Review Article

ADVANCED PHOTONICS

# Torsion pendulum driven by the angular momentum of light: Beth's legacy continues

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**Abstract.** The optical angular momentum is ubiquitous to the science of light, especially whenever the polarization state and the spatial distribution of the phase are involved, which are most often associated with the spin and orbital parts of the total angular momentum, respectively. Notably, the independent introduction of these two contributions to the total optical angular momentum was accompanied by suggestions regarding the possible detection of their mechanical effects using a torsion pendulum. Today, the classical and quantum mechanical aspects of spin and orbital angular momentum of light and their mutual coupling remain active research topics offering exciting perspectives for photonic technologies. Our brief historical overview shows how the torsion pendulum has accompanied scientific advances on mechanical effects based on the angular degrees of freedom of light since Beth's pioneering contribution published in 1935.

Keywords: light; polarization; optical angular momentum; optomechanics.

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## 1 Historical Context

The present paper is dedicated to the 30th anniversary of Allen et al.'s paper[1] that kickstarted a fruitful research topic related to the orbital angular momentum of light. Interestingly, the latter work not only identified that a Laguerre–Gaussian paraxial field with azimuthal integer order $l$ carries $l\hbar$ angular momentum per photon of an orbital nature, $\hbar$ being the reduced Planck constant. Inspired by Beth's spin angular momentum experiment,[2] it also suggested a way to detect and measure it using a torsion pendulum equipped with a Laguerre–Gaussian mode converter. This motivates the present aim at highlighting the place taken by the torsion pendulum since the advent of the concept of angular momentum associated with the polarization state of light, which dates back to Sadovskiĭ's work[3] in the late 19th century, according to Vulf'son.[4] The previous motivation is further supported by the fact that, a few years before Sadovskiĭ's work, Righi[5] mentioned an experimental attempt to detect the mechanical effects of circularly polarized waves on matter using a torsion pendulum, yet unsuccessful.

Independently from earlier works from Sadovskiĭ, Poynting conjectured from a mechanical analogy that the torque per unit surface exerted on an absorbing target by a circularly polarized (CP) paraxial light field equals the optical energy per unit volume multiplied by $\lambda/(2\pi)$ with $\lambda$ the optical wavelength and is oriented along the propagation direction of light.[6] Said differently, noting that the optical energy per unit volume corresponds to the optical pressure, Poynting suggested that the optical torque and force surface densities are proportional with a proportionality factor $\lambda/(2\pi)$, which highlights $\lambda/2\pi$ as the intrinsic lever arm of light. Recalling that the optical energy per unit volume in vacuum is $I/c$, where $I$ is the optical intensity and $c$ is the speed of light, Poynting thus stated that a paraxial light beam with power $P$ propagating along the $z$ axis and impinging on a perfectly absorbing target exerts on it a total torque $\mathbf{\Gamma} = (\sigma P/\omega)\mathbf{z}$, where the $\sigma = \pm 1$ refers to the left/right-handedness of the circular polarization state, $\omega$ is the optical angular frequency, and $\mathbf{z}$ is the unit vector along the $z$ axis. Since Einstein extended Planck's quantization of energy to the light by stating that the quantum of optical energy is $\hbar\omega$, Poynting's suggestion is reformulated at the level of a quantum of energy as the fact that the projection of the photon spin angular momentum associate to free space CP light field along its propagation direction is $\sigma\hbar$, where the $\sigma = \pm 1$ defines the photon helicity.

In his paper,[6] Poynting also suggested the use of a torsion pendulum for the mechanical detection of the torque arising from nondissipative rather than dissipative spin angular momentum transfer from light to matter. This is done using a linearly

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polarized (LP) light beam passing through a quarter-wave plate (QWP) whose neutral axes are oriented at $\pm\pi/4$ from the incident polarization direction. Aware that the mechanical detection is challenging, Poynting proposed to illuminate with an LP light beam a series of QWPs suspended by a torsion wire, intercalating between each of them a fixed QWP hold by external means to restore the initial linear polarization state before light passes through the next suspended wave plate, as depicted in Fig. 1(a). The use of $N$ suspended QWPs and $N-1$ fixed ones enables the incident light to exert a total torque oriented along the torsion wire with magnitude $NP/\omega$, provided that the optical axes of two subsequent QWPs are mutually orthogonal, while the sign of the torque depends on the $\pm\pi/4$ orientation of the incident linear polarization with respect to the slow axis of the first QWP. Such a trick nevertheless left Poynting rather dubious about a possible experimental success, as he reported "even with such multiplication, my present experience of optical forces does not give me much hope that the effect could be detected, if it has the value suggested by the mechanical model."[6]

It was not until 1935 that Beth announced the successful detection of the (spin) angular momentum of light[7] from a variant of the latter approach. In fact, Beth used a circular instead linear incident polarization state, a half-wave plate (HWP) instead of a QWP as the suspended birefringent element, and a reflective rather than transmissive multiplication approach owing to a fixed set of a QWP and a mirror, as illustrated in Fig. 1(b). In doing so, Beth obtained a multiplication factor $N = 4$, and the torque sign is controlled by the incident circular polarization handedness. The added value of Beth's apparatus is that both wave plates do not require either absolute or relative orientation of their optical axis, at least when using incident CP light. This allowed Beth not only to detect the sought-after mechanical effect[7] but also to measure it in the near-infrared domain with nominal wavelength of 1.2 $\mu$m. This was done by placing the torsion pendulum apparatus in vacuum ($10^{-9}$ bar) and assessing the differential angular deviation of the pendulum around its revolution axis obtained under in-phase and out-of-phase optical forcing. This is thoroughly reported in Ref. 2, where the dependence of the optical torque on wavelength and ellipticity of the incident light is studied.

In short, using a torsion pendulum consisting essentially of a 25.4 mm diameter HWP suspended from a 25 cm long quartz fiber, Beth demonstrated experimentally by mechanical means, up to a few percents precision, that the angular momentum carried by free space elliptically polarized paraxial light along the direction of propagation is $s_3\hbar$ per photon, where $s_3$ is the reduced third Stokes parameter.[8] Beth's experiment, which was quantitatively confirmed by Holbourn a few months later using a transmission scheme associated with $N = 2$,[9] has entered the history of sciences and is chosen as the starting experimental milestone of the present contribution.

Remarkably, the experimental demonstration of spin angular momentum transfer to matter was in fact achieved, albeit unnoticed, by Righi in 1883 when he observed and analyzed frequency shifts experienced by light as it passes through rotating optical elements.[10] These frequency shifts, now known as rotational Doppler frequency shifts, have been also identified in the presence of orbital angular momentum transfer[11] and in the presence of both spin and orbital contributions.[12] Rotational Doppler frequency shifts are indeed the signature of the rotational mechanical action of light on matter and are the angular counterpart of Doppler frequency shifts associated with light-matter linear momentum transfer. This was pointed out by Henriot[13] in 1934 and subsequently discussed by Atkinson[14] shortly before Beth's announcement.

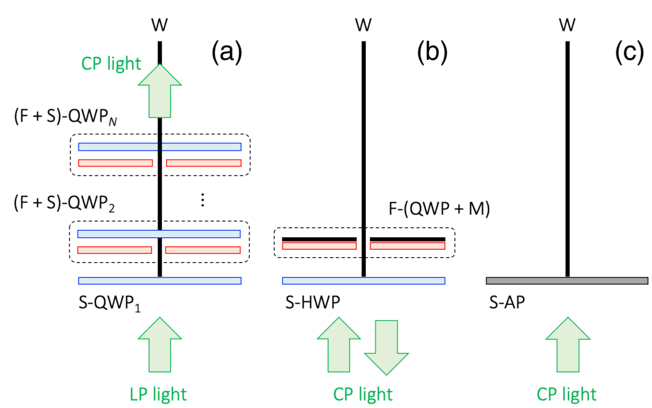


**Fig. 1** Selection of a set of pioneering sketches of torsion pendulum arrangements enabling mechanical detection of the transfer of $\pm N\hbar$ spin angular momentum per photon, $N$ integer, from fully polarized incident beam. (a) Poynting's suggestion based on the use of $2N-1$ QWPs and LP incident light within a nondissipative process. Prefixes F and S hold for fixed and suspended wave plates, respectively. (b) Beth's experimental approach providing $N = 4$ using a CP incident beam within a nondissipative process. (c) Carrara's experimental approach providing $N = 1$ using a CP incident beam within a dissipative process. W, torsion wire; M, mirror; AP, absorbing plate.

## 2 Microwave and Radiowave Experiments

Several years after Beth's and Holbourn's experiments dealing with nondissipative spin angular momentum transfer from light to birefringent media, Carrara reported a dissipative variant of it where the incident angular momentum from CP field is absorbed by the suspended element, as depicted in Fig. 1(c), which corresponds to $N = 1$. The experiment was performed in the microwave domain at 9.36 GHz frequency using an absorbing screen made of two subunits placed at the output of a waveguide.[15] The decrease in frequency by 6 orders of magnitude compared to Beth's experiment implies an increase in the applied torque by a factor of $10^6$ for a given input power, which makes *a priori* the detection of the effect much easier. Carrara also reported on the nondissipative approach using a reflective scheme. Indeed, by adapting the nature and the relative distance between the two subunits, the suspended system behaved as an effective suspended eighth-wave plate or QWP endowed with a reflective output facet, which, respectively, corresponds to $N = 1$ for incident LP wave (provided an appropriate polarization direction) and $N = 2$ for incident CP wave. Nevertheless, even though the mechanical detection of angular momentum transfer was successful and the observed angular deviation of the torsion pendulum corresponds to the expected order of magnitude, its quantitative assessment remained an issue. In particular, the ratio between the 3.2 cm wavelength and the transverse characteristic size of the suspended element (in the shape of a disk or a square) being near unity, the knowledge of the geometrical section of the absorber is not sufficient to determine with precision the amount of angular momentum transferred. This issue was addressed analytically by Toraldo Di Francia, who also pointed out the potentially important consequences of even a small deviation from the ideal circular polarization state on the applied torque.[16]

The latter diffraction effects associated with finite beam size effects can be avoided using waveguides, which attracted attention in the 1960s. According to Allen,[17] the first experimental demonstration of the mechanical effect of angular momentum transfer using a torsional pendulum placed in a waveguide, although not published, was made by Lahart. This experiment consisted in measuring the angular displacement of a suspended macroscopic dipole placed in the course of a CP microwave propagating inside a metallic waveguide. An experimental demonstration of it was reported by Steven and Cullen, who provided a precise measurement of the angular momentum $\sigma\hbar$ per photon carried by a CP transverse electric (TE) mode $\mathrm{TE}_{11}$ in a cylindrical waveguide.[18] In addition to this fundamental experimental demonstration, Steven and Cullen proposed an application of it as a power meter based on electromagnetic radiation torque at the frequency of ~35 GHz. This extended previous concept of power meters based on electromagnetic radiation force.[19]

Independently from previously mentioned works, Lahart's early attempt was picked up by Allen, who reported a full study at 9.3 GHz frequency.[17] For his study, he replaced the torsion wire with a needle pivot support or liquid drop suspension technique and used a 1.65 cm long (i.e., almost half-wavelength long) dipole made of aluminum foil. It was thus a rotating rather than an oscillating device, which appears today as a pioneering work in the field of optically induced rotational dynamics of objects, a subject that has blossomed with the advent of optical tweezers.[20] Allen adapted his apparatus to situations that correspond to $N = 1$ and $N = 2$ by working in transmission and reflection, respectively. However, the observed ratio 1/2.8 between the corresponding steady rotation frequencies under constant irradiation power, assessed by monitoring the rotational frequency shifts rather than the rotation of the dipole itself, was surprisingly far from the expected value of 1/2. Allen indeed reported that "the discrepancy, as yet unaccounted for, is much too large to be attributable to experimental error."[17] This problem remained unresolved for almost three decades before Kristensen et al.[21] revisited this experiment, this time with a torsion pendulum.

The starting point was to notice the crucial role of the angular momentum transfer cross section and possible mode conversion processes, which alter the spin-only picture for CP light in free space. In fact, in circular waveguides, TE modes labeled as $\mathrm{TE}_{mn}$ (or $\mathrm{H}_{mn}$) with integers $m$ and $n$ referring to azimuthal and radial indices, when CP, carry $\sigma m\hbar$ total angular momentum per quantum of energy for $m > 0$;[18] see also Ref. 22 for detailed calculation. Elaborating a carefully designed setup, Kristensen et al.[21] solved the problem faced by Allen and also extended the experimental approach to higher-order modes ($m > 1$). However, although this work highlighted the role of spin and orbital contributions in the transfer of electromagnetic angular momentum to matter, it was not until 2014 that a pure orbital experiment was performed in the microwave domain. This was done by Emile et al.[23] at 870 MHz frequency based on an earlier proposal by Vul'fson.[4] This proposal results from the analysis of the energy and angular momentum fluxes radiated by a rotating dipole, which was carried out to illustrate that these fluxes may not be collinear in the case of nonplanar waves and also to motivate their experimental evaluation.[4] In particular, outside the near-field zone, the spin and orbital angular momenta fluxes radiated by a rotating dipole flow perpendicularly to the plane of rotation and the in-plane angular momentum is purely orbital in nature.[23,24] The mechanical detection and measurement of the latter was achieved according to the apparatus depicted in Fig. 2(a), where a turnstile antenna is placed in the plane and in the center of a suspended ring absorber. The turnstile antenna radiates like an uniformly rotating dipole when the two orthogonal dipoles radiate in phase quadrature.[23] Alternatively, a source radiating angular momentum experiences a torque, as expected from angular momentum conservation.[18,26] This has been experimentally detected by Chute[25] in the radiowave domain at 14 MHz frequency, using a rotating dipole made of two loop antennas [see Fig. 2(b), where a turnstile antenna is depicted as an alternative option discussed in Ref. 25]. Noteworthy, beyond the fundamental aspect of the latter demonstration, the concomitant reaction torque exerted on the radiating antenna itself has been proposed to control the orientation of space vehicles.[25,27]

To conclude this section, we recall that the principle and realization of contactless mechanical torque induced by rotating electromagnetic fields date back to the end of the 18th century with the advent of the asynchronous electric motor. This was noticed in a few works dealing with microwave experiments; see, for instance, Refs. 26 and 28. The analogy is indeed striking, since a rotor absorbing a power $P$ from rotating fields generated by an $m$-pole pair machine experiences a radiation torque $mP/\omega$.[26] Recalling the quantum description of the latter classical formulation, which states that the field energy quantum carries an angular momentum of $m\hbar$, this is an interesting opportunity to rethink the way we look at a photon—usually associated with the optical domain—when it comes to everyday electric motors.

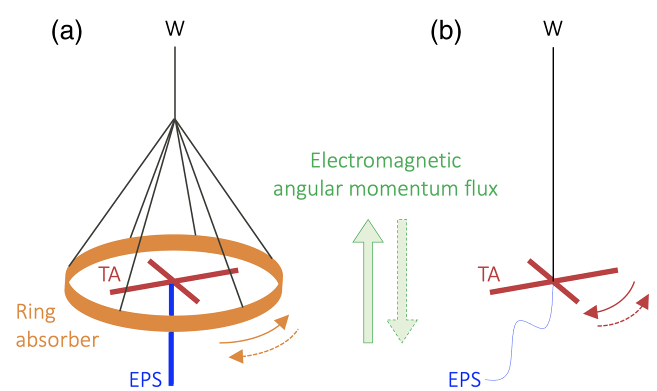


**Fig. 2** Illustrative sketches of torsion pendulum experiments dealing with the study of the mechanical effects of angular momentum radiation from a rotating dipole. (a) Apparatus to detect and measure the in-plane orbital angular momentum of the field from dissipative angular momentum transfer to matter in the microwave domain from a cotton wire pendulum.[23] (b) Apparatus to detect and measure the torque exerted on the source itself in the radiowave domain from a steel wire pendulum.[25] The electromagnetic angular momentum flux flows up or down depending on the direction of rotation of the dipole; see the corresponding mechanical motion indicated by solid/dashed arrow. TA, turnstile antenna; EPS, electric power supply connected to the antenna that is (a) fixed to a rigid post or (b) left free to rotate.

## 3 Optical Experiments

Despite the advent of lasers in the 1960s, Beth's and Holbourn's experiments were not replicated for decades in the field of optics, although they inspired the development of rotational optical manipulation of matter, as discussed in Section 4. This was done by Delannoy et al.[29] in the mid-infrared domain using a 10.6 $\mu$m wavelength $CO_2$ laser with a power of several tens of watts and a HWP suspended by a spider silk thread acting as a torsion wire. The obtained optical torque reached $10^{-12}$ N · m level, which corresponds to an increase by 3 orders of magnitude compared to the original experiment.[2] The observation of large angular deviations, up to 1 deg, allowed direct real-time monitoring and accurate measurement of the expected uniform angular acceleration of the suspended macroscopic device as a result of stationary spin angular momentum transfer from light to matter. Recently, Yasuda and Hatakeyama[30] reported a torque sensitivity level of $2 \times 10^{-17}$ N · m close to the thermal noise limit of the apparatus owing to the use of two torsion pendulum in series, one of them acting as a vibration isolator. This device was quantitatively tested by driving the pendulum at its resonance frequency via the absorption of CP light beam at 852 nm wavelength and ~0.1 W optical power.

Besides these modern macroscopic experimental demonstrations based on the original strategies depicted in Figs. 1(b) and 1(c), alternative torsion pendulum strategies have also been developed at much smaller spatial scales both for nondissipative and dissipative angular momentum transfer processes. This is illustrated in Fig. 3 in two situations where the torsion wire itself undergoes polarization-controlled mechanical effects driven at resonance as a result of time-dependent angular momentum transfer from light to matter. Figure 3(a) refers to the work by He et al.,[31] where the torsion wire is a birefringent waveguide. Optical torque sensing is mediated by the position-dependent optical coupling between a static waveguide [not shown in Fig. 3(a)] and a nanobeam fixed perpendicularly to the suspended torsion waveguide. Indeed, as the nanobeam is set into motion by light-induced torsion of the suspended waveguide, the gap between the nanobeam and the static waveguide varies, which leads to intensity modulation detected at the output of the static waveguide. Optical torque below $10^{-18}$ N · m at 0.1 mW power level and ~1.5 $\mu$m wavelength is measured. Such an optomechanical fully integrated approach was then extended to optical nanofibers by Fenton el al.[32] where, according to the authors, spin-based torsional optomechanics relies on optical angular momentum transfer by absorption rather than conversion. Torsional dynamics driven by near-infrared pump light induces time-dependent strain-induced birefringence that is monitored by analyzing the polarization state changes experienced by a probe light field guided through the nanofiber; see Fig. 3(b). Experimental investigations of torsional optomechanics of suspended waveguides now go beyond the detection and measurement of the mechanical effects of optical angular momentum transfer, for instance toward the elaboration of quantum experiments in the macroscopic world. This requires preparing the system as close as possible to its motional ground state, and one can mention very recent experimental attempts using either passive[33] or active[34] feedback approaches.

Notably, spin-driven torsional optomechanics of waveguides does not tell *a priori* about the spin or orbital nature of the transferred angular momentum from the propagating optical waves to the waveguide through which it propagates. In fact, anisotropic and/or inhomogeneous media can couple the polarization state of light with its spatial degrees of freedom, thereby redistributing the total angular momentum into its spin and orbital parts. This has been addressed numerically in the framework of torsional optomechanics of suspended silicon waveguides.[35] As far as the optical orbital angular momentum is concerned, this brings us to the work of Allen et al.[1] that formally extended Beth's torsion pendulum to the spatial degrees of freedom of light, as discussed hereafter.

Allen et al.[1] indeed proposed an orbital analog of the spin Beth's experiment to detect and measure the mechanical effect of the nondissipative transfer of orbital angular momentum from a paraxial Laguerre–Gaussian beam passing through a suspended afocal pair of cylindrical lenses; see Fig. 4(a). Such a refractive system reverses the sign of the azimuthal index $l$ of the incident paraxial Laguerre–Gaussian beam, hence depositing $2l\hbar$ orbital angular momentum per photon into the system.[1] The total torque exerted on the suspended system is thus oriented along the torsion wire and has a magnitude $2|l|P/\omega$ whatever the incident polarization state. Interestingly, the question of where does the mechanical effect occur for this two-part system was addressed a few months later by several authors; see Refs. 38 and 39. Still, it was not until 2005 that an experimental attempt in the visible domain was reported by Beijersbergen and Woerdman using the original macroscopic proposal depicted in Fig. 4(a), however unsuccessfully.[36] The authors concluded that the lack of rotational symmetry in the system makes it more sensitive to nonideal conditions, which ultimately prevents systematic errors from being overcome. The dissipative analog of this experiment allows recovering axisymmetry, for instance, using a suspended disk-shaped absorber plate and LP beams to cancel the contribution from spin angular momentum. This is depicted in Fig. 4(b), and its implementation was reported by Emile and Emile.[37]

In the same way that Beth's macroscopic spin-based experiments have been transposed to the field of integrated photonics, several orbital analogs have been discussed, but only theoretically so far to our knowledge. A recent example was reported by Kaviani et al.,[40] who discussed the expected optomechanical

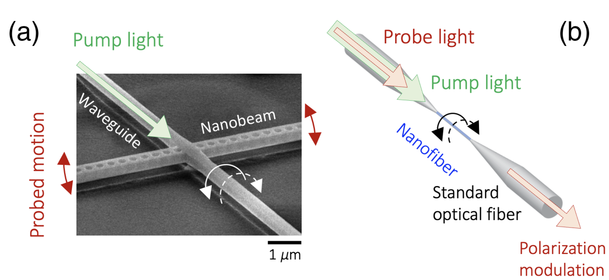


**Fig. 3** Illustration of two kinds of fully integrated optomechanical torsional dynamics experiments driven by a waveguided pump light exciting torsional motion of the waveguide itself. (a) Suspended birefringent silicon waveguide, for nondissipative angular momentum transfer demonstration. Scanning electron microscope image from Ref. 31. (b) Suspended isotropic optical nanofiber (subwavelength diameter) obtained by pulling a standard optical fiber locally molten using a flame brushing technique, for dissipative angular momentum transfer demonstration.[32] In both cases, the torsional dynamics is monitored by optical means via (a) nanobeam motion and (b) strain-induced birefringence; see text for details.

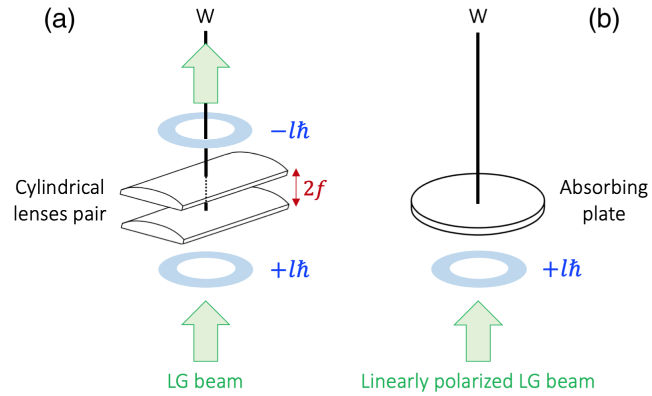


**Fig. 4** Macroscopic torsion pendulum systems for the mechanical demonstration of orbital angular momentum transfer from light to matter. (a) Nondissipative approach consisting of a suspended pair of cylindrical lenses distant by $2f$ with $f$ the focal length, which was proposed in Ref. 1 and implemented in Ref. 36, yet unsuccessfully. (b) Dissipative approach implemented in Ref. 37. The blue rings refer to the doughnut-shaped transverse intensity profile of a Laguerre–Gaussian beam with azimuthal index $\pm l$, which carries $\pm l\hbar$ per photon along the beam propagation direction.

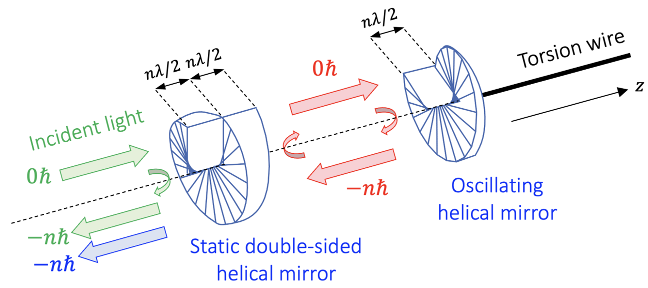


**Fig. 5** Revised illustration of the helical mode cavity design proposed by Battacharya and Meystre[41] (in Ref. 41, the displayed handedness of the helical mirrors do not match the required self-consistency for the building up of a cavity mode and here we also provide the correct orbital angular momentum content for the field inside and outside the optical cavity. Similar issues appear in Ref. 42.) that opened up the prediction of various kinds of entanglements involving light and matter and light–matter.[42–44] All helical reflective surfaces have the same handedness and $n\lambda/2$ step height ($n$ positive integer). The incident field is a Gaussian beam and the colored arrows refer to contributions of various kinds: purely extracavity (green), purely intracavity (red), extracavity arising from intracavity (blue). In the sketched example, on the one hand, the reflection on the oscillating helical mirror removes $n\hbar$ orbital angular momentum per photon along $\mathbf{z}$. On the other hand, the static helical element, which is a partially reflective split-disk mirror with a helical ramp, preserves the orbital state in transmission while its extracavity (intracavity) side removes (adds) $n\hbar$ orbital angular momentum per photon along $\mathbf{z}$ upon reflection. Using helical mirrors with opposite handedness reverses the sign of the orbital angular momentum changes.

performances of a on-chip torsional pendulum driven by optical orbital angular momentum transfer, be it of dissipative or nondissipative origin. Notably, an important contribution was made by Battacharya and Meystre,[41] who demonstrated the possible trapping and cooling of the rotational motion of a massive system to its ground state, considering the case of a 10 $\mu$m radius mirror with 10 $\mu$g. This proposal relies on an optical cavity made of two helical mirrors imparting orbital angular momentum changes for the reflected light, one of them being suspended to a torsion wire, as depicted in Fig. 5.

We note, however, that this approach left open the question of the role of the spatial distribution of the intracavity field when defining the nature and size of the helical mirror for a given operating wavelength, which seems particularly relevant when large values of $l$ are involved. By further exploiting the same cavity design, Battacharya et al.[42] showed that the optical torque exerted on the reflective orbital torsion pendulum can entangle the latter with a cavity mode. Since then, several variants have been discussed theoretically while exploring the manifestation of quantum effects using macroscopic systems. For instance, placing a ferrimagnetic sphere into the cavity, Cheng et al.[43] reported the tripartite entanglement between a cavity mode, the reflective orbital torsion pendulums, and a magnon, whereas Chen et al.[44] showed that replacing the static helical mirror of the original design by a suspended one, light–matter orbital angular momentum transfer can entangle the two reflective orbital torsion pendulums.

## 4 Wireless Optical Approaches

Torsional distortions of material systems caused by the transfer of optical angular momentum are of course not limited to the torsional pendulum as such. In fact, it is sufficient to have a restoring torque, which opposes the optical torque at the origin of the motion. Several experimental demonstrations of wireless torsional optomechanics driven by the angular momentum of light have been reported to date.

An illustrative example is the case of a thin film of liquid crystals, usually a few tens of micrometers thick, interacting with a focused laser beam. Indeed, the spin and orbital parts of the total angular momentum of paraxial light can be transferred independently or simultaneously to liquid crystals by nondissipative means. Liquid crystals, being birefringent viscoelastic fluids, can be set into rotational motion from spin angular momentum transfer as demonstrated by Santamato et al.[45] and Zolot'ko et al.,[46] and torsional dynamics for the collective molecular orientation can take place for incident elliptical polarization state.[47] Notably, the restoring torque can qualified as not being of a purely material origin as it depends on the light-matter interaction. The elastic restoring torque indeed depends on the light-induced orientational state of the liquid crystal. Torsional distortions of liquid crystals can also occur due to orbital angular momentum transfer when the excitation laser beam has a noncircular intensity cross section, as reported by Piccirillo et al.[48] Moreover, these authors also demonstrated that torsional dynamics can also result from the competition between spin and orbital optical angular momentum transfer.[48] However, the orientational viscosity of liquid crystals causes the system to be overdamped, preventing amplification of the oscillatory motion by periodic forcing, which nevertheless enriches the spectral response of the system, which is intrinsically nonlinear.[49]

Another example is that of transparent nanorods optically trapped in liquid by a tightly focused LP laser beam whose polarization azimuth rotates sufficiently faster. As shown by Bonin et al.,[50] this leads to the oscillatory motion of the nanorod orientation in a plane perpendicular to the beam propagation direction. The experimental demonstration of light-induced torsional dynamics of transparent elongated nanoparticles in vacuum came only more than one decade later; see, for instance, Refs. 51 and 52. These works were an important step toward the experimental realization of torsional cooling of nonspherical objects based on the polarization state rather than the spatial degrees of freedom, as had been proposed theoretically.[53,54] The most recent advances bring us even closer to the sought-after ground-state cooling of all 6 degrees of freedom of a levitated nonspherical nanoparticle.[55]

Finally, the wireless situation involving an optical torque that results from the interaction between the spin and orbital degrees of freedom has also been demonstrated experimentally. This was reported in Ref. 56, where a piecewise space-variant anisotropic plate with 6 mm diameter deposited at a bounded air–water interface is shown to behave as a light-driven overdamped in-plane torsional spring as CP light passes through it.

## 5 Beyond Electromagnetic Waves

A notable feature of scalar waves is that a paraxial field propagating along the $z$ axis (toward $z > 0$) and having an amplitude proportional to $\exp[i(-\omega t + kz + l\varphi)]$, where $\omega$ is the angular frequency, $k$ is the wave vector, and $\varphi$ is the azimuthal angle, carries orbital angular momentum. In particular, the ratio $l/\omega$ between the angular momentum and energy fluxes in electromagnetism[1] applies as well in acoustics.[57] Accordingly, the acoustic radiation torque exerted on a material system absorbing a sound wave endowed with a phase singularity with topological charge $l$ according to the preceding expression is $\mathbf{\Gamma} = (lP/\omega)\mathbf{z}$. Its mechanical detection and measurement using Beth's torsion pendulum approach [see Fig. 6(a)] was reported by Volke-Sepúlveda et al.[59] and Skeldon et al.[60] in the audible domain, in the air. The demonstration of a resonant torsional mechanical oscillator driven by acoustic orbital angular momentum transfer was reported only recently.[58] This was also done in the air, however, via a nondissipative process, using an ultrasonic acoustic field carrying zero angular momentum that reflects off a helical mirror imparting nonzero orbital angular momentum to the reflected field, as illustrated in Fig. 6(b).

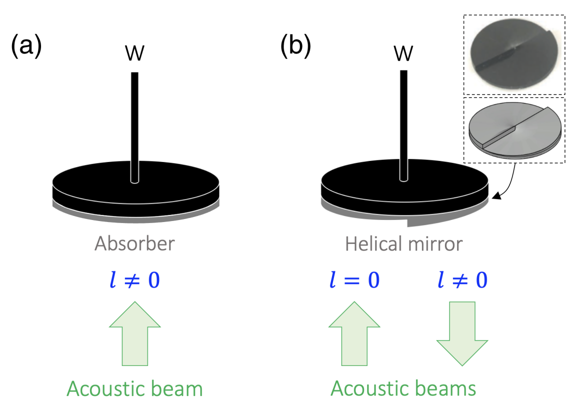


**Fig. 6** Sketches of torsion pendulum arrangements enabling mechanical detection of the transfer of orbital angular momentum from sound to matter by (a) dissipative and (b) nondissipative means. The inset of panel (b) shows the designed (bottom) and fabricated (top) 3D printed helically corrugated plates acting as a reflective acoustic vortex generator used for experimental demonstration.[58]

Interestingly, the wireless torsional dynamics driven by acoustic radiation torque has also been studied for some years in the context of ultrasound elastography, which is a technique used for noncontact quantitative palpation in medical diagnosis. The idea is to transiently twist a soft sound-absorbing medium through irradiation with a focused ultrasonic pulse that generates an orthoradial shear wave.[61,62] These works lay the foundation for a new imaging technique capable of determining the viscoelastic tensor of soft media in a way that goes beyond what can be done by ultrasonic elastography based solely on acoustic radiation forces.

## 6 Summary

Nearly 90 years after Beth's experimental demonstration that light can act mechanically on matter as a consequence of the transfer of spin angular momentum from light to matter, torsional optomechanics driven by the optical angular momentum remains a lively research topic in many respects, as has been discussed here. Notably, the transfer of angular momentum can also be of orbital or spin-orbit origin, depending on the nature of the light–matter interaction involved. In particular, angular momentum-based cavity optomechanics has paved the way for a whole range of attractive quantum mechanical experiments with material systems that are diversifying in nature and size thanks to ever-improving instrumentation and manufacturing technologies.[63] Finally, the exploration of mechanical torsional effects driven by the angular momentum of waves beyond electromagnetic ones has begun with sound waves, which already suggests interesting applications in metrology and biomedical imaging. Beth's legacy is not yet over.

### Acknowledgment

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