Tailoring Particles for Optical Trapping and Micromanipulation: An Overview

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Abstract— Optical trapping and micromanipulation has developed from an interesting novelty to a powerful and widely used tool, with the capability to move or trap microscopic live biological specimens and measure forces on the order of piconewtons, typical of forces in microbiological systems. Despite this, the range of particles typically trapped or manipulated is quite small, and it is unusual to see applications involving objects other than biological specimens or homogeneous isotropic microspheres, typically polymer or silica.

However, particles can be modified or specially fabricated to expand the possible applications of optical tweezers. For example, while non-absorbing homogeneous isotropic spheres cannot be rotated, optically anisotropic spheres can, and can therefore function as microscopic torque sensors, extending the usual translational micromanipulation and force measurement to rotational manipulation and torque sensing. The development of such particles has led to applications in microscale metrology and biophysics, along with potential deployment of optically-driven micromachines in lab-on-a-chip devices.

We present an overview of our work on the tailoring of microparticles for versatile optical trapping and micromanipulation. This includes approaches based on controlled chemistry — nanoassembly — and optical microfabrication. Beginning with the production of anisotropic vaterite microspheres, we review some of the applications, and difficulties encountered along the way. Some of these difficulties can be overcome by coating of the vaterite microspheres. We also discuss the use of anti-reflection coating to allow strong trapping of high refractive index particles. The alternative strategy of producing arbitrarily shaped polymer microstructures through two-photon photopolymerization is also discussed. This can be used to produce optically-driven microrotors or structurally anisotropic microspheres to replace vaterites for particular applications.

1. INTRODUCTION

Optical tweezers have developed from an interesting novelty of physics, directly demonstrating the transport of momentum by light, to a versatile and widely-used tool, especially for biological applications. A key element in this growth has been the ability to measure forces on the order of piconewtons—an optical tweezers trap can be approximated as a harmonic potential and measurement of displacement within the trap yields the optical restoring force. Optical tweezers are also useful for capturing, holding, and moving biological specimens. Despite this, the typical application usually involves the trapping of polymer or silica microspheres. Notably, this immediately removes the possibility of angular or rotational manipulation or torque detection, as the rotational symmetry of a sphere means that no optical torque can be exerted in the absence of absorption. Furthermore, trapping is limited by competition between the gradient force acting to trap particles, and the scattering force acting to push particles out of the trap in the direction of propagation of the trapping beam. Since the reflectivity of the particle increases as the relative refractive index increases, this restricts the range of particles that can be effectively trapped.

However, particles can be specially fabricated to extend the potential of optical tweezers, especially with regard to optical measurements of torque and rotational micromanipulation. We provide an overview of work carried out by ourselves and others in this field. Two different strategies have been applied: chemistry, and optical microfabrication. The first has yielded vaterite microspheres as the most promising tool for high-torque rotation in optical tweezers developed so far, and the latter allows the production of arbitrary structures, including a diverse range of optically-driven rotors.

For rotational manipulation, a key element is that the particle must not be rotationally symmetric. Rotational symmetry can be broken either on the microscopic scale, through the use of an optically anisotropic material, such as birefringent crystals or polymers, or on a larger scale, by a non-rotationally symmetric shape. Depending on the shape, the effect can be predominantly form-birefringence, optically identical to material birefringence in effect, or can involve coupling to modes of light carrying orbital angular momentum. The latter type of particle can be thought of as microscopic versions of the holograms often used to generate orbital angular momentum carrying beams.

When the torque is a result of birefringence, there is an accompanying change in the degree of circular polarization of the trapping beam. This can be measured optically, giving an all-optical determination of the applied torque [1]. This is the case for both material birefringence and form-birefringence [2]. This allows the rotational equivalent of the force-sensing applications that have become a standard application of optical tweezers, and has been a major motivation for the production of birefringent particles for optical trapping.

2. VATERITE MICROSPHERES

Although it was realised many years ago that optical measurement of the torque exerted on birefringent particles by the trapping beam offered the potential to measure other external microscale torques, such as the viscous or visco-elastic resistance of the surrounding medium, it was clear that spherical birefringent particles would be best for such purposes, since the surrounding fluid flow field is given by a simple analytical formula. The lack of a readily available spherical birefringent particle made metrological applications difficult — generally, there would be unknown viscous drag torques.

The synthesis and optical rotation of vaterite microspheres proved to be a decisive advance in rotational micromanipulation [3]. Vaterite is a semistable calcium carbonate ($CaCO_3$) mineral that rarely occurs in nature, and is a positive uniaxial birefringent crystal. It may, however, be grown in the laboratory, and under certain conditions, it forms polycrystalline spheres with radii on the order of microns. It is important that the material be positive uniaxial, since in that case, the optic axis will align with the electric field of a plane-polarized trapping beam, or will lie normal to the beam axis of a circularly polarized beam. Thus, the particle retains its deviation from rotational symmetry about the beam axis, whereas a negative uniaxial material will tend to align such that the optic axis lies on the beam axis, presenting a rotationally symmetric aspect to the trapping beam, which means that no optical torque can be exerted.

Vaterite microspheres have proved useful for microscale viscometry [3, 4], and have also seen use as optically-driven micromachines in lab-on-a-chip devices [5].

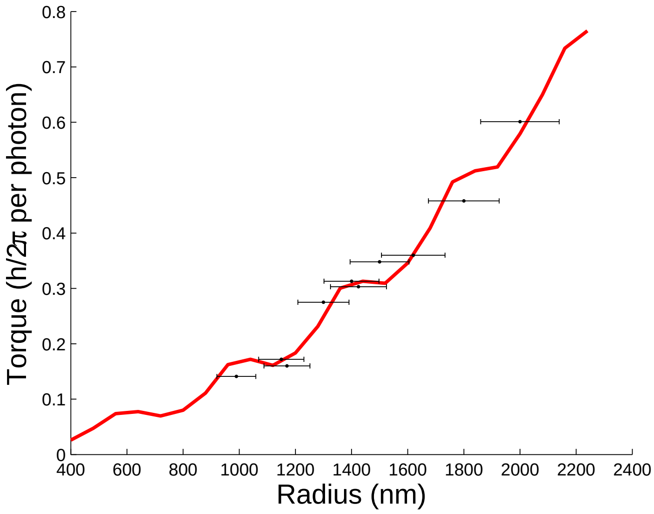

Figure 1: Calculated (solid line) and measured (points) optical torque on vaterite microspheres.

Interestingly, the vaterite microspheres appear to have a “sheaf-of-wheat” internal structure [6]. Modelling the optical trapping vaterites as inhomogeneous particles with a local optic axis given by this model closely matches the observed torque, as shown in Figure 1, supporting this model [7].

However, the application of vaterite to the study of biological systems such as rotational molecular motors and the rotational mechanics of biomolecules has been seriously hampered by the chemistry of vaterite. Firstly, as a calcium carbonate crystal, vaterites have a very short lifetime in many solutions of interest, such as commonly used buffer solutions for biological specimens, such as phosphate buffered saline (PBS). Secondly, specific attachment of molecules such as DNA to vaterite is difficult.

In an attempt to solve these problems, we have coated vaterite microspheres with silica. The coating is formed by condensation of tetraethoxysilane (TEOS) in ehtanol-water solution according to the Stöber method [8]. The thickness of the coating can easily be adjusted by varying the amount of TEOS used, and multiple coatings may be applied to achieve any desired thickness. The coating allows attachment of a greater range of biomolecules, and affords the underlying vaterite some protection from the environment.

3. ANTI-REFLECTION COATING

The ability to coat vaterites with silica — and the process will also work for other types of particles — suggests a further use for this type of modification of microparticles: anti-reflection coating for improved trapping. High refractive index particles are usually difficult to trap, because their high reflectivity results in a significant fraction of the trapping beam being back-scattered, with a resultant optical force, the so-called "scattering force", acting to push the particle out of the trap in the direction of propagation of the beam. Since anti-reflection coating of optical components is a standard practice to reduce reflection, a similar strategy would appear to be feasible for microparticles.

Since, ideally, the coating should have a refactive index of $n_{\text{coating}} = (n_{\text{medium}} n_{\text{particle}})^{1/2}$, it would be very useful to be able to control the refractive index of the silica coating. This is generally done by changing the porosity of the silica which, in turn, can be done in several ways. To some extent, the porosity of a TEOS coating may be varied by simply changing the ethanol/water ratio in base catalyzed reactions [9] or the water/TEOS ratio in acid catalyzed reactions [10]. High porosity may also be induced by the addition of surfactants such as octadecyltrimethoxysilane (C18TMS) [11, 12] or alkyltrimethylammonium bromide (CnTAB) [13] to the polymerization process followed by removal of the organic group by calcination. Interestingly, by using a multiple-coating approach, with variation of the refractive index, it should be possible to produce gradient-index coated particles. The improvement in trapping resulting from coating is shown in Figure 2.

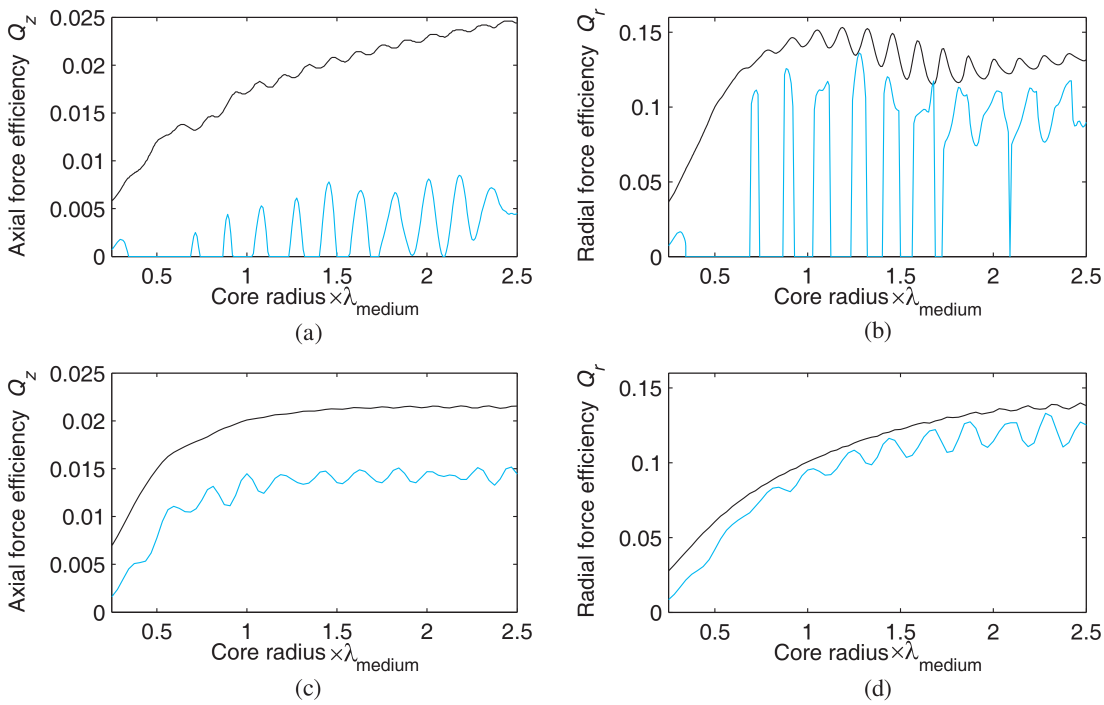

Figure 2: Axial and radial trapping efficiencies for coated (black) and uncoated (cyan/gray) particles with (a), (b) $n = 1.8$ and (c), (d) $n = 1.6$.

4. MICROFABRICATION BY TWO-PHOTON PHOTOPOLYMERIZATION

Another strategy for the production of specially-designed particles is to use optical microfabrication, based on two-photon photopolymerization. This technique was pioneered by Strickler and Webb in 1991 [14], following the application of two-photon excitation in two-photon laser scanning fluorescence microscopy [15]. The first 3D structures microfabricated using two-photon polymerization were reported in 1997 [16], spiral structures with a diameter of 6 µm and a wire width of 1.3 µm. Since then, various micromachines have been produced (micropumps, microgears, microneedles) with high resolution [17–19].

We use the NOA series of UV curing resins from Norland Products for the fabrication of our devices. They are based on a mixture of photoinitiator molecules and thiol-ene monomers. These resins are photopolymerized when exposed to light with wavelengths shorter than 400 nm and require an energy flux of 2–4.5 J/cm^2 for full curing. We use a femtosecond laser at 780 nm, with an 80 fs pulse length and an 80 MHz repetition rate. A computer-controlled shutter is used to control the beam, which is turned on or off as needed as the stage is moved, building up a three-dimensional structure voxel-by-voxel by layer-by-layer raster scanning (see Figure 3). Lateral steps are 100 nm, and steps in the z direction are 200 nm. The structures are grown upside down on the upper coverslip in an inverted microscope, with an objective of numerical aperture of 1.3. This top-down scanning method has the advantage that the laser beam does not pass through already exposed resin on the way to the focus, reducing the possibility of distortion of the focal spot.

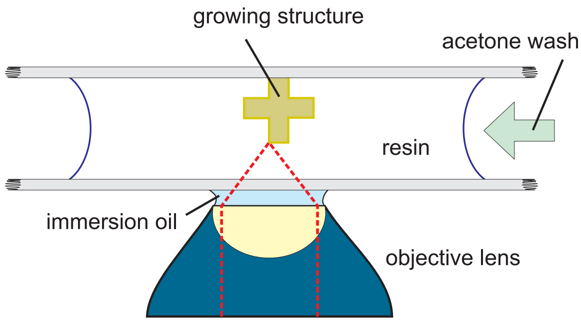

Figure 3: Two-photon photopolymerization.

After the polymerization, the unexposed resin is washed off with acetone, leaving the 3D structure attached to the coverslip. The first structures we produced were 3D chiral objects with 4-fold rotational symmetry (off-set crosses) which are ideal as optically driven microrotors [20, 21].

5. CONCLUSION

We have described some of the possibilities of, and existing applications of, the fabrication of particles specially tailored for specific applications in optical trapping. In particular, such particles can be electromagnetically or structurally anisotropic, allowing optical torques to be exerted. This greatly expands the manipulation possible with optical tweezers, introducing rotation and spinning, and allowing the measurement of microscale torques.

Optically microfabricated particles, produced using two-photon photopolymerization, have potential for use as optically-driven micromachines. Space does not permit a full coverage of this interesting field, but a recent review is available [22].

Finally, even simple modification of microspheres by coating offers improved trapping, the trapping of otherwise untrappable high-index particles, and permits the use of lower numerical aperture optical systems.

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