Passive torque wrench and angular position detection using a single-beam optical trap

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The recent advent of angular optical trapping techniques has allowed for rotational control and direct torque measurement on biological substrates. Here we present a method that increases the versatility and flexibility of these techniques. We demonstrate that a single beam with a rapidly rotating linear polarization can be utilized to apply a constant controllable torque to a trapped particle without active feedback, while simultaneously measuring the particle angular position. In addition, this device can rapidly switch between a torque wrench and an angular trap. These features should make possible torsional measurements across a wide range of biological systems.

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Optical trapping has proven to be an invaluable tool in the study of biophysical systems. The ability to measure the forces and displacements of nucleic acids, proteins, and molecular motors has allowed for further insight into the mechanistic functions of these important biological molecules [1,2]. Recent advances in optical trapping techniques have led to methods by which rotational orientation and torque can also be manipulated and measured via the coupling of the polarization state of light to an optically or spatially anisotropic particle [3–6]. We have previously developed such an angular optical trap and used it to measure the torsional properties of DNA [6–9].

In this Letter, we demonstrate a method to enhance the versatility of an angular optical trap. A constant optical torque may be exerted on a trapped particle without the need for active feedback or additional laser/optics to monitor the trapped particle angular position using a single beam with a rapidly rotating linear polarization. This method is particularly well suited to exert torques relevant to single-molecule biology experiments, ranging from near zero to several tens of piconewton nanometers (pN nm). Such an instrument can be rapidly switched to the standard angular trapping mode. In comparison with previous work, this approach is unique in several aspects. The current torque wrench has little torque noise, whereas the optical torque wrench we developed earlier requires active feedback for torque stabilization [6], and thus the noise from the Brownian motion can dominate for small torque values. Another study exerted torque using a similar method but requires the use of an additional laser/optics for the detection of the trapped particle's angular position [10]. A single circularly polarized beam can also provide a constant torque [11], but the magnitude of the torque is not controllable independently of the power of the trapping beam. In contrast, the current method provides a tunable constant torque without the need to change the laser power.

The passive torque wrench is achieved by spinning the input linear polarization so rapidly that the particle cannot keep up with it. At this limit, the angular stiffness of the trapping beam approaches zero, and it exerts an effectively constant torque on the particle in the direction of polarization rotation. The implementation of this method is outlined in Fig. 1(a). To understand this, consider a particle inside a trap with its polarization rotating at angular frequency $\omega = 2\pi f$. The equation of motion of the particle is

$$\gamma \frac{d\theta}{dt} = \tau_0 \sin[2(\omega t - \theta)], \tag{1}$$

where γ is the rotational viscous damping coefficient and τ_0 is the maximum optical torque. This describes a damped-forced oscillator at a low Reynold number, where the viscous drag torque balances the optical torque. A similar description also characterizes optically torqued nanorods and magnetic particles [12,13]. Below a critical frequency $\omega_{\text{critical}} = 2\pi f_{\text{critical}} = \frac{\tau_0}{\gamma}$, the particle tracks the polarization rotation with a torque-dependent angular offset, resulting in a linear increase in the optical torque [6]. However, above the critical frequency, the particle can no longer fully track the polarization and instead wobbles periodically in response to the polarization rotation. When $\omega \gg \omega_{\text{critical}}$, although the trap exerts a full amplitude oscillating torque on the particle, the resulting wobble amplitude of the particle becomes diminishingly small, as the particle simply cannot respond faster than its corner frequency in a stationary angular trap ($\omega_{\text{corner}} = 2\omega_{\text{critical}}$). At this limit, the polarization effectively scans a quasi-stationary particle, and only a minute biased optical torque is exerted on the particle averaged over a cycle of the scan. In general, the mean torque τ may be obtained from Eq. (1) [14]: $\tau = \gamma\omega$ if $\omega \le \omega_{\text{critical}}$ and $\tau = \gamma(\omega - \sqrt{\omega^2 - (\tau_0/\gamma)^2})$ if $\omega > \omega_{\text{critical}}$.

First, we demonstrate the use of a lock-in method for detection of the angular position θ of the trapped particle. In general, θ can be determined from the input polarization angle and the torque signal [6], because the optical torque is $\tau(t) = \tau_0 \sin[2(\omega t - \theta)]$, where θ may be time varying. In the limit of $\omega \gg \omega_{\text{critical}}$, θ varies slowly compared to ω, and its detection can be facilitated by a lock-in method. The reference signal is the intensity of the input beam polarized along the x axis fixed in the lab frame

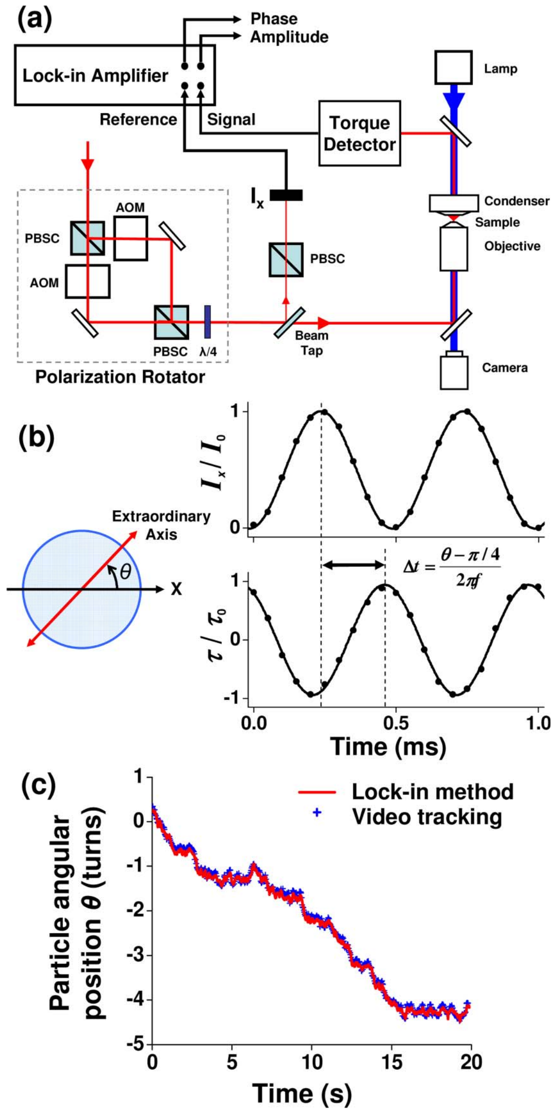

Fig. 1. (Color online) Method of constant optical torque generation and angular position detection. (a) Simplified schematic of the passive optical torque wrench. The optical setup is similar to what has been previously described [6] but with the important addition of a lock-in amplifier. (b) The lock-in amplifier uses $I_x(t)$ as a reference signal and the torque detector signal $\tau(t)$ as the input signal. The phase difference between these two signals provides the angular position θ of the cylinder. (c) Comparison of detected angular position of a quartz dust particle as simultaneously determined by the lock-in method (red curve) and video-tracking method (blue points). For both (b) and (c), $f_{\mathrm{critical}} = 9$ Hz and $f = 1$ kHz.

$I_x(t) = I_0 \cos^2(\omega t) = I_0[1 + \cos(2\omega t)]/2$, and the input signal is $\tau(t)$. Thus θ can be determined by the phase delay or time delay Δt output of the lock-in amplifier: $\theta = \omega \Delta t + \pi/4$ [Fig. 1(b)]. To verify the lock-in method, we applied it to an irregularly shaped, micrometer-sized quartz particle so that the particle angular position could be simultaneously recorded via video tracking. As shown in Fig. 1(c), the two methods agree to within the resolution of the video-tracking method, and the particle underwent a slightly biased rotational diffusion. In practice, for ease of use, calibration, and reproducibility, the trapping particles are nanofabricated quartz cylinders, which are uniform in size (~0.5 μm in diameter and ~1 μm in height), shape, and optical properties and are functionalized on the bottom surface for specific attachment to biomolecules, if desired [7].

Second, we demonstrate the use of this device as a passive torque wrench, with particular emphasis on the cases where $\omega \gg \omega_{\mathrm{critical}}$. Figure 2(a) shows examples of the angular position of a single cylinder, tracked with the lock-in method, at different polarization rotation rates. Under a positive (negative) polarization rotation rate, the cylinder underwent a small net positive (negative) rotation. This cylinder rotation rate (and, thus, the torque) decreased with an increase in the polarization rotation rate. At a given polarization rotation rate, the cylinder rotated smoothly, indicating that a constant optical torque was exerted on the cylinder. The optical torque was directly measured by the torque detector [bottom panel of Fig. 2(a)] and was found to be consistent with the corresponding viscous torque calculated based on the cylinder rotation rate [top panel of Fig. 2(a)]. Figure 2(b) shows the mean torque on a single cylinder measured under a wide range of polarization rotation rates and laser powers. As expected, as ω was increased from zero, torque increased linearly as per the well-known Stokes drag

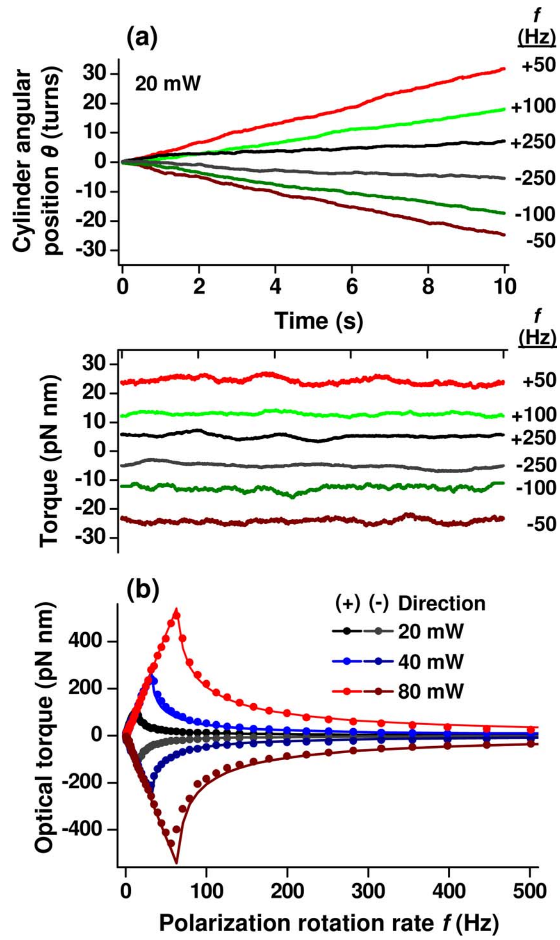

Fig. 2. (Color online) Demonstration of the passive torque wrench mode. (a) Single traces of cylinder angular position versus time for various polarization rotation rates and the corresponding measured torque. $f_{\mathrm{critical}} = 13$ Hz. (b) Direct measurement of the torque versus polarization rotation rate for various laser powers on a quartz cylinder. Solid curves are global fits to the expected mean torque.

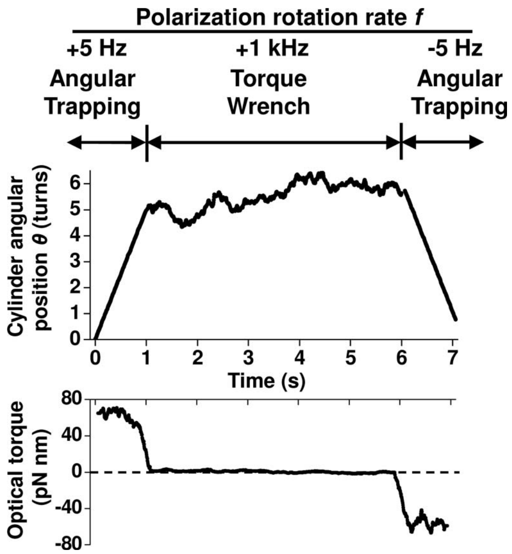

Fig. 3. Demonstration of rapid switching between an angular trapping mode and a torque wrench mode. $f_{\mathrm{critical}} = 9$ Hz. Polarization rate was set to $+5$ Hz at $t = 0$ (angular trapping mode), 1 kHz at $t = 1$ s (torque wrench mode), and –5 Hz at $t = 6$ s (angular trapping mode).

relation until $\omega = \omega_{\mathrm{critical}}$, beyond which the torque decreases as expected. In addition, the torque magnitude scales with the trapping laser power. Therefore, to dial in a desired torque, either the polarization rotation rate or the laser power can be changed.

Finally, we show that this device can be switched rapidly between two useful operating modes. When $\omega < \omega_{\mathrm{critical}}$, the cylinder is angularly trapped and tracks the rotation of the polarization. This mode should be used when a specific extent of cylinder rotation is desired. When $\omega \gg \omega_{\mathrm{critical}}$, the trap acts as a torque wrench. A constant torque is exerted on the cylinder, while the angle of the cylinder is allowed to vary. We demonstrate this capability in Fig. 3 by subjecting a cylinder to an angular trapping mode by slow (+) polarization rotation, switching to a passive torque wrench mode by rapid (+) polarization rotation, and then switching back to an angular trapping model by slow (–) polarization rotation. As shown, the cylinder underwent a constant rotation, followed by diffusive Brownian motion under a near-zero torque condition and then underwent a reverse rotation.

In conclusion, we have presented a method for generating constant torque and monitoring a trapped particle angular position within a single-beam optical trap without the need for active feedback on the torque signal. The passive torque wrench described here effectively reduces the angular trap stiffness to near zero, and thus the magnitude of the measured torque fluctuations are significantly reduced, and the torque provided by the trap can be much more precisely controlled. This trapping setup also allows for rapid switching between an angular trapping mode and a torque wrench mode without the need for additional beam paths or optics, reducing the possibility of systematic errors or cross talk often found in multiple-beam instruments. Such a device makes possible a number of interesting studies of biologically important systems, such as monitoring the rotational motion of a molecular motor as it works against a constant external torsional load, or measuring the relaxation kinetics of a mechanically torqued biomolecule.

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