Optically driven micromachines: progress and prospects

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ABSTRACT

The ability to exert optical torques to rotationally manipulate microparticles has developed from an interesting curiosity to seeing deployment in practical applications. Is the next step to genuine optically-driven micromachines feasible or possible? We review the progress made towards this goal, and future prospects.

Keywords: Optical tweezers, laser trapping, optical torque, micromachines, MEMS

1. INTRODUCTION

Although it was realised at the very advent of modern electromagnetic theory that optical torques could be exerted on birefringent materials,[1] the transport of angular momentum by light or other electromagnetic radiation[2] remained essentially a curiosity. That this was so is a remarkable contrast with the widespread use of transfer of angular momentum by electromagnetic *fields* in rotating electrical machinery of many types—these cases, however, making use of the *near field* rather than the *radiation* field. Even after optical forces had been experimentally measured, Poynting remained skeptical of the experimental detectability of optical torques, let alone their practical application, stating that "my present experience of light forces does not give me much hope that the effect could be detected".[2] Despite the difficulty of such an endeavour, optical torques were experimentally measured by Beth[3] and Holbourn[4]; the microwave equivalent followed in 1949.[5] Nonetheless, while the physics was interesting, and the laboratory achievements considerable and skillful, practical application appeared unlikely.

However, the spin angular momentum carried by an electromagnetic wave can be up to $\pm\hbar$ per photon. As a result, a circularly polarised beam carries $\pm P/\omega$ angular momentum about the beam axis, where P is the power, and ω is the angular frequency. This clearly shows that, *cetera paribus*, lower frequencies are more efficient at transporting angular momentum. Therefore, it is quite conceivable that at lower frequencies, a useful amount of torque can be exerted. For example, it was suggested that electromagnetic torques might be useful for controlling the orientation of spacecraft.[6]

A closer look at the scaling of electromagnetic torques shows us an interesting fact.[7] While the angular momentum carried by a beam might be P/ω, the amount of angular momentum that can be *transferred* to some object depends on what fraction of the beam is intercepted by the object. The minimum width of a beam of given frequency is on the order of the wavelength, so we can consider the minimum cross-sectional area of the beam to be on the order of λ^2. Therefore, the irradiance I is

$$I \approx P/\lambda^2 \tag{1}$$

and the power incident on an object approximately d across, smaller than the width of the beam, will be

$$P_{\text{inc}} \approx Pd^2/\lambda^2. \tag{2}$$

where d is the scatterer size. Therefore the torque that can be exerted on the object is on the order of

$$\tau \approx Pd^2/2\pi c\lambda. \tag{3}$$

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For small objects, greater efficiency results from the use of *shorter* wavelengths, suggesting that for microparticles, optical frequencies offer the best possible performance.

For objects larger than the beam, the scaling as P/ω suggests that better efficiency is obtained by the use of longer wavelengths. However, this assumes that only spin angular momentum is used. If orbital angular momentum, which can be hundreds of $\hbar$ per photon, is exploited, equivalent performance can be retained for shorter wavelengths. For a strongly focussed optical vortex mode carrying $m\hbar$ orbital angular momentum per photon, such as an LG_{0m} Laguerre–Gauss mode laser beam focussed by a high numerical aperture objective, the radius of the ring of light in the focal plane is approximately $m\lambda/2\pi$,[8] a direct consequence of the angular momentum of spherical wave modes.[9,10] The angular momentum carried by such a beam is mP/ω, and hence the angular momentum transferred to an object can be kept constant by increasing the orbital angular momentum per photon rather than the wavelength.

Therefore, for objects of the size typically encountered in laser traps, not only does the fact that optical forces can be usefully used to manipulate the object suggest that optical torques might also be useful for rotational manipulation, but the above considerations also mean that optical frequencies are also the most efficient for the rotational manipulation of such particles by electromagnetic radiation.

While a wide range of applications were readily found for optical tweezers shortly after its introduction,[11] it took close to a decade for the first real steps towards optical micromachines to be made.[12–27] This work both stimulated and benefitted from more general work on optical rotation and optical torque, most notably from the pioneering work of Les Allen[28–32] and work carried out at The University of Queensland,[7,10,33–39] the University of St Andrews[40–47] and the University of Glasgow,[48–59] and elsewhere.[60–78]

Despite this plethora of demonstrations, explorations, and proofs-of-principle, it has turned out to be far from simple to develop optical micromachines ready for deployment in practical applications. The sheer novelty of optical drive, and the difficulty of easy, cheap, and rapid fabrication of prototypes surely contribute to this. However, optically-driven micromachines are already seeing use in practical applications, such as a microviscometer.[79–81] The development of techniques for building complex optical micromachines has been impressive,[82,83] and practical devices appear imminent.

Notably, the optically-driven microviscometer is close to the simplest possible optical micromachine, consisting of a single birefringent microsphere, the trapping beam, and optics outside the microscope. Other simple microtools, intended to be manipulated by the trapping beam and used in a manner analogous to conventional tool use by humans, are at the stage where they could be used in appropriate applications.[84,85]

Three features distinguish most of the above micromachines and microtools from conventional micromachines: they are significantly smaller, being closer to a micron in size than a millimetre; they operate in a fluid environment, in intimate contact with the fluid; and they do not require physical contact with the surroundings. Where any or all of these elements are required, optically-driven micromachines are possible candidates for the task.

2. HOW OPTICALLY-DRIVEN MICROMACHINES WORK

Associated with the incident laser beam is an angular momentum flux. The angular momentum associated with the beam can be spin angular momentum, orbital angular momentum, or both.[86–88] The spin angular momentum density and flux is, by definition, independent of the choice of origin of the coordinate system, while the orbital angular momentum density, equal to the moment of the momentum density, $\mathbf{L} = \mathbf{r} \times \mathbf{S}/c^2$, where $\mathbf{S}$ is the Poynting vector, explicitly depends on the choice of origin. it is interesting to note that for optical vortices, characterised by integral orbital angular momentum per photon, have a *total* orbital angular momentum flux (ie the orbital angular momentum flux integrated across the beam profile) that is independent of the choice of origin; this has been termed "intrinsic orbital angular momentum".[52] In general, we can say that the spin angular momentum is determined by the polarisation of the beam, with left and right circularly polarised beams carrying $+\hbar$ and $-\hbar$ per photon, and the orbital angular momentum is determined by the shape and phase structure of the beam. For the orbital angular momentum about the beam axis to be zero, an azimuthal component of the Poynting vector is required. This can be provided by making use of optical vortices.

An object in the path of the beam can alter either the spin or orbital angular momentum fluxes, and since, in general, this will result in the outgoing angular momentum flux differing from the incident angular momentum flux, there will be a reaction torque exerted on the object.

We can distinguish two main mechanisms through which the angular momentum of the beam can be altered. Birefringence, whether microscopic in origin, as in birefringent materials, or macroscopic, in the case of shape or form birefringence, will alter the state of polarisation, and hence the spin angular momentum of the beam.

To alter the orbital angular momentum of the beam, the azimuthal component of the Poynting vector must be changed. This has led to a number of designs based on geometric optics, using chiral asymmetry to preferentially deflect the incident beam in one azimuthal direction. However, since optically-driven micromachines are typically of sizes where geometric optics cannot be relied upon, such explanations are not entirely satisfactory.

Instead, a more general picture of the transfer of angular momentum based of the effect of symmetry on scattering by an object can be used.[7,10] Essentially, rotationally symmetric particles cannot alter the angular momentum per photon about the symmetry axis, and hence optically-driven micromachines must deviate from rotational symmetry about an axis parallel to the beam axis. This is considered in more detail in the next section. For now, we can note that such a general picture, based on rigorous electromagnetic wave theory, is valid for all object sizes, wavelengths, and is free from any problems associated with breakdown of the clear separation of spin and orbital angular momenta in the paraxial limit for the tightly focussed beams employed in optical tweezers.

Since optical forces and torques result from scattering, in the general sense, the calculation of optical forces and torques is reduced to computational light scattering. Most work on light scattering has been restricted to spherical particles, due to the availability of analytical solutions, but there is a strong interest in, and active research in the scattering of light and electromagnetic radiation by nonspherical particles.[89,90] Although complications are introduced by the presence of a tightly focussed beam,[9] the computational methods employed in problems of light scattering by nonspherical particles provide a sound and working foundation for the calculation of optical forces and torques.[39,91]

The extension of these methods to complex structures results in greatly increased computational costs; in order to minimise the time and computational resources required, symmetries—such as discrete rotational symmetry, and mirror symmetry—can be (and should be!) exploited.[92]

3. DESIGN FUNDAMENTALS

The difficulty of computational modelling means that an element of initial design is required to obtain a suitable starting point, even if computational methods will be used to determine optimal parameters for the structure. Therefore, the general principles discussed above are of practical value as they can be readily applied to initial design.

The symmetry considerations noted above provide a suitable starting point. In general, rotating optical micromachines can be expected to be either birefringent or to possess discrete rotational symmetry.[10] The essential functioning of birefringent micromachines can be understood in terms of their function as waveplates[35,37]; micromachines depending on shape present a more complicated case. While geometric optics has often been applied to try to understand such structures, it should be realised that micromachines of this type, while of overall dimensions that suggest that geometric optics might be applicable, have features in the size range where geometric optics fails. Therefore, a more direct consideration of the effects of symmetry on the generation of optical torque is useful.[10]

A simplified picture of optical rotation can be obtained from this: optical micromachines as microholograms. While this picture of optically-driven micromachines may well be coloured by our prior experience with using holograms to transform the orbital angular momentum of laser beams, it appears to be a sound and reliable principle. The designs of practically all of the optical micromachines intended to be rotated by a single beam noted above can be understood in terms of this picture.

Figure 1 shows some simple examples of optically-driven rotors. Both of these can be considered as binary approximations of on-axis holograms as used for the introduction of orbital angular momentum into laser beams.[93]

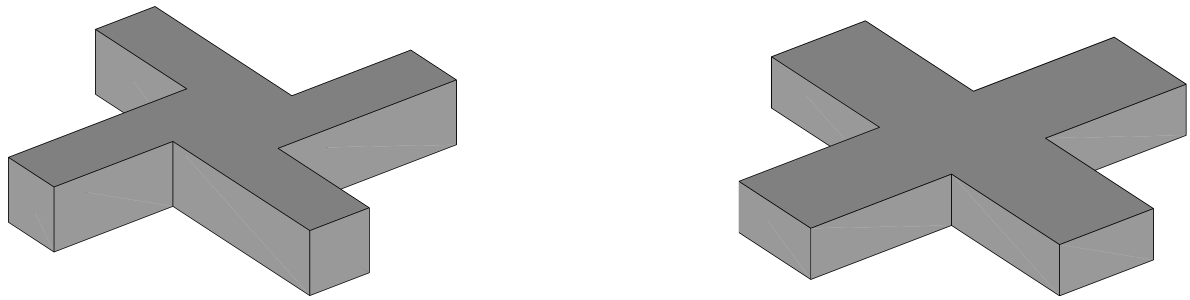

Figure 1. Optically-driven rotors.

The two rotors portrayed in figure 1 operate in a similar manner, but with one important difference: the left-hand rotor is chiral, while the right-hand rotor is mirror-symmetric. As both have fourth-order discrete rotational symmetry, incoming light is scattered into angular momentum modes with angular momenta differing from the incident angular momentum by an integral multiple of $4\hbar$ per photon.[10] If the incident beam carries zero angular momentum, the chiral rotor will tend to scatter light more strongly into, say, the $+4\hbar$ mode than the $-4\hbar$ mode, with a resultant torque. This is exactly the same mode of operation as the spiral zone plate holograms used by Heckenberg et al.[93] Noting that such a spiral hologram is the interference pattern between an optical vortex mode and a spherical wave, with the handedness of the interference pattern depending on whether the spherical wave is converging or diverging, the direction of the torque should also depend on whether or not the trapping beam is converging or diverging. That is, it should be possible to reverse the sense of rotation by shift the focal plane relative to the rotor; this behaviour has been observed.[26] The achiral mirror-symmetric rotor, on the other hand, will scatter the beam equally into both modes, and no torque will be generated. The practical application of such a rotor would be when the incident beam carries orbital angular momentum. In this case, the rotor can act to reverse (a portion) of this orbital angular momentum, with a resultant torque being generated. The mirror-symmetry is necessary to ensure torques of equal magnitude when the handedness of the driving beam is reversed.

An alternative design that can be employed to generate torque using a zero-angular-momentum incident beam is to use a blazed microhologram. Optical rotors with sloped surfaces on the upper or lower faces usually make use of this principle.

3.1. Realization of designs

It is of course necessary to, at some point, physically realise the design. While conventional microfabrication methods may be useful for mass production, they are less convenient for testing and prototyping. One useful technology is two-photon photopolymerisation; this technique is reviewed and described in detail by Knöner et al.[94]

Self-assembly may also be useful. The production of birefringent vaterite microspheres[79] is one example of the application of such a method.

4. PROSPECTS

Where then does the future of optically-driven micromachines lie? The survivability of optically-driven micromachines in fluid environments, and the ability to remotely deliver power to them, suggest that optical methods may be very useful for driving and controlling moving parts in lab-on-a-chip applications; significant progress towards this has already been made.[82, 95]

The small size that can be achieved also suggests the development of simple single-purpose one-piece microtools that can be used to manipulate, probe, and otherwise explore or influence the surroundings. This is probably of most interest in biological research, where such devices could be used to poke and prod live cells, and measure the responses, with a much finer spatial resolution that available using conventional optically trapped microbeads.

The vital components for the realisation and application of optically-driven micromachines are available. Our understanding of optical application of force and torque has greatly improved, computational methods for the modelling of devices have been developed, and are being constantly improved, and increasingly sophisticated microfabrication technologies become available. The optically-driven micromachine has developed from being an imaginative idea to being practically achievable.

For the moment, the vision of freely-moving complex optical micromachines that can be remotely moved and manipulated, with multiple moving parts that are themselves controlled and driven optically, used to perform various functions on demand, remains out of reach. Nonetheless, the more modest siblings of such devices are already available. If the first applications of the presently feasible micromachines prove rewarding, then further development and increasing sophistication will follow.

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