Optomechanical measurement of photon spin angular momentum and optical torque in integrated photonic devices

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Photons carry linear momentum and spin angular momentum when circularly or elliptically polarized. During light-matter interaction, transfer of linear momentum leads to optical forces, whereas transfer of angular momentum induces optical torque. Optical forces including radiation pressure and gradient forces have long been used in optical tweezers and laser cooling. In nanophotonic devices, optical forces can be significantly enhanced, leading to unprecedented optomechanical effects in both classical and quantum regimes. In contrast, to date, the angular momentum of light and the optical torque effect have only been used in optical tweezers but remain unexplored in integrated photonic systems. We demonstrate the measurement of the spin angular momentum of photons propagating in a birefringent waveguide and the use of optical torque to actuate rotational motion of an optomechanical device. We show that the sign and magnitude of the optical torque are determined by the photon polarization states that are synthesized on the chip. Our study reveals the mechanical effect of photon’s polarization degree of freedom and demonstrates its control in integrated photonic systems. Exploiting optical torque and optomechanical interaction with photon angular momentum can lead to torsional cavity optomechanics and optomechanical photon spin-orbit coupling, as well as applications such as optomechanical gyroscopes and torsional magnetometry.

INTRODUCTION

In vacuum, the linear momentum of a photon depends on its frequency $\omega$, as given by $\hbar k = h\omega/c$, where $k$ is the magnitude of the wave vector and $c$ is the speed of light. When the photon is right-handed (left-handed) circularly polarized (defined in Fig. 1A), it also carries a spin angular momentum of $+\hbar$ ($-\hbar$), which, noteworthy, is independent of $\omega$. The transfer of linear momentum of photons during light-matter interaction leads to optical forces (1), including radiation pressure and gradient force, which have long been used in optical tweezers and laser cooling (2–4). The gradient optical force can be particularly strong in nanophotonic devices, which afford tight spatial confinement and strong optomechanical dispersion that can be rationally engineered (5–8). The mechanical interaction between light and motional devices has recently been extensively explored in various optomechanical systems (9–14), with the most notable achievement being the backaction cooling of cavity optomechanical systems to the quantum ground states (12, 15). However, the other essential mechanical attribute of light, the angular momentum of photons (16), has only been used in optical tweezers (17, 18) and has not been investigated or used in integrated optomechanical systems.

Historically, the first measurement of the angular momentum of light was carried out by R. A. Beth in the 1930s (19), more than three decades after the first measurement of radiation pressure (20–22). Beth’s famous experiment was based on Poynting’s prediction (16) that circularly polarized light should exert a torque on a half-wave plate, which changes the helicity of the polarization state (Fig. 1A). By detecting the rotation of a wave plate suspended on a quartz fiber, which formed a torsional pendulum, as circularly polarized light passed through, Beth measured the optical torque and confirmed the angular momentum of light predicted by theory. Now, eight decades later, we are in the era of integrated photonics with lasers available as sources of coherent light. We set out to measure the spin angular momentum of light and use optical torque effect in on-chip optomechanical systems. The spin angular momentum of light is important in that it directly relates to the polarization state of light, which is an essential state variable in both classical and quantum optical information processing (23–25). In integrated photonic devices, the polarization state of light is frequently manipulated so that the angular momentum exchange between photons and devices is ubiquitous (24–27). Understanding and using photon angular momentum–induced mechanical effects should have important implications for these areas and spawn new principles of operation.

Instead of a wave plate, we consider a rectangular waveguide that supports two modes, designated as transverse electric (TE) and transverse magnetic (TM) modes, resembling the two orthogonal linear polarizations in free space (Fig. 1B). The two modes are quasi-linearly polarized with the major components of the electric field aligned with the $x$ and $y$ axes, respectively. The magnitudes of the wave vectors of the two modes are denoted by $k_{x,y} = n_{x,y}c/\omega$, where $n_{x,y}$ is the effective mode index. In contrast to a wave plate made of an anisotropic material, a rectangular waveguide made of an isotropic material such as silicon can have a particularly strong birefringence, $\Delta n = n_x - n_y$ and $\Delta k = k_x - k_y$, because of its geometric anisotropy. Therefore, waveguides are frequently engineered to manipulate the polarization state on a chip (26). We use the Jones vector to denote the polarization state of an arbitrary hybrid mode as $a_x a_y e^{i\varphi} \begin{pmatrix} a_x \ a_y \end{pmatrix}$, where $a_x$ and $a_y$ are the mode amplitude and phase difference of the electric field components of the TE and TM modes, respectively, so that $a_{x,y}^2 = P_{x,y}$ is the power of each mode. The polarization state is linear when $\varphi = 0$ or $\pi$, and it is right (left) circular when $a_x = a_y$ and $\varphi = - (+)\pi/2$. Because of...
birefringence, \( \phi \) is a function of propagation distance \( \phi(z) = \phi_0 + \Delta k z \) such that the polarization state of light, if it is not purely TE or TM \((a_x a_y \neq 0)\), continues to evolve as light propagates along the waveguide (Fig. 1B). Like the wave plate situation, accompanying the evolution between linear, elliptical, and circular polarization states is the angular momentum exchange between the light and the waveguide. As a result, the photons apply an optical torque on the birefringent waveguide to twist it. The total optical torque \( T(l) \) on a section of length \( l \) of the waveguide should be the integration of the time-averaged, local linear torque density \( \tau(z) \), which varies along the waveguide as the polarization state evolves and can be expressed as \( \tau(z) = -\Phi_\gamma(dS_z/dz) \), where \( \Phi_\gamma \) is the photon flux and \( S_z \) is the effective spin angular momentum of a photon. The mechanical effects of mode conversion at the input and output ends of the waveguide are not pertinent here. This principle is illustrated in Fig. 1 (B and C). In more detail, when the light of arbitrary polarization state propagates along the waveguide, the electromagnetic field generates a distributed force, hence a distributed torque \( \tau(x, y, z) \), inside the waveguide. A representative torque distribution inside a typical waveguide cross section where \( \phi = 0 \) is shown in Fig. 1D. The integration of this distributed torque over the waveguide cross section yields torque per unit length

\[
\tau(z) = -\Phi_\gamma \frac{dS_z}{dz} = \frac{\Delta k}{\omega} (2a_x a_y) \cos(\phi(z)) \quad (1)
\]

which leads to an expression of \( S_z \)

\[
S_z(\phi) = -\eta \hbar \frac{2a_x a_y}{a_x^2 + a_y^2} \sin(\phi) \quad (2)
\]

The coefficient \( \eta \) is equal to 1 in vacuum, and in dielectric materials, it accounts for interactions including dipole forces (1) and electrostrictive forces (28). In Eq. 2, it is evident that \( S_z = \pm \hbar \) when the polarization state is circular, whereas \( S_z = 0 \) when the polarization state is linear. In the Supplementary Materials, we have included a detailed theoretical analysis of the waveguide case, which shows that, for a waveguide made of silicon and with representative dimensions, the dipole and electrostrictive contributions to the optical torque are on the same order of magnitude, and the absolute value of the total angular momentum that can be transferred for the conversion between circular and linear polarization by each photon can amount to more than \( 1.6\hbar \).

**RESULTS**

**Torsional cavity optomechanical resonator**

To demonstrate and measure the photon spin angular momentum and the optical torque, we fabricated silicon nano-optomechanical...
devices using silicon-on-insulator (SOI) wafers. Figure 2A shows an optical image of the device. The core element of the device is a two-mode waveguide suspended from the substrate. With a rectangular cross section that is 400 nm wide (along the x direction) and 340 nm high (along the y direction), the waveguide was designed to have a strong birefringence for its TE and TM modes with $\Delta n = 0.16$ ($n_x = 2.4685, n_y = 2.3059$). Attached to the waveguide and also suspended from the substrate is a nanobeam in which two one-dimensional photonic crystal nanocavities are embedded, one on each side. The resonance modes of the nanocavities are optimized to be particularly sensitive to their distance from the substrate; thus, they provide very sensitive detection to the rotation of the waveguide actuated by the optical torque (29, 30). Therefore, the nanobeam with nanocavities is analogous to the mirror mounted on the quartz fiber in Beth’s apparatus. One of the nanocavities is coupled to a nearby waveguide (inset, Fig. 2C). The representative transmission spectrum through this coupling waveguide shown in Fig. 2B exhibits the resonance of the nanocavity, with a loaded (intrinsic) quality factor of 4200 (23,000).

**Controlling optical torque through synthesis of the polarization state**

The optical torque on the waveguide can be controlled by varying the polarization parameters ($\alpha_x, \alpha_y, \phi$). This was achieved with on-chip peripheral photonic circuits and an off-chip setup (Fig. 2C). Specifically, the TE and TM modes were derived from the same laser source, and their power ratio was controlled by a fiber polarization controller FPC (FPC1). After the electro-optic phase (EOM), the TE and TM modes were separated by a fiber polarization beam splitter (PBS) into two optical paths, where their polarization states were independently conditioned and their power was monitored. To accurately control and stabilize the relative phase $\phi$, an on-chip integrated interferometer provided the feedback, which was particularly effective for real-time compensation of the phase fluctuations in the optical fibers caused by room-temperature fluctuations. The output power of the interferometer ($P_I$) is determined by $\cos(\phi_I)$, where $\phi_I$ is the relative phase between the two interferometer arms. Although the actual difference between $\phi_I$ and $\phi$ cannot be practically predetermined by design, the difference $\phi - \phi_I$ remains consistent for any single device at a stabilized temperature. Therefore,

![Fig. 2. Optomechanical scheme to measure photon angular momentum and optical torque in a waveguide.](image)
$P_i$ was measured and used to control the bias of the EOM and a fiber thermo-optic phase shifter in the TM optical path, compensating for the fast and slow fluctuations of the optical phases in the system, respectively. At the same time, the measurement system was in an enclosure with temperature fluctuations controlled to be within ±0.2 K.

**Optical torque modulation and measurement**

To measure the optical torque, we used the resonance method used in Beth’s original experiment but in a modern fashion, by modulating the optical torque to actuate the resonant motion of the nanobeam hinged on the waveguide (Fig. 3A). To do so, we used the different modulation efficiency of the EOM for the TE and TM modes, which leads to relative phase modulation between the two modes. To understand the mechanical motion of the waveguide-nanobeam structure actuated by the optical torque, we show in Fig. 3B the simulated fundamental torsional mode of the structure, which is the dominant mode that is excited by the optical torque. In this mode, the waveguide undergoes pure torsional motion with its two ends fixed while the nanobeam tilts with it. This mode can be described as an effective torsional simple harmonic oscillator, the effective driving torque of which ($T_e$) is defined by the overlap integral of the optical linear torque density $\tau(z)$, given in Eq. 1, and by the normalized angular mode profile $\theta_n(z)$ along the waveguide as $T_e = \int \tau(z) \theta_n(z)dz = T_n \cos(\varphi_0)$, where $\varphi_0 = \varphi(z = 0)$ and the integration is simplified because $\theta_n(z)$ is an even function of $z$. Therefore, the effective torque $T_e$ changes sinusoidally with $\varphi_0$ and reaches extrema when $\varphi_0$ is equal to 0 or $\pi$. The maximal effective torque $T_m$ depends on the waveguide length and birefringence, and after approximating $\theta_n(z)$ to a triangular function (see the Supplementary Materials), it can be expressed as

$$T_m = -S_e \left(\frac{\pi}{2}\right) \Phi_0 \frac{2 \sin^2(\Delta k l/4)}{\Delta k l/4}$$ (3)

To confirm the theory described above and achieve quantitative measurement of the optical torque, we measured devices with various suspended waveguide lengths $l$. Figure 3C shows the noise power spectral density (PSD) measured from the transmitted probe laser power of a representative device with $l = 10.5 \mu$m. Four mechanical resonance peaks due to thermomechanical fluctuation are observed, with the peak at 358.7 kHz corresponding to the fundamental torsional mode, which is plotted in detail in Fig. 3D, showing a quality factor of 12,000. We used this thermomechanical noise PSD measurement to calibrate our system’s measurement sensitivity (31). The measured resonance frequencies of seven devices with various waveguide lengths $l$ (9.0, 10.5, 12.0, 13.5, 15.0, 16.5, and 18.0 $\mu$m) are summarized in Fig. 3E. The results agree well with the simulation results (blue line) using an elasticity matrix for silicon that is 19% lower than the typical value for bulk silicon (red line) (32).

When performing resonance measurement, the EOM was driven by a network analyzer to sinusoidally modulate the phase $\varphi_0$ by a small amplitude of $\delta \varphi_0$ and thus generate a dynamic, effective torque. **Fig. 3. Mechanical characteristics of the torsional optomechanical device.** (A) Zoom-in scanning electron microscope image showing the suspended waveguide-nanobeam structure. (B) Simulated fundamental torsional mode of the waveguide-nanobeam structure. Also plotted on the $yz$ plane are the normalized angular mode profile $\theta_n(z)$ (in purple) and its representative overlap integrand with torque distribution $\tau(z) \theta_n(z)$ (in red), the integration of which along the waveguide yields effective torque $T_e$ for a representative waveguide of 10.5 $\mu$m long. (C) Broadband thermomechanical noise PSD measured by the probe nanocavity resonance, showing four prominent mechanical modes. They are, with increasing frequency, fundamental out-of-plane torsional, fundamental out-of-plane flapping, fundamental in-plane torsional, and fundamental in-plane flapping modes. (D) Zoom-in view of the fundamental torsional mode resonance at 358.7 kHz, showing a quality factor of 12,000. The PSD unit has been calibrated and converted to rotational angle. (E) The fundamental torsional resonance frequency of devices with various waveguide lengths $l$. The measurement results show lower frequency than simulation using the typical bulk value of silicon’s elasticity matrix (red line), indicating that the elasticity matrix of the silicon layer in the SOI is effectively lower (blue line).
on the waveguide: \( \delta T_e \cos(\Omega t) = -T_m \sin(\phi_0) \delta \phi_0 \cos(\Omega t) \). By performing only phase modulation and avoiding amplitude modulation, the photothermal effect was minimized (11, 33, 34). Additionally, the structural symmetry of the device and the large gap between the waveguide and the substrate eliminated the “light-pressure torque” effect (19), although a small residual amplitude modulation might remain because of instrumental nonideality. We first measured the nanobeam’s resonance responses with constant \( \delta \phi_0 \) and optical power \( P \) (and \( \alpha_x = \alpha_y \)), whereas \( \phi_0 \) was varied (through controlling \( \xi \)). The quadrature components of the responses from a representative device (\( l = 10.5 \) \( \mu \)m) are plotted in Fig. 4A, showing that the fundamental torsional mode of the nanobeam is excited by the optical torque. The data measured for six different values of \( \phi_0 \) reveal that both the amplitude and sign of \( \delta T_e \) depend on \( \phi_0 \). In the experiment, the actuated mechanical rotation amplitude was kept low at a few microradians to avoid inducing nonlinearity. From the response for each value of \( \phi_0 \), \( \delta T_e/\delta \phi_0 \) is calculated and plotted in Fig. 4B, showing a clear sinusoidal dependence predicted by \( -T_m \sin(\phi_0) \), from which the value of \( T_m \) is obtained.

To further investigate the dependence of \( T_m \) on the polarization state, we first varied the ratio between \( P_{\text{TE}} = \alpha_x^2 \) and \( P_{\text{TM}} = \alpha_y^2 \) with a constant total power of \( P = \alpha_x^2 + \alpha_y^2 = 95 \) \( \mu \)W. From the measurement of two devices (\( l = 10.5 \) and \( 9 \) \( \mu \)m), we observed a semicircular dependence (Fig. 4C), which originates from the \((2\alpha_x \alpha_y)/(\alpha_x^2 + \alpha_y^2)\) term in Eq. 2. With the same two devices, we also measured the dependence of \( T_m \) on the power \( P \) with \( \alpha_x = \alpha_y \) (Fig. 4D). The results show that the optical torque \( T_m \) deviates from linear dependence on power at above 100 \( \mu \)W. Control experiments have been performed to rule out the typical Duffing mechanical nonlinearity as the origin of this nonlinear behavior, which requires further investigation but does not affect the measurement results obtained within the linear region. For the 9-\( \mu \)m-long waveguide, \( T_m \) remains linear with an optical power of up to 0.5 pN. Finally, we investigated the dependence of \( T_m \) on the waveguide length \( l \) with fixed power (95 \( \mu \)W and \( \alpha_x = \alpha_y \)). The result in Fig. 4E is fitted to Eqs. 2 and 3, with \( \eta \) and \( \Delta \eta \) as the free parameters, showing a good agreement with the theory. From the fitting, the \( \Delta \eta \) obtained is 0.18, which is very close to the designed value of 0.16, whereas the \( \eta \) obtained is 2.2 \( \pm \) 1.0. Therefore, the measured value of photon spin angular momentum in the waveguide is (2.2 \( \pm \) 1.0) \( \hbar \). The theoretical value of \( \eta \) is calculated to be 1.5 (see the Supplementary Materials), which is therefore within the measurement uncertainty of the experiment.

**DISCUSSION**

Our experiment provides the first unambiguous measurement of spin angular momentum of photons and optical torque generated in an
integrated photonic device. The result shows that the optical torque is determined by the geometric birefringence of the waveguide, which can be rationally engineered to enhance the effect. These designs can be achieved in other nanophotonic structures such as plasmonic devices, metasurfaces, and metamaterials to generate even more pronounced effects (35). Furthermore, because the photon angular momentum is only dependent on the polarization state and independent of the optical frequency, the optical torque effect is universal over a broad spectral band, providing great leeway for engineering. Our experiment measured the photon angular momentum inside a waveguide, and the result we obtained favors the Minkowski photon angular momentum (36) and supports the electrostrictive contribution (28). In addition to spin angular momentum, photons can also have orbital angular momentum, and optomechanical effects arising from the spin-orbit interactions of light in nanophotonic systems will be even more intriguing (37, 38). Exploiting optical torque and optomechanical interaction with photon angular momentum can lead to efficient all-optical excitation and transduction of torsional nanomechanical devices with applications such as optomechanical gyroscopes (39) and torsional magnetometry (40).

**MATERIALS AND METHODS**

**Device fabrication**

The devices were fabricated on an SOI wafer with a 340-nm-thick device layer and a 3-μm buried oxide layer. The silicon structures were first patterned using electron beam lithography (Vistec EBPG5000+) and fluorine-based plasma dry etching processes. The electron beam resist (ZEPT520A) was developed at −15°C after exposure to enhance the resolution. The critical dimensions of the silicon structure were confirmed with scanning electron microscopy to be within ±5 nm of the designed values. The waveguide and nanobeam were subsequently released from the substrate in two steps using photolithography and wet etching processes. In the first step, only the substrate below the waveguide was selectively etched by 210 nm with buffered oxide etch, whereas in the second step, the substrate below both the waveguide and the nanobeam was etched by 330 nm with diluted hydrofluoric acid. The resultant gap below the waveguide is 540 nm, which is large enough to decouple the waveguide modes from the substrate and to minimize gradient optical force, whereas the gap below the nanobeam is 330 nm, which is small enough to enable sensitive transduction of the torsional motion. After wet etching, we dried the sample in a critical point dryer to avoid the stiction problem during solvent evaporation.

**Optical torque measurement**

To minimize air damping, the devices were measured in a vacuum chamber with a pressure less than 1 × 10⁻⁴ torr. A fiber array was used to access them through the on-chip grating couplers. All the off-chip experimental equipment that is sensitive to the temperature fluctuations was enclosed in a plastic shield. In the experiment, the temperature fluctuations inside the plastic shield and the vacuum chamber were controlled to be within ±0.2 K. The probe laser (blue path in Fig. 2C) was sufficiently attenuated to avoid dynamic cavity optomechanical backaction and optimally detuned from the nanocavity resonance to transduce the torsional motion. The width of the coupling waveguide for the nanocavity is tapered down to 320 nm to achieve phase matching with the cavity mode. The probe laser output was measured by PD1. The pump TE and TM modes were derived from the same laser source (red path in Fig. 2C) for optimal coherence between them. The FPC1 was used to tune the power ratio of the TE and TM modes in the EOM (Lucent 2623NA) coupled to the linearly polarized laser source. The half-wave voltage of the EOM (Vₜₚ) is 3 V for the TE mode and 9 V for the TM mode. Therefore, the voltage applied on the EOM linearly modulates the phases of both modes with different efficiencies, equivalently modulating φ₀ with Vₜₚ = 4.5 V. The fiber PBS was used to separate the TE and TM modes of the EOM into two optical paths, where their polarization states were conditioned with FPCs for their respective grating couplers and their power was tapped (10%) with beam splitters and monitored with PDs, before they were coupled on-chip. With the beam splitters and combiners in the on-chip peripheral photonic circuits (green path in Fig. 2C), half of the TE and TM mode power was split from their respective input grating couplers and combined into the suspended waveguide, where the induced optical torque was measured with the nanobeam. The junction between the suspended waveguide and the nanobeam is optimized for minimal perturbation to the propagation of both modes inside the waveguide. After the suspended section, the waveguide width is adiabatically tapered down to 80 nm so that the pump laser was emitted into free space with minimal reflection. To implement the on-chip integrated interferometer that provides the feedback used to control and stabilize φ₀, the other half of the TE and TM mode power was guided into their respective interferometer arms, where the TE mode was converted into pure TM mode with an on-chip mode converter and filter. The interferometer output P₁ is determined by φ₀ and the optical power in the two interferometer arms, P₁ and P₁₂, as

\[ P₁ = \frac{P₁₁}{2} + \frac{P₁₂}{2} + \sqrt{P₁₁P₁₂} \cos(φ₀) \]

which was measured by PD4. The extinction ratio (ER) of the interferometer, defined as the ratio between the maximum and minimum output power (P max/P min), is determined by P₁₁/P₁₂ as

\[ ER = \frac{P_{\text{max}}}{P_{\text{min}}} = \left(\frac{\sqrt{P₁₁/P₁₂} + 1}{\sqrt{P₁₁/P₁₂} - 1}\right)^2 \]

In practice, our feedback and control scheme performed satisfactorily when ER > 1.5, requiring that 0.01 < P₁₁/P₁₂ < 100, which was naturally met in most of the situations. However, a minor limitation of this feedback scheme is that it fails to function when |cos(φ₀)| → 1, where the dependence of P₁ on φ₀ becomes insensitive and nonmonotonic. In the actual experiment, we always kept |cos(φ₀)| ≤ √3/2, which provided satisfactory phase stabilization and was more than sufficient to reveal the sinusoidal dependence shown in Fig. 4B.

Electronic equipment (orange path in Fig. 2C) was used for both measurement and control. A bias tee was used to combine the radio frequency (RF) signal from the network analyzer and the bias voltage from the proportional-integral-derivative (PID) controller. We used a network/spectrum analyzer (Agilent 4396B) for the measurement. For the thermomechanical noise measurement shown in Fig. 3 (C and D), spectrum mode was used to measure the PSD of the PD1 output, which was used to calibrate the optomechanical measurement.

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transduction factors by theoretical curve fitting. For the resonance response measurement shown in Fig. 4, network mode was used to drive the EOM through the bias tee RF port and simultaneously measure the response signal from PD1. Meanwhile, the PID control scheme used the feedback from the PD4 output to control and stabilize $\phi_0$ by compensating for the random phase fluctuations in the optical fibers in real time. We used a two-stage PID control scheme tailored for our experiment. The first stage consists of an analog PID controller (SRS SIM960), which directly stabilizes the PD4 output by tuning the EOM bias voltage through the bias tee dc port, whose bandwidth is more than sufficient to compensate for the fastest phase fluctuations in our experiment. The second stage consists of a homemade PID controller, which minimizes the EOM bias voltage to reduce Joule heating in the EOM by tuning the fiber thermo-optic phase shifter in the TM optical path. In this configuration, the first stage provides a fast response and the second stage slowly takes over any accumulated burden on the first PID stage with its large tuning range.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/suppl/2/9/e1600485/DC1

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