical forces. The emergence of optical torques has further enhanced the capabilities and possibilities of optical micro/nano manipulation, opening the door to exciting new applications. In this review, we delve into the fundamentals and recent breakthroughs in the realm of optical micro/nano manipulation using optical torques. We introduce the advancements in optical manipulation based on optical torques from engineered light fields and objects, and highlight the latest developments in applying optical torques to cutting-edge physical and biological scenarios, with a special emphasis on the detection and manipulation of biological structures. Finally, we conclude by outlining our vision for the current and future directions of this field, including the integration of optical torque and micro/nano technologies, the utilization of special light fields, and the development of deep-learning-assisted optical torque design.

Keywords: optical torque; optical manipulation; negative optical torque; positive optical torque; biological application

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Introduction

Optical force arises when there is an interchange of the momentum between light and matter. Optical forces have achieved great achievements in the fields of physics, chemistry, biology, medicine, and nanotechnology in the

past few decades^{1–6}. For instance, Steven Chu, Claude Cohen-Tannoudji, and William D. Phillip were awarded the Nobel Prize in Physics in 1997 for their work on atom cooling using lasers². Arthur Ashkin was awarded the half the Nobel Prize in Physics in 2018 due to the

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invention of optical tweezers (OTs) and his contributions to biomedical applications^{3,4}. Besides, it also facilitates the trapping, sorting, transport, and assembly of micro/nanoparticles or cells in a contact-free manner^{7–11}.

Light carries both linear and angular momenta^{12–14}. The angular momenta consist of the spin angular momentum (SAM) and orbital angular momentum (OAM). Both of them, when transferred to particles, can generate an optical torque^{15–21}. In most cases, the direction of the optical torque is aligned with the direction of the incident angular momentum, which is called a positive optical torque (POT)^{18–20}. Counterintuitively, when the momentum direction of the optical torque is opposite to the direction of the incident angular momentum, it is referred to as a negative optical torque (NOT)^{22–24}. As

shown in the central schematic of Fig. 1, the SAM of the incident light field rotates counterclockwise. A particle experiencing POT rotates counterclockwise, in the same direction as the SAM, while a particle experiencing NOT rotates clockwise. When the incident light has no angular momentum, it is generally not distinguished whether the optical torque is positive or negative. In recent decades, there has been significant attention directed towards POTs and NOTs due to their unique capabilities in optical manipulation^{25–27}, which are unattainable by conventional optical forces.

In 1909, Poynting found that circularly polarized light has SAM¹³ (Fig. 2). Both directly detected and measured optical torque by observing the deflection of a quartz wave plate when polarized light carrying SAM was

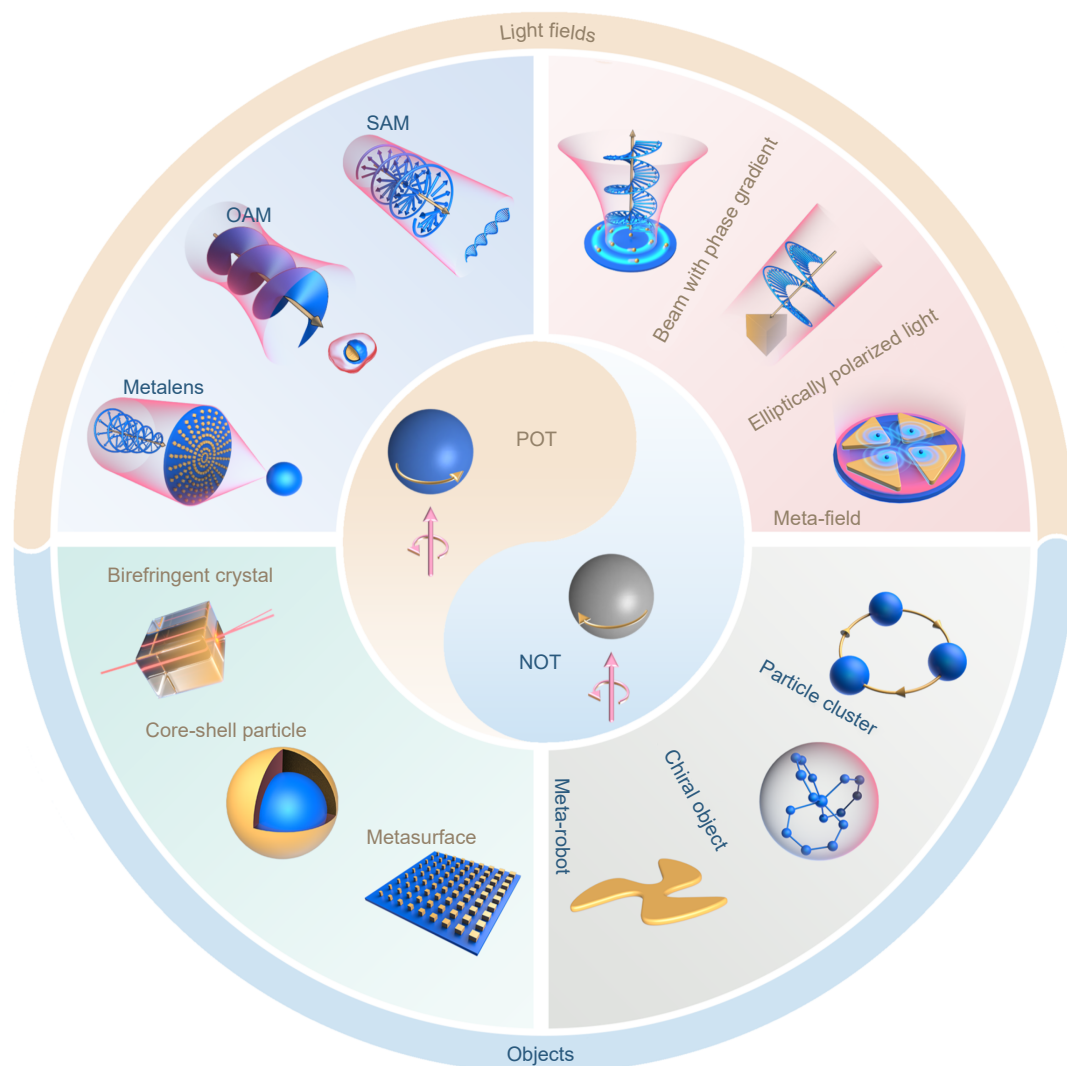


Fig. 1 | Schematic illustration of various implementations for the POT and NOT. These implementations are categorized into two primary approaches: manipulation of incident light fields and control of the objects themselves.

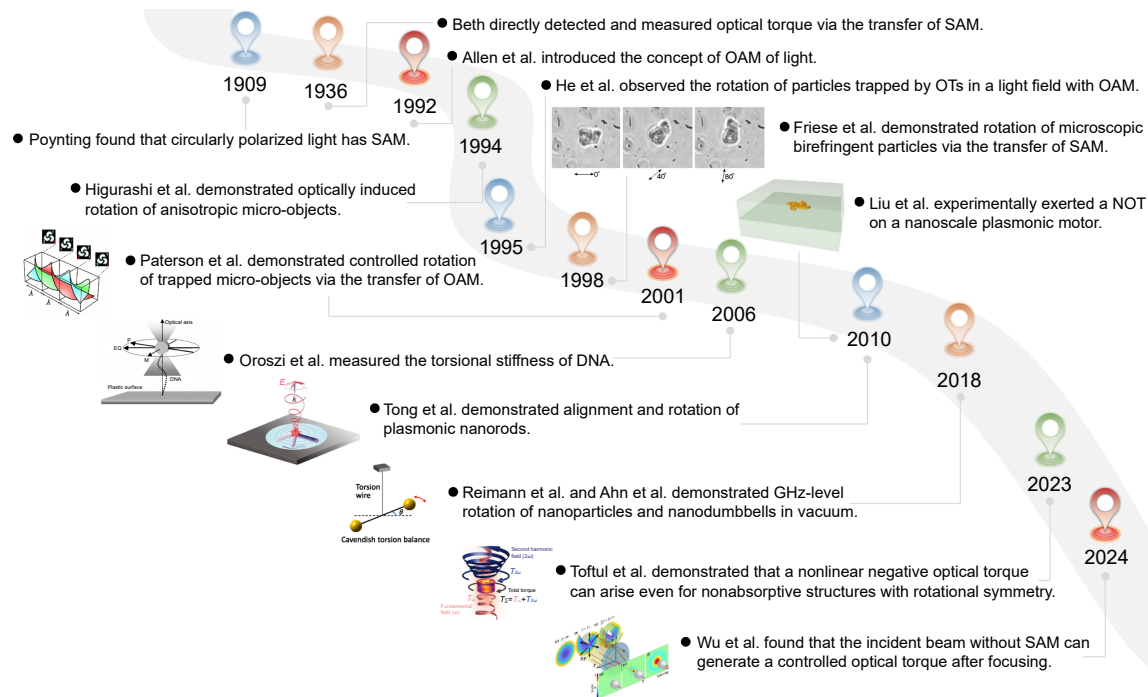


Fig. 2 | Roadmap for the development of optical torques. The discovery of SAM in circularly polarized light was made¹³. Beth directly detected and measured optical torque via the transfer of SAM²⁸. Allen et al. introduced the concept of OAM of light¹⁴. The optically induced trapping and rotation of anisotropic micro-objects fabricated using reactive ion-beam etching were demonstrated²⁹. He et al. observed the rotation of particles trapped by OTs in a light field with OAM³⁰. Friese et al. demonstrated light-induced rotation of microscopic birefringent particles via the transfer of SAM from light to the material. Adapted with permission from ref.³¹, 1998 Springer Nature. Paterson et al. demonstrated controlled rotation of trapped micro-objects via the transfer of OAM. Adapted with permission from ref.³², 2001 American Association for the Advancement of Science. Oroszi et al. measured the torsional stiffness of DNA using optical torque. Adapted with permission from ref.³³, 2006 American Physical Society. Tong et al. demonstrated alignment and rotation of individual plasmonic nanostructures with lengths from tens of nanometers to several micrometers using a single beam of linearly polarized near-infrared laser light. Adapted with permission from ref.³⁴, 2010 American Chemical Society. A NOT was experimentally observed in a nanoscale plasmonic motor. Adapted with permission from ref.⁴², 2010 Springer Nature. Reimann et al. and Ahn et al. drove the rotation of nanoparticles and nanodumbbells in vacuum at frequencies exceeding 1 GHz. Adapted with permission from ref.^{35,36}, 2018 American Physical Society. Toftul et al. demonstrated that a nonlinear negative optical torque can appear for the case of nonabsorptive dielectric structures with a rotational symmetry. due to the excitation of resonant states at the harmonic frequency with higher projection of angular momentum. Adapted with permission from ref.³⁸, 2023 American Physical Society. Wu et al. found that an incident beam without SAM can generate a controlled optical torque after focusing. Adapted with permission from ref.³⁹, 2024 American Physical Society.

incident upon it²⁸. A widely used method introduced by Allen et al. is to employ carefully arranged beams carrying OAM to generate the optical twist required by POTs¹⁴. Subsequently, through the transfer of optical angular momentum, a series of studies further expanded the experimental approaches for realizing optical torques^{29–32}. Oroszi et al. proposed an optical trapping method that provides the opportunity to exert and measure optical torque on the manipulated molecule³³. Tong et al. further demonstrated alignment and rotation of individual plasmonic nanostructures with lengths from tens of nanometers to several micrometers using a single beam of linearly polarized near-infrared laser light³⁴. In back-to-back studies in 2018, Reimann et al. and Ahn et

al. demonstrated the rotation of nanoparticles and nanodumbbells in vacuum at frequencies exceeding 1 GHz^{35,36}. It is generally believed that symmetric objects can solely undergo rotation through absorption optical torque, whereas scattering torque applies exclusively to asymmetric objects³⁷. However, Toftul et al. revealed that the angular momentum imbalance between the fields at the fundamental and second harmonic frequencies can lead to an optical torque, showing that a negative optical torque can arise even for nonabsorptive dielectric structures with a rotational symmetry³⁸. Optical torques can also be generated by incident light without angular momentum, through the specific optical responses of the object, such as the intrinsic or mimicked anisotropy of

the material. Recently, controlled spinning of the birefringent microparticles has been demonstrated using a tightly focused radially polarized vortex beam, which exhibits no SAM prior to focusing³⁹. The rapid development of nanophotonics has opened up new opportunities for studying optical torque, particularly through the directional design of light fields and artificial objects^{40,41}. Key developments and milestones in optical torque are highlighted in the roadmap in Fig. 2.

Since the theoretical proposal of NOT⁴³, it has greatly extended the understanding of the interaction between light and matter in the field of opto-mechanics. Actually, symmetry has proved to be of considerable importance in realizing NOTs. NOTs can be achieved and enhanced by manipulating the incident light fields^{44,45} or the objects^{25,46}. For example, NOTs have been observed in various mesoscopic systems⁴⁷, including particle clusters²⁵, chiral particles⁴⁸, meta-robots⁴², triangular prisms²⁶ and so on. To the best of our knowledge, despite the optical torques have played a significant role in many physical and biological applications, there is a lack of comprehensive review articles on the advancement of optical torques, which hinders the further exploration.

In this paper, we will revisit the basic theory of optical torques first, including the generation conditions of POT and NOT. Subsequently, the advances and emerging directions of optical torques via distinct light fields and objects are summarized (Fig. 1). At last, we introduce the fascinating applications of optical torques and cast our perspectives on the potential future directions.

Fundamentals of optical torques

Light carries both linear momentum and angular momentum, the latter comprising SAM¹⁶² and OAM^{14,49}. SAM is related to the polarization state of light; for circularly polarized light, each photon carries spin angular momentum of $\pm\hbar$. OAM can be divided into intrinsic orbital angular momentum (IOAM) and extrinsic orbital angular momentum (EOAM). EOAM is associated with the trajectory of the beam, while IOAM originates from structured beams with helical phase fronts characterized by a topological charge l , carrying orbital angular momentum of $l\hbar$.

When the angular momentum of the light field transfers to a particle, an optical torque is exerted on the particle. The optical torque acting on particles of arbitrary size and shape can be expressed as²⁶:

$$\mathbf{M} = \oint_S (\mathbf{r} \times \langle \mathbf{T} \rangle) \cdot \hat{\mathbf{n}} dS, \quad (1)$$

where $\langle \mathbf{T} \rangle$ is the time-averaged Minkowski stress tensor, $\mathbf{r}$ is the position vector, $\hat{\mathbf{n}}$ is the unit normal vector on the closed surface S enclosing the object. This formula includes contributions from both SAM and OAM to the optical torque.

To clearly express the components of the torque, we consider an object with m_s -fold rotational symmetry illuminated by light. The z -component of the optical torque exerted on the object can be written as²²:

$$M_z = \sum_{m_i} \frac{m_i}{\omega} W_{\text{ext}}^{(m_i)} - \sum_m \frac{m}{\omega} W_{\text{sca}}^{(m)}, \quad (2)$$

where ω is the angular frequency of light. Here, m_i represents the azimuthal channels of the incident waves, and $W_{\text{ext}}^{(m_i)}$ is the energy extinction rate for incident wave from channel m_i . Each of the photons from channel m_i carries $m_i\hbar$ of angular momentum, including both OAM and SAM. m represents the azimuthal channels of the scattered waves, written as $m = m_i + nm_s$, where $n = 0, \pm 1, \pm 2, \dots$. And $W_{\text{sca}}^{(m)}$ is the energy extinction rate for incident wave from channel m .

The first term on the right side represents the rate at which the object acquires angular momentum from the incident wave, while the second term accounts for the recoil. The first term depends only on the angular momentum of the incident waves and always aligns with the incident wave's angular momentum direction. It is commonly referred to as POT. The second term depends on both the incident waves and the particle's properties. Its sign and magnitude, determined by m , can lead to interesting phenomena. If the negative contribution ($m < 0$) dominates, causing the second term to exceed the first, the optical torque M_z will be in the opposite direction to the incident wave, referred to as the NOT. The sign and magnitude of m can be controlled by factors such as the light fields and the object's properties, including its material, shape, size, etc. The classification of optical torques into POT and NOT is of great significance, as it reveals the distinct underlying physical mechanisms and helps identify the origin of optical torques. POT is usually dominated by the direct transfer of the angular momentum from the incident wave, whereas NOT reflects a more complex redistribution of angular momentum, where the torque direction may reverse due to factors such as the particle's shape, size, material, or multipolar scattering effects. Distinguishing and analyzing the gen-

eration conditions and mechanisms of POT and NOT contributes to a deeper understanding of angular momentum regulation in light-matter interactions. And provides a theoretical foundation for developing novel optical micromanipulation strategies and expanding the application of optical torques.

When the particle diameter is much smaller than the wavelength ($d \ll \lambda$), it can be approximated as a point dipole. In this case, the optical torque mainly arises from the interaction between the external electromagnetic field and the dipole. Based on the classical dipole model, the optical torque can be expressed as²⁶:

$$\mathbf{M} = \frac{1}{2} \text{Re} (\mathbf{d}_e^* \times \mathbf{E} + \mathbf{d}_m^* \times \mathbf{H}) , \quad (3)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the complex electric and magnetic fields, and $\mathbf{d}_e^*$ and $\mathbf{d}_m^*$ are the complex electric and magnetic dipole moments respectively, given by $\mathbf{d}_e = \alpha_e \mathbf{E}$, $\mathbf{d}_m = \alpha_m \mathbf{H}$.

For Mie particles whose sizes are comparable to the wavelength, the optical torque becomes more complex, requiring multipole expansion analysis of angular momentum transfer and optical torque within Mie resonances^{50,51}.

Positive optical torques

Optical torque is a fundamental consequence of an optical force with respect to some reference points. Optical torque is induced when the angular momentum is transferred from the light field to an object^{52,53}. Therefore, the properties of the light field and the object are the most significant factors that influence the optical torque⁵⁴. In the early stage, light beams carrying angular momentum have been widely utilized to rotate a microscopic particle directly³⁰, which is referred to as "optical spanners"⁵⁵. Later, complex vector beams and particles with custom-designed optical properties are employed to investigate the generation and properties of optical torques^{21,56}.

Positive optical torques induced by diverse light fields

Both SAM and OAM can transfer to particles, generating optical torques that drive rotational motion^{57–59}. SAM arises from the polarization state of light. In 1936, Beth experimentally demonstrated that photons with left- and right-handed circular polarization possess SAM of opposite signs²⁸. When circularly polarized light interacts with a microscopic particle that absorbs or scatters light, the

conservation of angular momentum induces the particle to spin around its own axis. Rayleigh nanoparticles with absorption can be captured within a single highly focused Gaussian beam and undergo a rotational motion by the action of SAM¹⁷. Metal nanowires also rotate at a certain angular frequency harnessing the SAM transfer of circularly polarized light³⁴. The rotation speed largely depends on the optical properties of the objects and the viscosity of the liquid environment, as well as the laser power. As illustrated in Fig. 3(a), gold particles with radii of approximately 200 nm can achieve rotation frequencies in the kilohertz scale⁶⁰. The high rotation frequencies are attributed to the synergistic effects of advantageous optical properties of the particles and the reduced local viscosity resulting from significant heating of the particle's surface layer. This unique feature has paved the way for diverse applications in the realms of physics and biology, such as microfluidic stirring³⁴, torque measurement³³. Interestingly, although absorption has been considered the primary mechanism for generating optical torque, Lee et al. demonstrated that the contribution of scattering can be enhanced to 80% through multipolar plasmon resonances⁶¹. This scattering-dominated optical torque is accompanied by distinct modes, which should be distinguished from absorption-dominated mechanisms. This discovery can be applied to nanoscale optical manipulation as well as the novel design of meta-material structures. For example, the single plasmonic nanorods can be rotated at a speed reaching up to 43 kHz through optical torques dominated by scattering⁶².

OAM, conversely, stems from the spatial phase structure of light, such as that present in a helical LG mode, can apply non-conservative optical forces on the particle¹⁴, driving it to orbit around the beam's propagation axis. More than 30 years ago, Allen et al. introduced the groundbreaking concept that light beams can possess an additional angular momentum independent of the photon spin¹⁴. This extraordinary angular momentum is OAM which is characterized by an azimuthally varying phase^{7,63,64}. Shortly thereafter, the transfer of OAM from a laser mode to a trapped particle was experimentally demonstrated, showing that OAM could induce the rotation of absorptive particles⁵⁵. Paterson et al. introduced a general scheme for rotating trapped micro-objects by rotating the pattern generated by interfering an annular shaped laser beam with a reference beam. And the rotation of the pattern is achieved by changing the optical path length³². Structures such as silica micro-

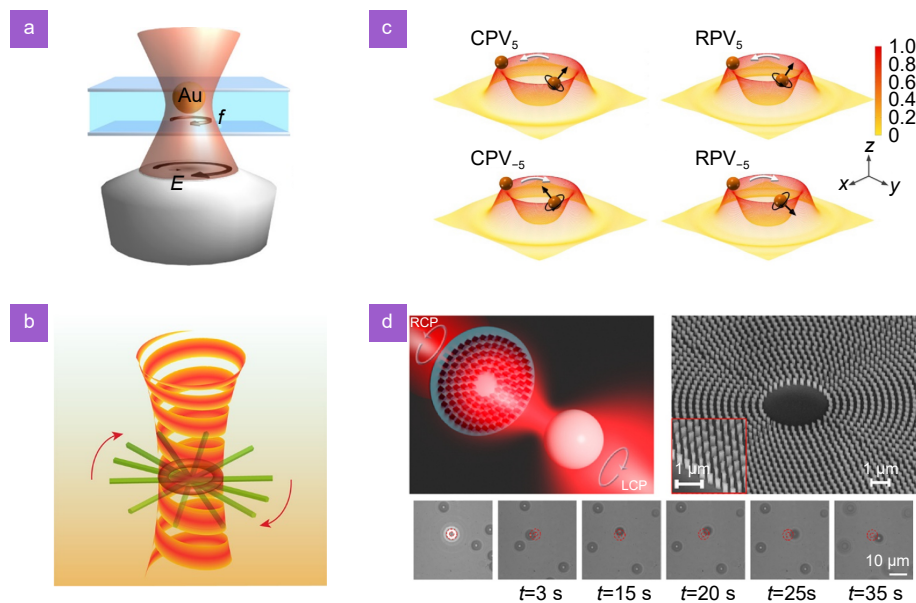


Fig. 3 | Positive optical torques from diverse light fields. (a) The ultrafast spinning of gold nanoparticles in water by utilizing SAM transfer of photons. By targeting particles with a beam of circularly polarized light, rotation frequencies can reach several kilohertz. (b) Illustration of an optical vortex-induced rotation of a single Ag nanowire. (c) Illustration of the spin and orbital motion of particles illuminated by circularly and radially polarized vortex beams with topological charges. (d) Vortex metalens based on the geometric PB phase enables the OAM transfer onto particles, driving the rotation of the particle. Figure reproduced with permission from: (a) ref.⁶⁰, 2013 American Chemical Society; (b) ref.⁷², 2013 American Chemical Society; (c) ref.⁹¹, 2016 Optica Publishing Group; (d) ref.¹¹³, 2020 Optica Publishing Group.

spheres, microscopic glass rods, and chromosomes have been successfully set into rapid rotation with frequencies exceeding 5 Hz. This technique is universally applicable to particles of various shapes, making it of significant importance for applications such as biotechnology⁵⁷ and other areas^{10,65}. Using a single gold plasmonic Archimedes spiral, Tsai et al. engineered plasmonic near fields into a plasmonic vortex for isotropic dielectric microparticle rotation⁶⁶. Apart from dielectric particles, the optical manipulation of metal particles^{67–69} holds great promise for the development of plasmonic lab-on-a-chip systems^{37,58,70}. A 400 nm gold nanosphere was driven by a Laguerre-Gaussian (LG) beam to perform an orbital rotational motion with a radius of 2 μm at a frequency of 86 Hz⁷¹. As shown in Fig. 3(b), a study conducted by Yan et al. demonstrated that the OAM of photons in LG beams can induce rotation of single silver (Ag) nanowires with lengths of over 10 μm , which is governed by plasmonic interactions of the Ag nanowires with light beams⁷². Furthermore, the rotation direction of the nanowire can be reversed from clockwise to anticlockwise by varying the topological charge from positive to negative.

The interplay and interconversion between SAM and OAM reflect the spin-orbit interaction (SOI) of light. SOI couples SAM and OAM, enabling conversion be-

tween them⁷³. Allen et al. observed that paraxial beams with cylindrical symmetry exhibit a well-defined total angular momentum per unit energy flux¹⁴, which can be decomposed into orbital and spin components. This characteristic may be an artifact of the paraxial approximation. However, in non-paraxial beams, near-field optics, and complex structured light fields, this separation is not always straightforward^{74,75}. An analysis of angular momentum flux is used to account for various components in non-paraxial beams^{76,77}. The interaction between SAM and OAM creates new opportunities for optomechanical effects and optical manipulation, including the ability to trap and rotate objects^{78–81}. A typical example of the spin-orbit angular momentum interaction of light occurs when a non-paraxial light beam is focused by a high numerical aperture lens or scattered by a microscopic particle. In such cases, the SOI significantly influences the distribution of the optical field^{82–86}. Focusing a beam not only causes a mixing of angular momentum components in a beam carrying both spin and orbital angular momenta, but it can also lead to the generation of OAM in a beam that initially possesses only SAM^{87,88}, and vice versa⁸⁹. For instance, when a strongly focused beam with circular polarization is used, SAM can be converted into OAM in non-paraxial fields⁹⁰. By

focusing optical vortex beams with circular or radial polarization, which inherently carry both SAM and OAM, non-axial spinning and orbiting motion of absorptive particles can be achieved. Such a particle can be trapped at the circle of maximum intensity^{91,92}, where it experiences transverse spin torque along the azimuthal direction, longitudinal spin torque, and orbital torque, as illustrated in Fig. 3(c). By utilizing the optical orbital Hall effect to regulate the spin angular momentum density distribution in the focused field, Wu et al. introduced the orbital angular momentum superposition state into the incident radially polarized light, and effectively controlled the radial separation between the two spin components³⁹. This enables the localized transfer of SAM from the focused field to microscopic particles, ultimately achieving controllable rotational manipulation of the particles. Besides, the transverse spin in evanescent waves represents a unique manifestation of the SOI of light, independent of geometric phases. In an evanescent wave, light propagating along the z -axis generates both SAM and OAM, which are locally coupled. This coupling results in the Mie particle being simultaneously pushed and rotated⁹³.

The use of light beams with angular momentum for controlling particle rotation is of great interest due to its potential applications. A typical approach to generating laser beams that carry SAM or OAM is using various optical waveplates or spatial light modulators^{94,95}, leading to a bulky volume. In recent years, metasurfaces which consist of planar meta-atoms with specific order have been introduced to generate complex light fields^{96–100}, such as Bessel beam¹⁰¹, Airy beam¹⁰², holographic light field¹⁰³ and so forth¹⁰⁴, in a compact way. An emerging direction to manipulate objects by optical forces involves the meta-field^{105,106}, which means engineering light field via metasurfaces^{107–109}. The simplest example is particle manipulation based on a metalens^{110,111}. Thanks to the polarization-sensitive characteristic of metasurfaces, the position of the particle can even be controlled by the polarization of the incident light, which is a challenge for conventional OTs¹¹². Furthermore, it was demonstrated that optical vortex metalens based on geometric PB phase can drive polystyrene microbeads in a rotational movement by generating OAM¹¹³, as shown in Fig. 3(d). By utilizing geometric and dynamic phases, high-numerical-aperture focal spot with coaxial vortex was achieved, enabling the integration of OTs and optical spanners into a single metasurface¹¹⁴. The versatility of the metasurface

significantly simplifies the system, which has potential applications in next-generation compact optical-manipulation devices. Although rotation manipulation based on far-fields has proven highly successful, the near-field configuration¹¹⁵ allows for manipulation and trapping of objects at the nanoscale. Wang et al. demonstrated a rotation of a nanoparticle with a diameter of 110 nm near a plasmonic metasurface by exciting its plasmonic dipole resonance¹¹⁶. The rotation can be realized by changing the polarization of the incident linear polarization light or through the momentum exchange of the circularly polarized light.

Positive optical torques exerted on diverse objects

Alternatively, there are additional methods to exert efficient optical torque on objects and induce their rotation. For example, anisotropic objects like birefringent crystals can be rotated using laser beams without the angular momentum. The calcite CaCO_3 ³¹, quartz SiO_2 ^{117,118}, rutile TiO_2 ^{119,120} and so on are the most popular choices to induce optical torques. Arita et al. rotated nanovaterite crystals made of CaCO_3 with a radius of 423 nm at a frequency of 4.9 kHz in heavy water. Vaterite is a positive uniaxial birefringent material, which may change output polarization and thus the SAM present in the circularly polarized incident light, leading to rotation of the particle⁹². Rutile TiO_2 possesses the highest birefringence among all naturally occurring dielectric crystals, with a birefringence value approximately 29 times larger than that of quartz SiO_2 . This exceptional property opens up the potential for attaining higher optical torques in optical manipulation applications¹²¹. As shown in Fig. 4(a), Ha et al. demonstrated that rutile TiO_2 nanocylinders exhibit an exceptional efficiency as torque transducers in aqueous environments¹²². Significantly, they achieve this by utilizing moderate laser powers to apply nN-nm torques at kHz rotational frequencies on tightly trapped particles. The capability facilitates measurements on systems that encompass a wide range of torque-speed regimes, including the bacterial flagellar motor¹²³. Optical torque is not only an effective tool for manipulating nanometer-scale objects but also an advanced tool for larger objects with sizes of several wavelengths¹²⁴.

Although birefringent particles have been manipulated in various ways, the magnitude of optical torques induced in birefringent particles is not large enough. For this reason, nanoscale core-shell particles were proposed to enhance the optical torques originating from the overlap

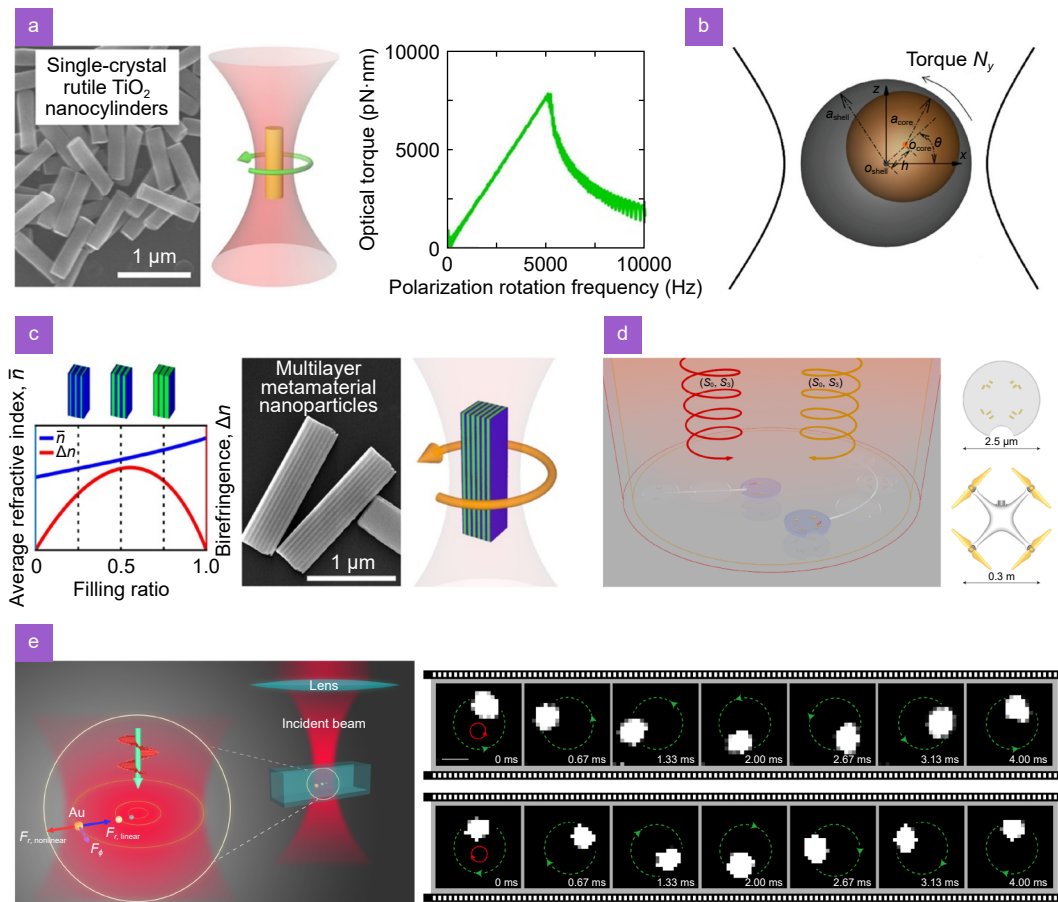


Fig. 4 | Positive optical torques are exerted on diverse objects. **(a)** Optical torques on single-crystal rutile TiO_2 nanocylinders. These nanocylinders have high refractive index and exceptionally large birefringence, allowing for the application of $\sim\text{nN}$ -scale forces and unprecedentedly high 1–10 $\text{nN}\cdot\text{nm}$ torques. **(b)** Optical torques on eccentric nanoscale core-shell particles. Breaking centro-symmetry leads to a significant increase in optical torques. **(c)** Schematic of a multilayer metamaterial square-cuboid particle. Its refractive index and birefringence can be designed by adapting the ratio of layer thicknesses, accessing broader regimes of force and/or torque transduction. **(d)** Illustration of the microdrone, which is driven by recoil forces and torques resulting from reflector elements. **(e)** The setup and experimental results for the rotation of the nonlinear particle. The green lines and arrows denote the direction of motion of the nonlinear gold nanoparticles, while the red arrows indicate the handedness direction of a circularly polarized femtosecond laser. Figure reproduced with permission from: (a) ref.¹²², 2019 American Chemical Society; (b) ref.¹²⁶, 2021 American Chemical Society; (c) ref.¹³⁴, 2020 American Chemical Society; (d) ref.¹⁴¹, 2022 Springer Nature; (e) ref.¹⁴⁶, under a Creative Commons Attribution 4.0 International License.

of trapping wavelength and plasmonic resonance region¹²⁵. As shown in Fig. 4(b), Sun et al. investigated optical torques exerted by both linearly and circularly polarized Gaussian beams on three types of eccentric spherical core-shell nanoparticles with different shells, showing that they can generate considerable optical torques¹²⁶. Under a moderate illumination power of 20 mW, the eccentric spherical core-shell particle (Au@SiO_2) whose diameter is only 180 nm can be rotated at a frequency over 800 Hz, which is hard to do with currently used birefringent particles under the same condition. The rotational speed of birefringent particles are limited by the diameter¹²⁷, embedded environment¹²⁸,

laser power⁶⁰, heating effect⁹² and so on. The rapid rotation of nanometric-sized objects is of important potential applications in areas of levitated optomechanics¹²⁹ and biophotonics^{130,131}.

Previous researches mainly focused on the optical torques exerted on objects composed of naturally occurring materials. When optical responses of objects can be designed at will, more fascinating phenomena and intricate manipulations are anticipated to arise. Recently, metamaterials and metasurfaces¹³² with artificially defined optical responses have caused an upsurge in optical committee and gradually began to be applied to investigate optical forces¹³³. As shown in Fig. 4(c), Tang

et al. proposed a multilayer metamaterial¹³⁴ consisting of Nb₂O₅ and SiO₂. By changing the filling ratio, the metamaterial emulates a negative uniaxial birefringence and the value of the birefringence can be fixed anywhere between its minimal and maximum value. The optical torques induced on multilayer metamaterial particles make the long axis consistent with the direction of laser beam propagation¹³⁴. It was also demonstrated that the multilayer metamaterial particles with higher material filling ratios exhibited big rotational speed, at speeds up to ~5 kHz in water. Besides, the highest torques (~16 nN·nm) were obtained when the filling ratios were low. Notably, the maximal torques are 2 times larger than that for rutile TiO₂ nanocylinders. Besides, other types of metamaterials such as hyperbolic metamaterials also shine in the field of optical torque manipulation for their designable optical properties^{115,135}.

With the enhancement of optical forces and torques exerted on metamaterials and metasurfaces, researchers are now exploring methods to achieve directional motions in meta-structures^{136,137}, giving rise to the concept of a "meta-robot"^{138,139}. In 2021, Andr  n et al. demonstrated a microscopic metavehicle by utilizing the unidirectional scattering of optical metasurfaces¹⁴⁰. The metavehicle can move forward and turn to the right or left. The ability to turn the metavehicle comes from the torque induced by the spin momentum exchange of circularly polarized light. The torque is in the same direction as the handedness of the incoming circularly polarized light. While the metavehicle introduces a novel approach to motion control, its actuation was restricted due to the fact that turning was consistently coupled with forward translation at a fixed radius. As shown in Fig. 4(d), Wu et al. exhibited a microdrone consisting of four plasmonic nano-antenna that can be maneuvered by two overlapping unfocused light fields of 830 and 980 nm wavelength in three independent degrees of freedom including left and right, up and down, clockwise and counter-clockwise motions¹⁴¹. By manipulating the total power and polarization states (S_0 and S_3 , respectively, as described by the Stokes parameters), one can effectively apply the desired force and torque to maneuver the microdrone with a precision control. This microdrone could serve as a new experimental platform for tremendous biomedical applications¹⁴², nanomanipulation⁸ and solar sails¹⁴³. To further enhance the capabilities of motion control, there is a need for further exploration in achieving arbitrary motion states in three-dimensional

space¹⁴⁴.

In addition to rotational speed, the rotation of nanoparticles at subwavelength scales is also attractive due to its significant applications^{32,145} in optical micro-machines and biotechnology. Qin et al. achieved stable orbital rotation at deep subwavelength scales¹⁴⁶, with a record-small orbital radius of 71 nm, far beyond the diffraction limit. This achievement was based on nonlinear optical effects rather than sub-diffraction focusing, as depicted in Fig. 4(e).

Negative optical torque

Optical force and torque are two similar optical means in manipulating matter opto-mechanically. Analogy to optical pulling force¹⁴⁷, NOT can be considered, to a certain extent, as the angular counterpart of the optical pulling force, but the conditions for their realization differ¹⁴⁸. In fact, NOTs are ubiquitous as they can be realized under the illumination of various types of laser beams¹⁴⁹ or light fields⁴⁵ and in many structures^{42,150}, such as transparent structures, weakly absorptive structures, chiral particles, meta-robots and so on.

Negative optical torques induced by diverse light fields

Since the numerical prediction of NOT was proposed⁴³, formular innovations about NOT were reported in succession^{22,48,151,152}. Hakobyan et al.¹⁵³ proposed an indirect approach to demonstrate the NOT by analyzing the mechanical action of matter on light. This approach was improved by directly analyzing the mechanical action of light on matter¹⁵⁴. The NOTs were demonstrated in an experiment with circularly polarized Gaussian light beams by the use of an inhomogeneous and anisotropic transparent macroscopic medium^{153,154}. It is worth noting that it is not a NOT by reversing the direction of angular momentum because the sign of optical torque still follows the direction of the incident angular momentum. In order to facilitate the experimental observation of NOTs, it is typically necessary to capture the object first. Light with intensity gradient is usually used to simultaneously control the position and rotation of objects¹⁵⁵. However, the tightly focused laser beam with a high laser power is not friendly to biological applications for its inevitably strong heating effects. To avoid this issue, an easy question to ask is, when there is no intensity gradient in the light field, can an object still be controlled in both position and rotation? To answer this question,

Nan et al. demonstrated a stable optical trapping and switchable optical rotation of nanoparticles under light fields with programmed two-dimensional phase gradients⁴⁴. By only modulating the phase gradients, the optical torque magnitude and rotation direction can be switched as shown in Fig. 5(a). The phase gradient serves as a switch to change the rotation direction of the array of nanoparticles that rotate under the action of optical torque arising from circular polarization. Such torque reversal originates from the scattering of light among the particles and the interference between the scattered light from different particles. And the total optical torque is highly sensitive to the geometry of the cluster. The combination of tailored phase-gradient forces and optical torques can work in synergy to enable sophisticated and multifunctional application. Recently, curve-shaped traps based on structured light have been developed, allowing particles of various shapes to be optically transported along arbitrary trajectories driven by tailored phase-gradient force fields, while simultaneously spinning at frequencies ranging from Hz to several kHz un-

der the optical torque^{156,157}.

In addition to phase gradients, spatial variations in the polarization of light beams significantly influence the optical torque experienced by the particle. Gradients in polarization affect not only the distribution of SAM and OAM but also exert additional optical forces and torques on particles through interference among scattered fields. Albaladejo et al. demonstrated that in light fields with non-uniform polarization, scattering forces comprise not only components determined by the Poynting vector but also non-conservative components related to the curl of SAM, which can substantially affect particle trajectories¹⁵⁸. Elliptically polarized light waves, as a general form of circularly polarized light, also have the angular momentum and can rotate nonspherical particles via exerting POT. Ruffner and Grier's research indicated that SAM in elliptically polarized beams can be converted into OAM through spin-to-orbit angular momentum conversion, thereby generating significant optical torque on isotropic particles¹⁵⁹. However, when the elliptically polarized light waves imping on dielectric nanoparticles

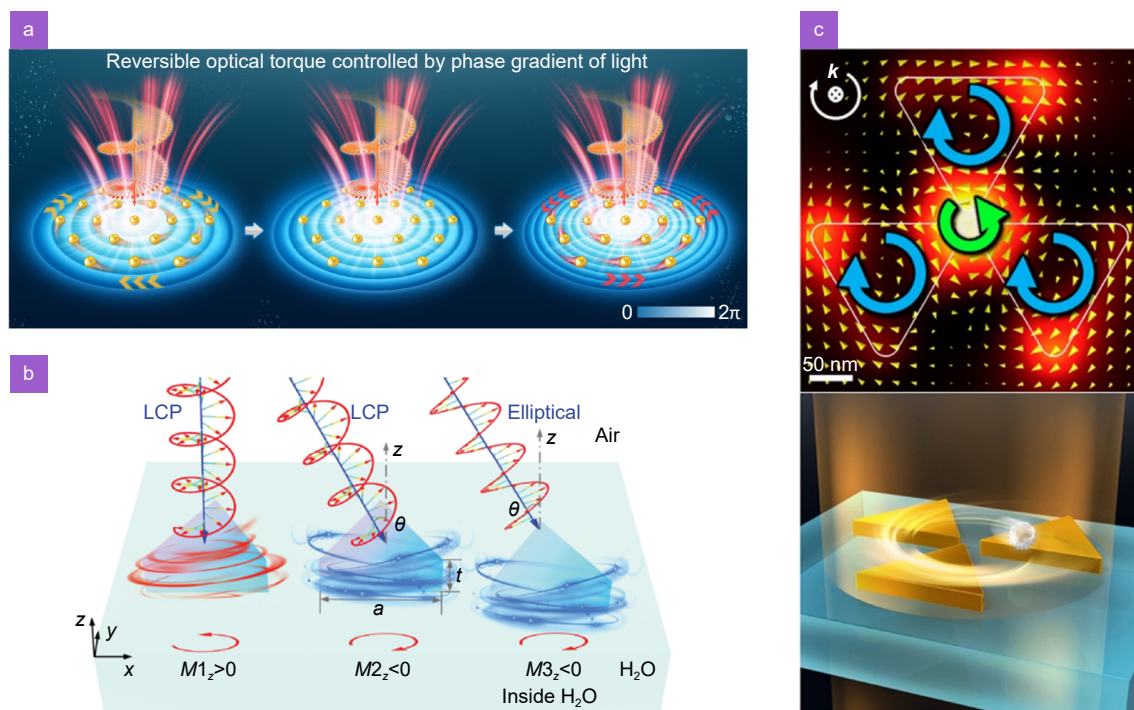


Fig. 5 | Negative optical torques from diverse light fields. (a) Schematic of optical torque reversal by increasing the optical phase gradient. (b) Schematics of the triangular prism placed at the interface of air and water under the illumination of an obliquely incident light beam. The prism rotates following the direction of the SAM when the beam is at normal incidence, and the optical torques shift from positive to negative when increasing the incident angle. (c) The NOT on a gold trimer nanoantenna based on light-matter angular momentum transfer, demonstrating the controlled orbital rotation of a single fluorescent nanodiamond, and the rotation direction is opposite to the light's polarization rotation. Figure reproduced with permission from: (a) ref.⁴⁴, 2022 American Association for the Advancement of Science; (b) ref.²⁶, 2022 American Physical Society; (c) ref.⁴⁵, 2021 American Chemical Society.

obliquely²⁶, the NOT emerges counterintuitively but veritically, as shown in Fig. 5(b). This interesting phenomenon dates from the geometric anisotropy of dielectric nanoparticles¹⁶⁰. The optical torque originating from the scattering light by the dielectric triangular prisms can be negative and neutralize the contribution of POT from the SAM. By simply changing the incident angles, Shi et al. pointed out that the rotation direction of the particle can be switched between clockwise and counterclockwise easily, which is a simple method to control the sign of optical torque, which is different from introducing the phase gradient of light²⁶. What is worth mentioning is that some special laser beams can also induce NOTs, such as non-diffracting non-paraxial fractional Bessel vortex beam¹⁶¹.

Metasurfaces play an important role in the realization of POT due to their powerful ability to regulate the light field. Similarly, the meta-fields created by metasurfaces have a significant impact on the implementation of NOT⁴⁵. A gold metasurface composed of trimer nanoantenna was proposed to create a specific distribution of electric field, as shown in Fig. 5(c). When the incident linearly polarized light is rotated, individual nanotriangles would be excited sequentially in the reverse order and generate NOT. When the circularly polarized light is applied, a Poynting vector vortex of reversed handedness would generate, leading to a transfer of angular momentum between the circularly polarized light and the trapped particle. Based on such a platform, Fujiwara et al. rotated the fluorescent nanodiamond with an orbital radius of 28 nm in a direction opposite to the rotation direction of linearly polarized light or circularly polarized light⁴⁵. Recently, Xu et al. clarified the fundamental mechanism by which OAM induces particle rotation¹⁶². They found that OAM couples with curl torque, influencing particle rotation even when the particle is trapped off the optical axis. By augmenting momentum curl with topological charges, NOT can be achieved in the direction opposite to both the incident SAM and OAM.

Negative optical torques exerted on diverse objects

While controlling the light field to achieve the NOTs, research into NOTs realized by changing the nature or morphology of objects is also progressing rapidly¹⁶³. Actually, the key to the occurrence of the NOT is breaking the symmetry. Chen et al. showed that a NOT can be exerted on a dipolar Ag-Au core-shell sphere via exciting Fano-like resonance using two linearly polarized plane

waves as shown in Fig. 6(a). It is interesting that the NOT exerted on core-shell nanoparticles comes completely from the electric quadrupole terms rather than an electric dipole⁵⁰. Apparently, the NOT can be adjusted by changing the incident wavelength and the core (shell) radii of the nanoparticle. Moreover, the generation of NOT can break through the limitation of bandwidth to a certain extent. It has been proved that the spin-orbital angular momentum conversion can induce broadband NOT on a metallic nanohelix¹⁶⁴. This broadband NOT arises from the special eigen modes of the helix, which induce optical torques with signs determined by the polarization and excitation frequency of the modes.

Multiple particle assembly is another important kind of configuration to generate the NOT²². Electrodynamically bound dimer was demonstrated to rotate in a reversed direction with respect to that of the incident circular polarization²³. The NOT from the retardation of the scattered fields is the pushing hand of opposite-handed rotation. Recently, the NOT was observed in dimers of 300 nm diameter Au or 490 nm diameter polystyrene nanoparticles, as shown in Fig. 6(b). In this condition, the forward scattering is enhanced greatly by multipolar resonances in nanoparticle dimers with large diameters²⁵. As a result, the NOT can be created due to conservation laws. Because the optical force is proportional to the incident beam power, the rotation frequency can be increased by enhancing the incident beam power, even reaching kHz²³.

Although the relevant theory predicts that multiple nanoparticles can generate NOTs²², it is still a challenge to observe stable and tunable NOTs in experiments. Han et al. devoted to experimentally generating NOTs in a complex multi-nanoparticle system²⁴. The optical matter array, composed of silver nanoparticles in a liquid sample cell, is illuminated by a light beam with SAM. The rotation of the nanoparticles is indicated by the green arrow, which points opposite to the direction of the SAM represented by the blue arrow (as shown in Fig. 6(c)). Furthermore, it is proved that the number, separation and configuration of the arrays can affect the NOT greatly²⁴. Experimental results showed that there is a crossover from POT to NOT with different parameters of the constituent nanoparticles.

The interaction between light field and chiral matter has received significant attention due to its potential applications in enantioselective manipulation^{165–169}, which holds considerable importance in fields such as medicine

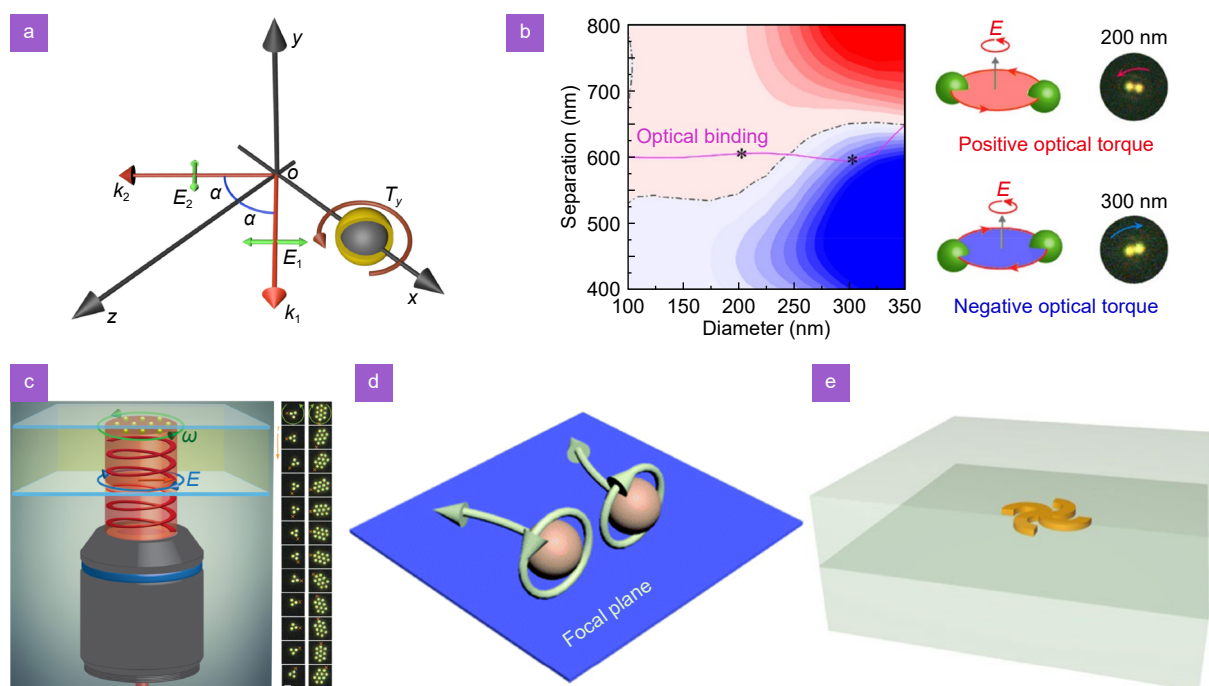


Fig. 6 | Negative optical torques are exerted on diverse objects. (a) NOT on Ag-Au core-shell nanoparticle induced by Fano-like resonance. The particle immersed in water is illuminated by two linearly polarized plane waves, inducing a torque whose direction is opposite with that of the incident angular momentum. (b) Optical torques on nanoparticle dimers. NOT exists for small interparticle separations at a certain particle size, and POT exists for large separations. (c) NOT on the multi-nanoparticle system in a liquid sample cell illuminated by a circularly polarized laser beam. The sign of optical torque depends on the number and configuration of the system. (d) The optical torques on chiral objects induced by azimuthally polarized hollow beams. (e) Schematics of the meta-robot. It can rotate when illuminated with a linearly polarized plane-wave or Gaussian beam and the rotation direction is changeable. Figure reproduced with permission from: (a) ref.⁵⁰, 2022 American Physical Society; (b) ref.²⁵, 2022 American Chemical Society; (c) ref.²⁴, 2018 Springer Nature; (d) ref.⁴⁶, 2019 Royal Society of Chemistry; (e) ref.⁴², 2010 Springer Nature.

and biology^{170,171}. It has recently been recognized that the chirality of objects can promote the recoil effect¹⁷². The chiral objects can receive the angular/linear momentums with reverse directions for their opposite chirality⁴⁶ as shown in Fig. 6(d). The POT and NOT induced by chiral surface-plasmon-polaritons are also called the quantum spin Hall effect¹⁷³. Besides, the cross-coupling of linear and angular momenta between the light field and the chiral object can also give rise to a NOT operation, representing a competitive interplay between nonchiral and chiral contributions to dissipative optical torques⁴⁸. In addition to chiral particles, some special particles like nonlinear particles can also produce nonlinear negative optical torque. This phenomenon arises from the excitation of resonant states at harmonic frequencies with higher angular momentum projections³⁸.

Meta-robot has recently been used as one of the best materials/objects for applying NOTs, since the absorption and scattering properties of meta-robot can be designed directionally¹⁷⁴. As shown in Fig. 6(e), a plasmonic meta-robot is designed to enhance the cross-section of

the light-matter interaction. The NOT is exerted on the meta-robot when the illumination wavelength is switched to excite different plasmonic modes reaching the condition of strong photon scattering⁴². Although the meta-robot is only 100 nm in size, it can still drive a micrometre-sized silica disk which is 4000 times larger than meta-robot. The optical torques can be enhanced further by arranging the meta-robot in arrays. NOT in meta-robot is a necessary supplement to the POT in order to realize the omnidirectional motion control of the meta-robot¹⁷⁵.

In the previous sections, we introduced POT and NOT. However, recent studies have shown that the mechanisms underlying optical torque generation are evolving toward more diverse and complex forms. One representative advance is the realization of time-varying three-dimensional (3D) optical torques¹⁷⁶. In this work, 3D optical torque and dynamic switching between multiple rotation axes has been achieved on birefringent microparticles by engineering the SAM vector with different orientations. To facilitate 3D control of SAM, the

researchers proposed a design for an incident field, which can be generated with a spatial light modulator (SLM) by manipulating the so-called asymptotic spiral phase. Experimentally, controlled 3D rotation and dynamic switching between multiple rotation axes of cubic calcite microparticles have been achieved within a single-beam optical trap. Furthermore, the controlled 3D rotation of individual living cells was also demonstrated. Metasurfaces offer unprecedented opportunities for controlling the momentum exchange between light and matter, and thereby the forces and torques that light can exert. Metaspinners, which generate torque via photon recoil, are capable of bending light into high angles and creating OAM¹⁷⁷. When two or more metaspinners are trapped in a laser beam, they collectively orbit around the beam axis in a direction opposite to their intrinsic spinning motion. This work highlights the vast potential of metasurfaces for fundamental explorations of optical torque. These advancements expand the theoretical framework and practical applications of optical torques. We anticipate that further developments in light field engineering and nanophotonics will continue to uncover even more complex and tunable torque phenomena.

Applications

With the refinement of the optical torque theory and the demonstration of various phenomena of particle manipulation by optical torques, the optical torque gradually begins to appear in various application scenarios¹⁷⁸. Optical torque has enabled a wide range of applications in physics and biology due to its high precision, non-invasive nature, and micro/nano-scale characteristics^{33,179,180}.

Generation of angular momentum beams

Photons can carry SAM and OAM. Unpolarized laser light can be converted into circularly polarized beams carrying SAM using a polarizer and quarter-wave plate combination, with a half-wave plate reversing the SAM helicity. Under non-paraxial conditions involving evanescent waves or tight focusing, transverse SAM components orthogonal to propagation emerge in structured fields such as plasmonic waves, waveguide modes, and interferometric systems^{93,181–185}. For OAM generation, vortex beams are typically engineered through several approaches. The pioneering LG modes were generated using cylindrical lens mode converters¹⁸⁶, while alternative solutions include Bessel, Mathieu, and Ince-Gaussian beams^{187–189}. Practical OAM generation leverages

spiral phase plates (SPPs) inducing azimuthal phase gradients, fork-pattern holograms, or SLMs for dynamic control¹⁹⁰. Metasurfaces and liquid-crystal q -plates further enable SAM and OAM design^{191,192}. Beyond spatial domains, spatiotemporal optical vortices (STOVs) carrying transverse OAM orthogonal to propagation have been realized through space-time wavefront engineering^{193–195}. Recently, the plasmonic vortices (PVs) have also attracted considerable attention due to their strong near-field confinement and spin dependence^{196,197}. Metallic nanostructures such as plasmonic vortex lenses^{198,199} and plasmonic vortex nanosieves²⁰⁰ can generate spin-dependent PVs through plasmonic spin-orbit coupling, enabling the generation of beams carrying OAM.

Detection of rotation and enhancement of optical torques

Prior to implementing specific applications, precise measurement and characterization of particle rotation is essential for quantitative analysis of optical torque. Once the rotational rate of particle is measured precisely, the optical torque can be directly determined and characterized²⁰¹. This lays the foundation for extending the application of optical torque across diverse fields. Generally, particles with sizes exceeding the diffraction limit can be tracked via high-spatiotemporal-resolution cameras. This universal method can be used for any material particle and excels for orbital motion characterization but requires particle asymmetry for reliable spin detection. For sub-diffraction nanoparticles (e.g., metallic nanoparticles), dark-field illumination⁶² amplifies scattering signals to enable visualization. Meanwhile, temporal resolution extensions such as stroboscopic illumination¹²⁸ or image post-processing compensates is needed for camera frame-rate limitations. For high-frequency rotation (e.g., GHz-range vacuum levitation), fast photodetectors can be used to overcome the limitations the fast rotation rate of highly spherical or small particles. For birefringent particles modulate beam polarization. Conversion to intensity signals via polarizing beam splitters enables precise angular tracking¹²⁸. Irregularities in spinning particles induce periodic intensity variations in forward/backscattered trapping or auxiliary laser beams, which can be monitored via photodetectors⁶⁰. The rotation of the particle can also be monitored via the rotational Doppler effect²⁰² and orientation-dependent luminescence^{203,204}, where the emission spectral shifts in

anisotropic fluorophores can be used to track the rotational motion.

Measurement of particle rotation serves as the foundation for applications, while enhancement is the key step toward enabling effective implementation. It is necessary to amplify the optical torque before applying it to practical applications, due to the relatively small magnitude of optical torque²⁰⁵. The most straightforward method is to directly increase the intensity of the laser power. However, blindly increasing the laser power to enhance the optical torque would cause additional thermal issues or damage problems, especially for metallic or biological objects. Therefore, optical methods involving interactions between light and objects were developed. To maximize optical force and torque on arbitrary micro- and nanoscale objects, a numerical framework for designing vector-field illumination via computational inverse design was proposed. A 20-fold enhancement in optical torque on a plasmonic nanoparticle was realized²⁰⁶. Rahimzadegan et al. identified and analyzed the contributions of different light-matter interaction channels to optical torque on isotropic particles. They showed that the optical torque can be decomposed into two parts: one arising from electric interactions and the other from magnetic interactions. By analyzing the contributions from each channel, they defined that the maximum optical torque can be achieved when the particle is in the critical coupling regime that the radiative loss equals the nonradiative loss. Under the optimal condition, they derived analytical expressions for the maximum of optical torque, providing a framework for determining the maximum achievable torque in any given scenario²⁰⁷. By using optimal structures and incident fields, the optical torque can approach the upper bounds²⁰⁸ as shown in Fig. 7(a). Recently, Shi et al. found that giant positive and negative optical torques can be induced in a triangular prism with the optical gain²⁰⁹. The positive and negative optical torques can be enhanced over 800 and 200 times larger than the ordinary lossy counterparts. As shown in Fig. 7(b), the enhancement of positive and negative optical torques can be achieved from the superhybrid mode, which is composed of electric toroidal dipoles and magnetic multipoles. As for particle clusters, the optical torques can be enhanced conspicuously by the strong mutual scattering²¹⁰. In addition to optical methods, mechanical and chemical approaches can also be employed to enhance light torque^{211,212}. Geng et al. proposed a giant optical torque

which is transferred to the target by rotating the ring resonator connected with it. Since the torque is determined simultaneously by the optical force amplitude and force arm, both of them were enhanced with the utilization of a ring resonator. The force arm can be increased efficiently by the radius of the ring resonator and the force could be enhanced by selecting the incident frequency detunes from the resonance center of the ring. Results show that the optical torques can be 3 orders larger than those obtained using the orbital and spin angular momenta of light at the same incident level²¹². Optical torques can also be enhanced in dye-doped nematic liquid crystals, benefiting from the two-photon effect²¹³.

Physical applications

The optical torque has the ability to rotate the microscopic matter^{214–216}. An apparatus called "optical torque wrench"^{178–180} was proposed to measure the instantaneous torque applied to the matter. The instantaneous torque is equal in magnitude but opposite in direction to the rate of alteration in angular momentum of the trapping beam as it traverses through the matter. This framework is applicable for quantifying the rotational Brownian motion of the entrapped matter and evaluating the angular trap stiffness²¹⁷. The optical torque wrench can also facilitate the characterization of micrometer- and nanometer-scale particles by allowing for a correlation between their geometrical properties and measured torques²¹⁸, which is beneficial to promote the development of micrometer- and nanometer-scale particles in different practical applications, such as nanomedicine²¹⁹, biosensors²²⁰, catalysis²²¹, imaging techniques²²², etc.

The particle clusters propelled by optical torque also find utility within microfluidics^{9,223,224}. The rotational motion of these particles induces a flow within the encompassing fluid medium forming an optically driven pump. By strategically situating the rotating particles proximal to the confines of two-channel walls, a cumulative fluidic flow ensues along the channel's length. Modulating the rotational direction of the particles can effectuate a reversal in the fluidic pumping direction. As depicted in Fig. 8(a), when the spinning particles are in close proximity to the channel wall²²⁵, the resultant pumping effect yields a maximum flow velocity of $8.3 \mu\text{m}\cdot\text{s}^{-1}$. This device is engineered for precise conveying minute liquid volumes. However, the presence of a microfluidic channel constrains its applicability within certain systems. This limitation has been mitigated by sub-

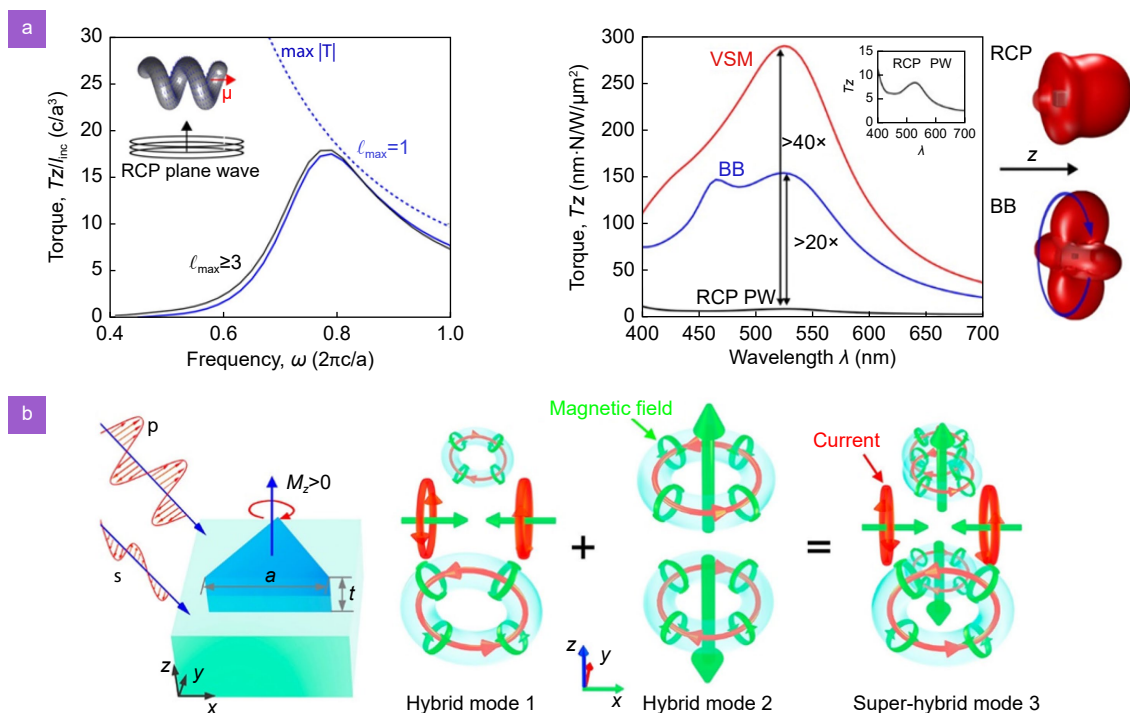


Fig. 7 | Optical torques enhancement. (a) Optimization of structures and incident fields to enhance optical torques. After optimization, the helical structure can achieve a larger optical torque, and the incident field can provide a 20–40 times improvement. (b) Enhancing positive and negative optical torques through superhybrid mode. The superhybrid mode is composed of electric toroidal dipoles and magnetic multipoles. Figure reproduced with permission from: (a) ref.²⁰⁸, 2018 American Chemical Society; (b) ref.²⁰⁹, 2022 American Chemical Society.

stituting particle rotation with an optical vortex²²⁶, resulting in an enhanced operational scope.

Due to the action of optical torque, non-spherical particles tend to align along the linear polarization direction of the laser field. When the laser polarization rotates, the particle alignment follows accordingly^{31,227,228}. If a particle deviates from the polarization direction, it undergoes angular oscillations around the equilibrium position. Tong et al. experimentally demonstrated the optical alignment and rotation of individual plasmonic nanostructures using a single linearly polarized near-infrared laser beam. The results show that silver nanorods and gold nanoparticle dimers align along the laser polarization due to their higher polarizability along the long axis, whereas silver nanowires unexpectedly align perpendicular to the polarization³⁴. Leveraging angular oscillations, Lamperska et al. developed a novel optical torque measurement platform based on a microbarbell—and quantitatively determined the optical vortex torque through analytical and numerical modeling, achieving higher measurement precision compared to other methods²²⁹. Angular oscillations induced by optical torque offer a new approach for high-sensitivity torque measurement and mechanical sensing at the micro- and nanoscale³⁵.

By studying the rotational behavior of nonspherical particles in a vacuum^{230,231}, it is found that different polarizations of light can induce different rotational motions of nonspherical nanoparticles²²⁷. The torsional vibration of nonspherical nanoparticles tends to align with the polarization direction of the incident light. As a consequence, this characteristic was used as an ultrasensitive nanoscale torsion balance²³² as shown in Fig. 8(b), whose torque detection sensitivity reaches 10^{-29} Nm·Hz^{-1/2}. This balance can also facilitate the detection of Casimir torque through a configuration involving an optically levitated nanorod positioned adjacent to a birefringent plate within a vacuum environment²³³, as shown in Fig. 8(c). The Casimir torque acts on the nanorod to minimize the energy when the nanorod is not aligned with the axis of the birefringent plate. The torsional vibration of the nanorod will dynamically change the polarization of the laser beam. By measuring the torsional vibration of the nanorod with the laser polarization, the Casimir torque can be indirectly measured. Xu et al. calculated the Casimir torque to be on the order of 10^{-25} N·m for a silica nanorod with a length of 200 nm and a diameter of 40 nm, which was levitated by a 100-mW OT in a vacuum at 10^{-7} torr. The optically levitated silicon nanorod can

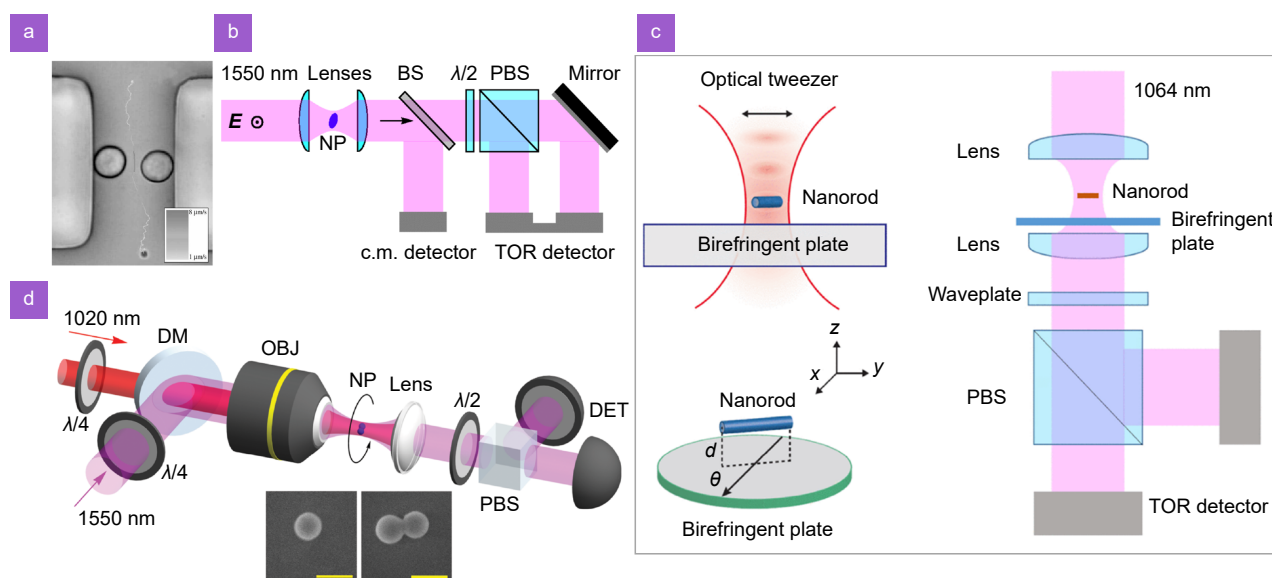


Fig. 8 | Physical applications of optical torques. (a) Diagram of the optically driven pump for generating flow within a microfluidic channel. The pump consists of two counter-rotating birefringent vaterite particles, demonstrating the ability to displace fluid within microchannels. (b) Experimental diagram of the ultrasensitive nanoscale torsion balance. A nanodiamond is levitated by a tightly focused linearly polarized laser beam. Since the torsional vibration of the nanodiamond will change the polarization of the laser beam, the torsional vibration and center-of-mass motion of the nanoparticle can be detected with a polarizing beam splitter and a balanced detector. (c) Schematic diagram for the measurement of the Casimir torque. The Casimir torque is measured by measuring the torsional vibration of the nanorod with the laser polarization. (d) Experimental schematic of the dual beam torque sensor. The motion of the trapped nanoparticle was monitored with the trapping laser. Figure reproduced with permission from: (a) ref.²²⁵, 2008 SAGE Publications Ltd; (b) ref.²³², 2016 American Physical Society; (c) ref.²³³, 2017 American Physical Society; (d) ref.²³⁵, 2020 Springer Nature.

also serve as a sensor to probe structured transverse OAM²³⁴. Furthermore, a dual-beam torque sensor²³⁵, which is based on an optically levitated nanosphere or nanodumbbell^{36,236} in vacuum, was proposed to achieve a sensitivity of $(4.2 \pm 1.2) \times 10^{-27} \text{ Nm} \cdot \text{Hz}^{-1/2}$. As depicted in Fig. 8(d), the nanomotor is levitated in a vacuum using a tightly focused 1550 nm laser through an objective lens. A 1020 nm laser is utilized to apply an external torque to the nanomotor. It is noteworthy that a remarkable rotation speed exceeding 5 GHz was also demonstrated. Optically levitated particles demonstrate great potential for applications in precision measurements^{237,238} and quantum mechanics²³⁹.

Biological applications

Since the invention of OTs, the optical force has been widely used in biological applications. For instance, OTs are used to enable precise force measurements at the molecular level²⁴⁰, manipulate the biomacromolecule²⁴¹, facilitate the study of individual molecules in real-time²⁴² and so forth. The advance of optical torques has further expanded the biological applications of OTs. It is well known that DNA molecules carrying genetic informa-

tion are twisted into coils due to the biological torques. The biological torques are generated by the movement of enzymes. Although the biological torques are very tiny, i.e., at the piconewton-nanometer level, they can be measured using an angular optical trap composed of a nanofabricated quartz cylinder acting as a "handle" that securely grasps one end of a DNA strand²⁴³, as shown in Fig. 9(a). Biological torques of around 10 piconewton-nanometers were measured. It was further determined that the biological torques can regulate transcription rate and pausing²⁴⁴.

The isolation and purification of bioparticles play a crucial role in advancing disease diagnostics and therapeutics. Microfluidics²⁴⁵, acoustics²⁴⁶ and optical force²⁴¹ are extensively used to separate nanoparticles and biomolecules with different diameters or refractive indices. However, sorting label-free submicron particles that have similar volume and refractive index but distinct shapes presents formidable challenges for these techniques. In contrast, optical torque is shape-dependent and is well-suited for separating particles with different shapes. Shi et al. proposed a strategy to use a sawtooth-like light field to induce shape-dependent optical torques

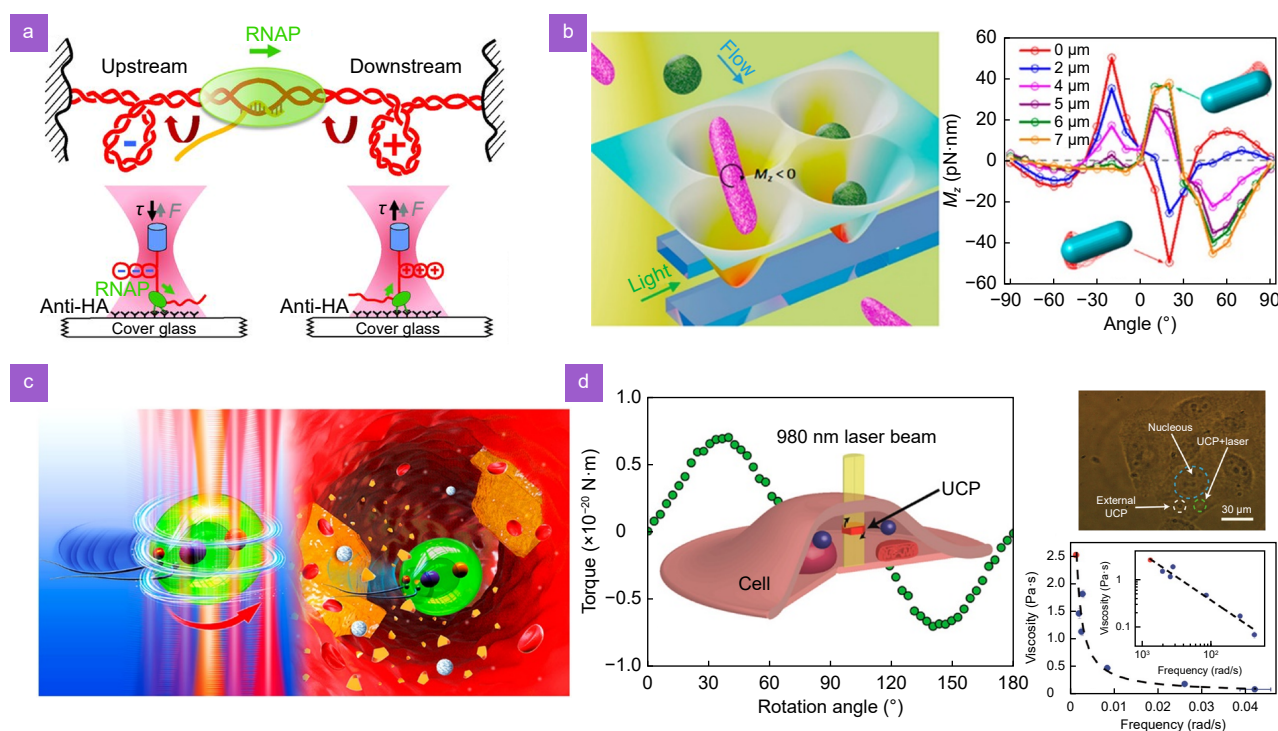


Fig. 9 | Biological applications of optical torques. (a) Schematic diagram for measurement of biological torque by optical torque. Using optical trap to grasp the end of a DNA strand, DNA's torques were measured. (b) Illustration of sorting and dynamics of bacteria in the optofluidic chip. Sorting of unstained bacteria with different shapes was realized based on the hotspots impose different optical torques on the particles according to their shapes. (c) Illustration of the *Chlamydomonas reinhardtii* micromotors. The micromotor's locomotion can be carefully controlled, exhibiting the capabilities to perform multiple tasks. (d) Estimation of the intracellular dynamic viscosity. A UCP rotates inside a HeLa cell, and viscosity as a function of the rotation frequency was measured. Figure reproduced with permission from: (a) ref.²⁴³, 2013 American Association for the Advancement of Science; (b) ref.²⁴⁷, 2019 American Chemical Society; (c) ref.²⁵², 2020 American Chemical Society; (d) ref.²⁷, 2016 American Chemical Society.

on particles²⁴⁷, as demonstrated in Fig. 9(b). The spherical *Staphylococcus aureus* (*S. aureus*) and rod-shaped *Escherichia coli* (*E. coli*) have completely different dynamic behavior inside the optofluidic chip. The *S. aureus* was stably trapped in the hotspots of the light field, while *E. coli* escaped from the chip with efficiencies of 95% and 97%. It is worth mentioning that the rod-shaped bacteria are subjected to different torques at different angles and positions, which leads to their escape behavior.

Biological materials have the unique characteristics of self-repair, self-assembly and high biocompatibility²⁴⁸. Therefore, controlling the natural cells and their derivatives as biological micromotors to perform complex and special tasks is a frontier direction in microrobotic research. Due to their small size and remarkable capabilities, biological micromotors offer an efficient means of noninvasively navigating into confined and challenging biomedical microenvironments²⁴⁹ that are typically inaccessible using conventional medical tools. While magnetic force and phototaxis have been proven to be effective

methods for manipulating micromotors^{250,251}, their success heavily relies on the specific properties of the motor materials. Optical force-based manipulation represents a universal approach for controlling micromotors, as long as there exists a difference in refractive index between the motors and their surrounding environment. Xin et al. showcased living and multifunctional micromotors that utilize optical force and torque on *Chlamydomonas reinhardtii*²⁵², as depicted in Fig. 9(c). Through precise control over the movement and rotation of *Chlamydomonas reinhardtii* cells, it is possible to indirectly manipulate biological targets and disrupt biological aggregates. These biological micromotors offer an active actuation platform with numerous *in vitro* biomedical applications^{253,254}, including medicine delivery and release, target manipulation, and the removal of biological aggregates.

The optical manipulation of small particles is a useful tool in probing fluid properties at the microscale²⁵⁵. The rotation of microscale particles can be used to probe lo-

cal viscosity²⁵⁶. The viscosity information of the medium can be obtained by utilizing the relationship between the transition time of particles to a steady state and the environmental dynamic viscosity. Arita et al. conducted measurements of the viscosity of air, carbon dioxide, and argon through the recording of the terminal rotation velocity and the associated polarization alteration of the incident light²⁵⁷. Due to the noninvasive characteristic of optical torques, optical torques are also used to measure the viscosity of different body fluids, such as tears²⁵⁶, intracellular fluid²⁵⁸, etc., providing a good technical means for the development of biology. It has been proved that the upconverting hexagonal particle can be driven to its stable orientation at which the optical axis of the upconverting particle orientates parallel to the electric field vector (Fig. 9(d)) by optical torques²⁷. The time-resolved single particle polarized spectroscopy was used to monitor upconverting particles in real time for the determination of the transition time. The static and dynamic cytoplasmic viscosity were estimated by this optical torque-assisted method²⁷. The viscosity values are comparable to the values in published literature after considering experimental errors.

Conclusions and outlook

In summary, developments of both theories and techniques of optical torques are advancing the field of optical manipulation. The emergence of many practical applications, especially biological ones, further proves the broad prospect of optical-torque-based manipulation. Despite being proven effective tools for non-contact spatial manipulation of micro/nano objects, including living biological samples, optical torques still possess certain limitations. For instance, the optical forces and torques decrease significantly as the size of the objects decreases, resulting in low manipulating speeds. Additionally, the functionality of optical forces and torques is relatively simple, primarily encompassing capture, movement, rotation, and positioning. By integrating optical forces and torques with a variety of micro and nano technologies, including optofluidic technology²⁵⁹, optothermal technology^{260,261}, microscopy and spectroscopy technology^{262–264}, and more, it becomes possible to perform more precise and complex manipulation of micro/nano-scaled objects²⁶⁵, and obtain a more comprehensive range of information²⁶⁶. This is highly desired for applications of micro-bioreactors, chip diagnostics, and microprocessing systems.

The optical force and torque come from the interaction between the light field and particles. Therefore, special light fields can bring new opportunities for optical force and torque manipulation. The recent emergence of singularities such as bound states in the continuum (BICs)^{267–270} and exceptional points (EPs)^{271–275} has gained substantial attention as a complementary route to optical force and torque²⁷⁶. BIC modes have high-Q resonances and enable the enhancement of optical forces and torques²⁷⁷, which is beneficial to the on-demand control of light vehicles. On the other side, vector EPs can be used to generate a superchiral gradient field to induce extremely strong chiral gradient forces^{278,279}. Therefore, we believe that the EP field can be further exploited to exert optical torques on objects, which may stimulate exciting applications^{280,281}.

As the burgeoning development of deep learning^{282–285}, optical design and inverse design with large amounts of data and degrees of freedom become feasible and easier^{286–288}. The deep learning approach has achieved state-of-the-art results in the prediction of the optical performance of nanophotonic devices^{289,290} and the nanophotonic inverse design^{291,292}. Recently, neural networks were also demonstrated to improve the speed of optical force calculation^{293,294}. However, there have been few reports of reverse engineering of optical force or torque using deep learning. When the fast and accurate reverse design of optical force and torque can be achieved, it will also be possible to freely customize the movement mode and path of objects, paving an avenue toward optical manipulation.

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