African Journal of Biotechnology Vol. 7 (25), pp. 4663-4666, 29 December, 2008
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB08.1018
ISSN 1684–5315 © 2008 Academic Journals

Review

Torque and optical traps

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Accepted 11 December, 2008

Optical traps are an important tool for research in the field of single molecule biophysics. Recent advances in optical trapping have extended their functionality from simple linear manipulation and measurement of forces, to now the ability to rotate objects and measure torques. This mini review summarizes these recent developments of the optical trap as a tool to apply and measure torque in biophysical applications.

Key words: Torque, optical trap, angular momentum, biophysics.

INTRODUCTION

The field of laser based optical trapping was pioneered by Arthur Ashkin in the early 1970's (Ashkin, 1970), eventually leading to the widely used single-beam gradient force optical trap developed by him and his co-workers (Ashkin et al., 1986). The optical trap works on the principle that a change in linear momentum leads to the production of force. In the same way a change in angular momentum produces a resulting torque. In the optical trap, the optical forces acting to trap a micro particle result from the transfer of momentum from the trapping beam to the particle due to the scattering of incident photons. Since light can also carry angular momentum, transfer of angular momentum through scattering can be used to produce optical torque.

Light can carry angular momentum in two distinct forms: spin angular momentum, associated with the polarization state of the beam and orbital angular momentum, associated with the spatial distribution of the beam (Padgett and Allen, 2000). Torque is produced if either of these two forms of angular momentum is altered during the scattering of light.

The first instance of optical torque was observed in 1936 by Richard Beth, well before the advent of either lasers or optical traps (Beth, 1936). Using a tungsten filament light source and a series of quarter wave plates to produce circularly polarized light, Beth demonstrated the transfer of spin angular momentum to a birefringent quartz wave plate suspended from a quartz fiber. The quartz fiber served to effectively 'trap' the quartz wave plate in space, allowing it to interact with the photons of light from the tungsten light source. This review will focus on the different methods employed to produce optical torque when the trapping mechanism is also optical, with special attention placed on the applicability of these methods to the field of biophysics.

TORQUE TRANSFER THROUGH ABSORPTION

In standard optical trapping, a focused Gaussian laser beam with planar wave fronts produces a rotationally symmetric trap that does not exert any torque (Neuman and Block, 2004). However, Laguerre-Gaussian (LG) laser modes produce helical wave fronts (Figure 1a) that carry significant amounts of orbital angular momentum due to the light pattern they produce (Allen et al., 1992). It is well understood that circularly polarized light carries spin angular momentum, with each photon being assigned a spin of $\sigma\hbar$, where σ is ±1. LG modes carry an orbital angular momentum of $l\hbar$ per photon (Allen et al., 1992), where l is a mode index; the angular momentum carried by a photon of a polarized LG mode is then given by $(l + \sigma)\hbar$.

The transfer of angular momentum carried by such laser beam modes has been demonstrated for absorbing particles (He et al., 1995; Friese et al., 1996; Simpson et al., 1997). In particular Friese and coworkers showed that an absorbing particle trapped and rotating in a focused plane-polarized LG beam rotates faster if the beam is changed to be circularly polarized with spin of the same helicity as the LG beam, and slower for circular polarization with spin of the opposite sense to that of the helicity (Friese et al., 1996), as shown in Figure 1b. This effectively demonstrated that the transfer of both orbital

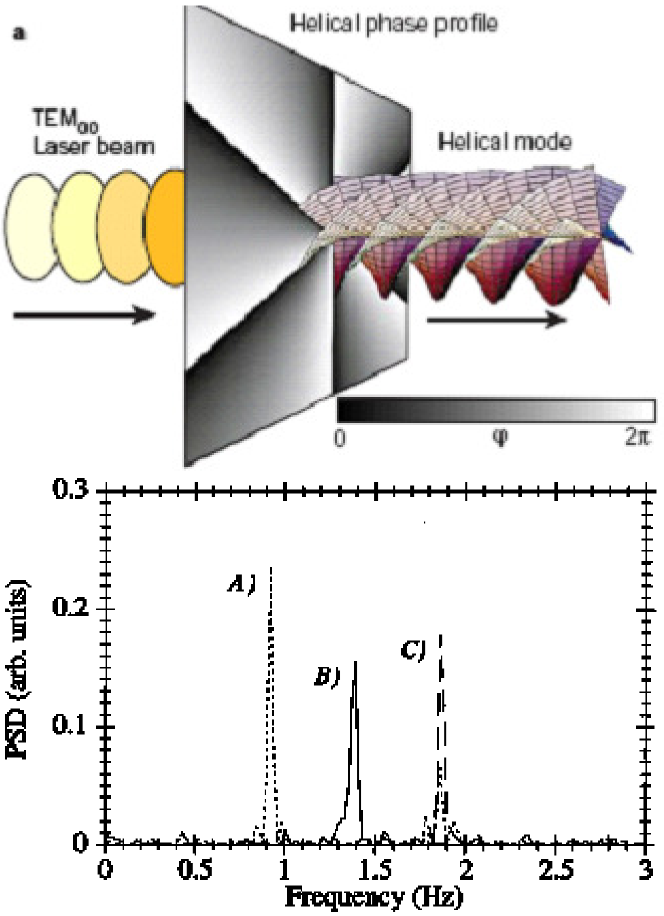

Figure 1a. Helical phase profile converts planar Gaussian beam to helical LG wavefronts. Courtesy David Grier (2003). **1b.** A): Left-circularly-polarized right-helical LG beam. B): Plane polarized right-helical LG beam. C): Right-circularly-polarized right-helical LG beam.

and spin angular momentum was experimentally observable in an optical trap for absorptive particles.

In these kinds of experiments a main concern is the absorption of heat by the particles, which can lead to over-heating. This places restrictions on practical applications, as it is difficult to achieve high power in such experiments resulting in low rotation rates of a few hertz.

BIREFRINGENT PARTICLES AS WAVEPLATES

As birefringent particles refract light differently associated with different crystallographic directions, they are commonly used as waveplates to convert linearly polarized light to circularly polarized light. This change in the polarization state of the transmitted light will in turn change the angular momentum of the transmitted light. This property of birefringent particles has been exploited to generate torques in optical traps for non absorptive particles (Friese et al., 1998; Higurashi et al., 1998).

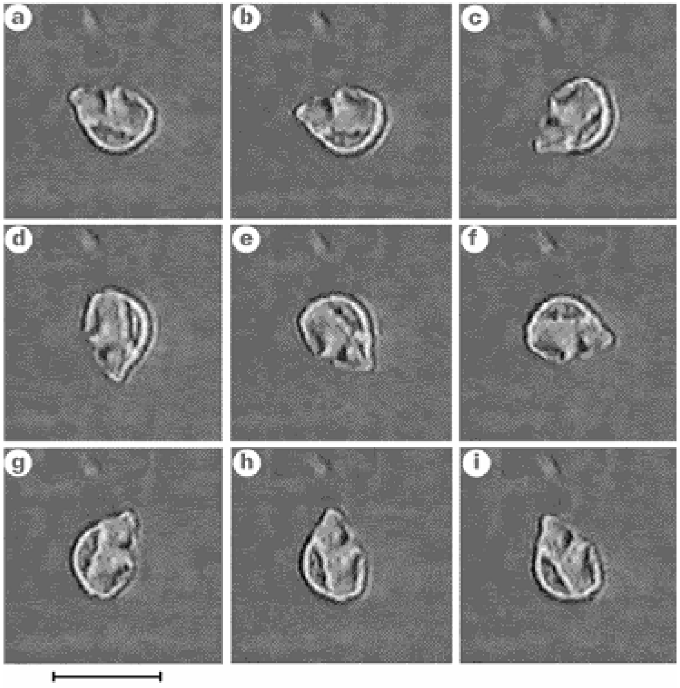

Figure 2. Nine Frames of a trapped calcite crystal showing free rotation due to an elliptically polarized trapping beam. Source: Friese et al. (1998).

Using a trapping beam that was initially linearly polarized, Friese and co-workers demonstrated the rotation of trapped particles of crushed calcite (Friese et al., 1998). The calcite fragments were trapped in plane-polarized light, causing them to be aligned in a particular orientation. As the plane of polarization was rotated using a half-wave plate, the particle's alignment exactly followed the rotation of the plane of polarization, thus allowing an optically trapped particle to be rotated through a preset angle, Figure 2. In addition, in circularly polarized light, the calcite particles rotated at a constant frequency proportional to the laser power. As these particles are transparent, they overcome the main concern of trapping absorptive particles, as they can now be held in optical traps at very high power without heating, leading to rotation rates of over 350 Hz.

FORM BIREFRINGENCE

The method described above has the important restriction that the trapped particle has to be intrinsically birefringent. In biophysics, optical traps are often used to trap and manipulate biological specimens such as living cells and organelles that do not possess such intrinsic birefringence, thus limiting this method's applicability. In their 2003 paper, Bishop and co-workers demonstrate the rotation of a trapped particle that possesses form birefringence (Bishop et al., 2003). Since elongated parti-

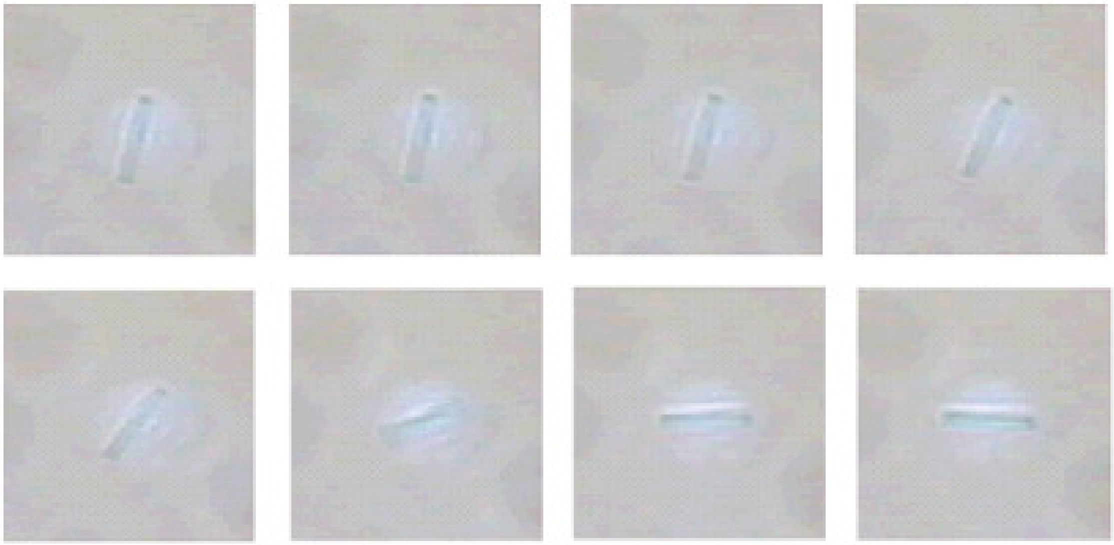

Figure 3. Microscopic glass cylinders following the rotating plane of polarization of the trapping beam. The length of the cylinder is 1.8 µm. Source: Bishop et al. (2003).

cles have different dielectric polarizabilities along their long and short axes (Jones, 1945), they are effectively birefringent, due to their form, and as such are readily rotated in an optical trap (Figure 3) based on the principle already described. Rotation rates up to 20 Hz were achieved for plane polarized light and 10 Hz for circularly polarized light.

Since in this case the main requirement is that the trapped particle be non-spherical, this method has broad generality especially in the field of biophysics as many biological specimens are asymmetric.

OPTICAL TORQUE WRENCH

In biophysics, optical traps are not solely used to trap and manipulate biological objects. An important aspect of the field has been in using microspheres as handles attached to biomolecules in an effort to measure the forces associated with various biological molecules and processes. The analog to this for rotating biomolecules is to manipulate handles attached to these biomolecules in order to measure the associated torques.

In 2004, LaPorta and Wang presented the optical torque wrench as an apparatus that does exactly this (LaPorta and Wang, 2004). Using nominally spherical anisotropic quartz particles, they demonstrate the ability to combine angular trapping with a detector that allows them to instantaneously measure the torque acting on the particle. They are also able to measure the rotational Brownian motion of their trapped particle, using that to determine their angular trap stiffness, while employing a feedback to control the applied torque or particle angle. Using an optical power of ~10 mW, they are able to rotate micron size particles with angular velocities up to 200 rad/s while generating several hundred pN·nm of torque (LaPorta and Wang, 2004).

Their torque detection is based on the conservation of angular momentum, which requires that the torque acting on the particle is equal and opposite to the rate of change of the angular momentum of the trapping beam as it passes through the particle. As they use birefringent particles, the angular momentum is transferred to the polarization state of the transmitted beam. Since they use linearly polarized light for their input trap beam, their initial beam contains no net angular momentum as it is composed of equal quantities of left and right circular polarizations. Generating a torque “τ” on a particle causes an imbalance in the power of the left and right circular components (P_L and P_R) of the transmitted beam, such that $\tau = (P_R - P_L)/\omega_0$, where ω_0 is the optical angular frequency. Direct measurement of this quantity is made by their torque detector. The measurement of torque acting on a particle spinning at uniform velocity is shown in Figure 4a. The traces show fluctuations in the torque signal with different mean values, the fluctuations arising from Brownian rotational motion of the particles.

To enable a feedback mechanism, they exploit the fact that the torque signal is related to the deviation of the particle from the trap polarization angle. By having a feedback to the polarization angle, they are able to demonstrate active stabilization of their torque signal, a feature they call a torque clamp. This is shown graphically in Figure 4b. With the ability to instantaneously measure the torque and stabilize it as needed, the applicability of this technique to measure the torque generated by various molecular motors is readily apparent.

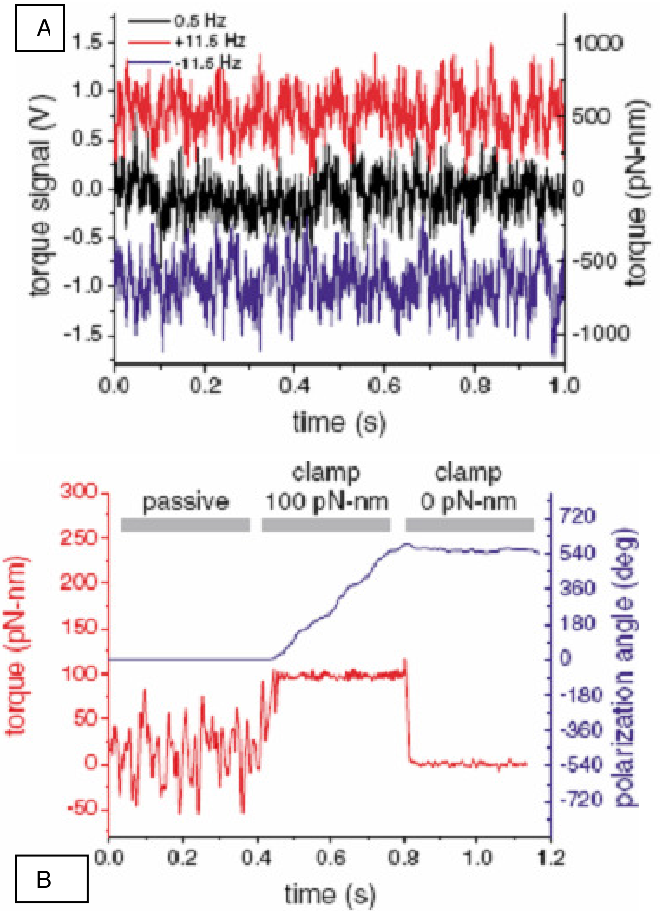

Figure 4a. Torque signal of a particle spinning in opposite directions. **4b.** Graphical demonstration of a torque clamp. Source: LaPorta and Wang, (2004).

SUMMARY AND OUTLOOK

The extension of the optical trap as a tool that combines trapping with the ability to manipulate the linear and rotational motion of particles is one that has greatly expanded the resourcefulness of the optical trap as a tool to study biological microscopic systems. From the ability to directly rotate biological objects, to using handles that enable instantaneous torque measurement and stability, the optical trap has increased in its robustness of function. Looking at the torque generated by molecular motors, or the super coiling of DNA are just some examples of topics of interest that can now be probed using the optical trap. An interesting corollary is to explore the application of these techniques in creating micro machines with rotating parts that could be useful for cell sorting, or lab-on-a-chip endeavors.

ACKNOWLEDGEMENTS

The author would like to thank George Shubeita for helpful discussions. The Schlumberger Foundation, through the Faculty for the Future program, is gratefully acknowledged for support.

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