Left-handed optical radiation torque

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Optical forces and torques are two mechanical degrees of freedom available to manipulate matter, and form the basis of optical tweezing strategies. In contrast to the Keplerian intuition that objects should be pushed downstream against an incident photon flux, the concept of ‘negative’ optical forces has recently been described and has triggered many developments. Here, we report on the counterintuitive analogues of negative optical forces by demonstrating that circularly polarized Gaussian light beams give rise to torque with opposite sign to that of the incident optical angular momentum. Such a ‘left-handed’ mechanical effect is demonstrated by the use of an inhomogeneous and anisotropic transparent macroscopic medium. Practical difficulties associated with the direct observation of optically induced spinning of a macroscopic object are circumvented via the rotational Doppler effect. These results shed light on spin–orbit optomechanics and equip the left-handed optomechanical toolbox with angular features.

The redirection of a photon flux by a material system is essentially associated with non-conservative optical radiation forces. In particular, negative optical forces occur when the linear momentum of light experiences a net forward scattering that depends on the structure of the incident electromagnetic fields, the properties of the objects and their surrounding environment. Quite naturally, because scattering is a universal feature common to all waves, the concept of negative forces is also found in acoustics. Intriguingly, its angular counterpart has not yet emerged. This concept of negative forces is also found in acoustics and mechanics and equip the left-handed optomechanical toolbox with angular features.

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In practice we used azimuthally patterned birefringent disk-shaped glass slabs with , whereas right-handed ORT takes place when , as shown in Fig. 1c. In addition, the particular case of , corresponds to vanishing ORT, as expected from the rotational invariance around .

A straightforward experimental approach for observing the optical torque would consist of direct observation of the light-induced spinning of a free-to-rotate sample around the -axis, the left-handed nature of the ORT being retrieved from a sense of rotation opposite that prescribed by the incident spin angular momentum. However, considering a transfer of angular momentum per photon that impinges on-axis onto the azimuthally patterned slab will emerge from it with a total angular momentum per photon of , where , and are respectively the spin and orbital contributions. The angular momentum balance thus gives

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A straightforward experimental approach for observing the optical torque would consist of direct observation of the light-induced spinning of a free-to-rotate sample around the -axis, the left-handed nature of the ORT being retrieved from a sense of rotation opposite that prescribed by the incident spin angular momentum. However, considering a transfer of angular momentum per photon, a light beam with power and angular frequency produces a torque of magnitude , so .

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under 1 W visible light illumination. Then, assuming free rotation in an inviscid medium one finds a rotation frequency \( \nu \) that depends on the illumination time \( T \) following \( \nu(T) = \Gamma T/(\pi m R^2) \), where \( m \) is the mass of the slab. According to the sample parameters (the sample is structured over an area of diameter \( d = 4 \text{ mm} \) centred on a disk-shaped glass substrate of radius \( R = 12.7 \text{ mm} \), thickness \( H = 3 \text{ mm} \) and density \( \rho = 2.5 \times 10^3 \text{ kg m}^{-3} \)) one typically obtains \( \nu = 1 \text{ mHz} \) after a three-month illumination at \( P = 1 \text{ W} \), which clearly prevents a realistic experimental implementation.

The practical difficulty of observing the mechanical consequence of the spin–orbit scattering process on matter is circumvented by probing the mechanical effect of the ORT on the light itself. This is implemented using a rotational Doppler experiment \(^{15,16} \) by rotating the slab at controlled angular velocity \( \Omega \) around the \( z \) axis. Non-zero ORT therefore causes a frequency shift \( \delta \omega \) for the output light, whose expression can be derived from energy conservation, namely \( w + \hbar \delta \omega = 0 \) where \( w = \tau z \Omega \) is the work per photon produced on the slab. This gives

\[
\delta \omega = 2\sigma \Omega (q - 1)
\]

Because \( \tau = -\hbar \delta \omega /\Omega \), we stress that the determination of the rotational Doppler frequency shift is actually an ORT measurement.

The experiment was carried out by observing the intensity patterns that result from the non-collinear superposition of the output light field and a reference Gaussian beam with angular frequencies \( \omega + \delta \omega \) and \( \omega \), respectively, as outlined in Fig. 3a. Indeed, we observe 2\( q \)-fork interference patterns that are
reminiscent of the optical phase singularity with topological charge $2\pi\sigma$ emerging from the sample, as illustrated by the snapshots shown in Fig. 3b–d for $q = (1/2, 1, 3/2)$. The determination of $\delta\omega$ is achieved by analysing the dynamics of these intensity patterns, denoted $I(x, y, t)$, with time $t$. Indeed, by constructing spatiotemporal interferograms $I(x = x_0, y, t)$ we obtain fringing patterns that may or may not drift along the $y$-axis depending on $q$, $\sigma$ and $\Omega$. This is illustrated in Fig. 3e–g, for $q = (1/2, 1, 3/2)$ when $\sigma\Omega > 0$.

The sign of the latter drift gives access to the sign of $\delta\omega$ from a mere visual inspection. In other words, with our set-up, when $\sigma\Omega > 0$, a drift towards $y < 0$ refers to $\delta\omega < 0$ (Fig. 3e), whereas a drift towards $y > 0$ indicates $\delta\omega > 0$ (Fig. 3g), and no drift implies $\delta\omega = 0$ (Fig. 3f) (Supplementary Section 1). Because $\sigma\Omega = -\delta\omega/\sigma\Omega$, our results indicate that $\sigma\Omega < 0$ when $q = 3/2$, hence demonstrating that left-handed ORT takes place.

Regarding the magnitude of $\delta\omega$, we define the time-dependent quantity $I(t) = \{\int I(x_0, y, t)\,dy - \{\int I(x_0, y, t)\,dy\}$, (Fig. 4a), where $\{\}$ holds for time averaging, where the spectrum exhibits a well-defined peak at frequency $|\delta\omega|/2\pi$ (Fig. 4b), as demonstrated in Supplementary Section 2. The dependence of $\delta\omega$ as a function of $\Omega$ is shown in Fig. 4c,d, corresponding to the range $|\delta\omega|/\omega = 10^{-17} - 10^{-16}$ for $q = (1/2, 3/2)$ and $\sigma = \pm 1$. In Fig. 4c,d, the solid lines refer to the theoretical results given by equation (2), from which we can infer the excellent agreement between the experimental data and theoretical predictions. We thus obtain the precise experimental determination of both the sign and magnitude of the rotational Doppler frequency shift, thereby allowing the quantitative identification of left-handed ORT.

Next we address the question of whether left-handed ORT may occur for $\Delta \neq \pi$. In this case the incident light field emerges from the slab with a total angular momentum per photon of $j^\text{out} = \alpha(\cos\Delta + 2\sin^2(\Delta/2))\hbar$ (Supplementary Section 3) from which results an ORT of

$$\tau_z = 2\sigma(1 - q)\sin^2(\Delta/2)\hbar \quad (3)$$

Previous conclusions are therefore unaltered whatever the value of $\Delta$, up to a factor of $\sin^2(\Delta/2)$ for the ORT magnitude. Experimentally, this situation is explored by detuning the incident wavelength from 532 nm, setting it at 632.8 nm, so $\Delta = (532/632.8)\pi$ (that is, 0.84 rad). The results are displayed in Fig. 5, where the rotational Doppler effect is assessed independently for the two output light field components with opposite helicities $+\sigma$ and $q = (1/2, 1, 3/2)$. This is done by using a circularly polarized reference beam with helicity $\sigma_{\text{ref}} = \alpha$ (Fig. 5b–d) and $\sigma_{\text{ref}} = -\alpha$ (Fig. 5e–g), respectively. We conclude from Fig. 5b–d that photons whose helicity is unchanged did not produce ORT. In contrast, helicity-flipped photons give rise to right-handed, zero or left-handed ORT depending on $q$, as shown in Fig. 5e–g. Noticeably, the factor $f = \sin^2(\Delta/2)$ in equation (3) corresponds to the fraction of output photons that produce work on the sample (Supplementary Section 3). In addition, because the energy conservation condition per photon should be written ‘per working photon’, hence $\tau_\Omega + \frac{\delta\omega}{\beta} = 0$, the predicted magnitude of $\delta\omega$ is unchanged with respect to the case $\Delta = \pi$. This has been quantitatively verified and can be qualitatively grasped from a comparison of Fig. 3e–g and Fig. 5e–g. We thus generalize the proposed concept of left-handed ORT to arbitrary values of birefringent phase retardation.

The above results remain valid for any superposition of left- and right-handed circularly polarized Gaussian beams. Indeed, accounting for an electric field of the form $\alpha G_{+1} + \beta G_{-1}$, where $(\alpha, \beta) \in \mathbb{C}$ and $G_x$ refers to a Gaussian field with helicity $\sigma_x$, one obtains $s^\text{in}_\sigma \tau_z = 2[(\alpha^2 - |\beta|^2)/(\alpha^2 + |\beta|^2)](1 - q)\sin^2(\Delta/2)\hbar$, which leaves the previous conclusions unchanged. Namely, $s^\text{in}_\sigma \tau_z < 0$ for $q > 1$ whatever $s^\text{in}_\sigma$.

In the context of previous experimental studies on light-induced rotation of optically isotropic transparent non-axisymmetric micro-objects, we note that a Gaussian beam has been shown to lead to either clockwise-only or anticlockwise-only spinning motion independently of the incident angular momentum, and therefore cannot be considered as a left-handed optomechanical manifestation. This is also the case for the reversed orbiting motion of a microparticle with irregular shape induced by a linearly polarized vortex beam (reported in ref. 28), because the observed sense of rotation is independent of the sign of the incident angular momentum, and also for the polarization-dependent rotational motion of an achiral microparticle with well-controlled shape induced by a polarized vortex beam (reported in ref. 29), where the observed sense of rotation is given by the sign of the incident angular momentum, hence corresponding to a right-handed ORT. On the other hand, in the case of optically induced torque driven by absorption only, the sign of the figure of...
torque is always the same as that of the incident angular momentum, whatever the polarization state and orbital content of the incident light field (shown in ref. 30), which precludes a left-handed effect. In the general case where absorption and/or birefringence and/or scattering can be at play, the circumstances under which a left-handed rotational effect takes place certainly deserve further study.

By addressing the rotational degree of freedom, the present study strengthens the emergence of a novel field in optical trapping and micromanipulation—left-handed optomechanics driven by spin–orbit scattering of light. As already emphasized for the case of negative optical forces, a left-handed optomechanical toolbox—characterization of the samples was carried out using incoherent illumination at a wavelength of 532 nm provided by a halogen lamp, in front of which were placed tracing paper and a 2-mm-diameter beam (at 1/e² of its maximum intensity) using a homemade optical telescope made of a pair of plano-convex lenses whose focal lenses were adapted to the laser source used. The slabs were placed in a rotating holder whose angular velocity was controlled by a voltage-controlled d.c. motor. The interference intensity patterns were recorded using a CMOS video camera (Thorlabs) and the videos were processed using homemade Matlab code. In all experiments the polarization state of the light was ensured using a 3-mm-thick solid-state laser (Cobolt) operating at 532 nm or a He Ne gas laser (Melles Griot) operating at 632.8 nm. Both laser sources operated on the fundamental TEM₀₁ Gaussian mode. The incident light beam impinged at normal incidence onto the slab (and was centred on it), and was collimated into a ~2-mm-diameter beam at 1/e² of its maximum intensity using a homemade optical telescope made of a pair of plano-convex lenses whose focal lenses were adapted to the laser source used. The slabs were placed in a rotating holder whose angular velocity was controlled by a voltage-controlled d.c. motor. The interference intensity patterns were recorded using a CMOS video camera (Thorlabs) and the videos were processed using homemade Matlab code. In all experiments the polarization state of the light was ensured using either linear or circular polarizers (Meadowlark Optics).

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Methods

The three samples with \( q = (1/2, 1, 3/2) \) were form-birefringent nonstructured glass slabs from Altechna R&D. The azimuthal distribution of their optical axis is shown to satisfy \( \psi = \phi \), where \( \phi \) is the polar angle in the plane of the slab. The glass substrates had a diameter of 1 inch, a thickness of 3 mm, and the structured area corresponded to a 4-mm-diameter region centred on the substrate. The samples were designed to exhibit a uniform birefringent phase retardation over the whole structured area, which equalled \( \pi \) at a wavelength of 532 nm. The polarscopic characterization of the samples was carried out using incoherent illumination at 532 nm provided by a halogen lamp, in front of which were placed tracing paper and an interference filter (wavelength of 532 nm) with 10 nm spectral width (Thorlabs). The rotational Doppler experiments were performed using either a diode-pumped solid-state laser (Cobolt) operating at 532 nm or a He Ne gas laser (Melles Griot) operating at 632.8 nm. Both laser sources operated on the fundamental TEM₀₁ Gaussian mode. The incident light beam impinged at normal incidence onto the slab (and was centred on it), and was collimated into a ~2-mm-diameter beam at 1/e² of its maximum intensity using a homemade optical telescope made of a pair of plano-convex lenses whose focal lenses were adapted to the laser source used. The slabs were placed in a rotating holder whose angular velocity was controlled by a voltage-controlled d.c. motor. The interference intensity patterns were recorded using a CMOS video camera (Thorlabs) and the videos were processed using homemade Matlab code. In all experiments the polarization state of the light was ensured using either linear or circular polarizers (Meadowlark Optics).

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Author contributions

D.H. realized the experimental set-up and conducted the experiments. E.B. conceived the experiment and supervised the project. D.H. and E.B. wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.B.

Competing financial interests

The authors declare no competing financial interests.