Optically driven plasmonic nanorotors

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Optical trapping using focused laser beams (laser tweezers) has been proven extremely useful for contactless manipulation of a variety of small objects, including biological cells, organelles within cells and a wide range of other dielectric micro/nano objects. Colloidal metal nanoparticles have drawn increasing attention in the field of optical trapping because their unique interactions with electromagnetic radiation, caused by surface plasmon resonance effects, enable a large number of nano-optical applications of high current interest, such as plasmon based biochemical sensing, surface-enhanced Raman spectroscopy and optothermal control at the nanoscale [1].

We found that single-crystal gold nanorods with side-lengths of the order 160 nm could be easily trapped and manipulated by laser tweezers inside thin liquid cells compatible with standard optical microscopy [2]. The nanorods could be rotated extremely, reaching rotation frequencies above 40 kHz (2.5×10^6 r.p.m.), by applying circularly polarized laser light with power as low as a few mW. To the best of our knowledge, this is the fastest rotation of any kind of object, natural or man-made, in a liquid environment. The driving torque, caused by transfer of photon angular momentum (spin), is dominated by plasmonic resonant scattering rather than absorption, which drastically reduces laser-heating effects. The nanorods rotational dynamics was found to be highly dependent on their surface plasmon resonance properties, which can be finely tuned through their nanoscale morphology. Single nanorods could be kept continuously rotating for hours and applied for measurements of molecular binding, local viscosity and temperature with high sensitivity by reading out their rotation frequency or their surface plasmon resonance frequency versus time. By varying the applied laser power, the surface temperature of the rotating nanorods could be varied from close to room temperature to well above the boiling point of water, thus affording a simple means of thermal control over chemical or conformational reactions of adsorbed molecules. Because of their biocompatibility, stability and record rotation speeds in aqueous solution, these rotary nanomotors could potentially advance technologies to address a wide range of nanooptical, nanomechanical and bioanalytical questions in fields such as biophotonics, nanomotors, macromolecule manipulation, microfluidic flow control and nano-rheology.

References

Figure 1: (a) We trap plasmonic gold nanorods using laser tweezers and rotate them using circularly polarized light. (b) The nanorods are single nanocrystals (scale bar = 100 nm). (c) The rotational dynamics can be measured by recording the scattering autocorrelation function. The example shows a rod that spins at 42.5 kHz. (d) Maxwell stress tensor calculations showing that the optical torque is dominated by resonant light scattering. (e) Ensemble averaged extinction spectra of nanorods with varying aspect ratios and plasmon resonances. (f) Rotation frequency vs. laser power (λ = 830 nm) for individual nanorods from the batches in e). (g) Measured temperature extracted from the autocorrelation decay for the same nanorods. (h) Calculated temperature for the same nanorods. (i) Rotation frequency vs. viscosity for nanorods in different water:glycerol solutions. (j) Rotation frequency vs. time as a monolayer of thiolated polymers form on the surface of a spinning nanorod.
Beam shaping of light can be performed with devices such as spatial light modulators (SLMs) and digital micromirror devices (DMDs). Beam shaping has applications in optics, quantum mechanics, communication, 3D printing, and optical manipulation. Several single-pass beam shaping methods [1, 2, 3] are investigated in terms of the wavefunctions of scattered light to rationalise the different methods into a consistent framework. For uniform polarisation on a discrete device a scalar approximation of light can be used to model the state:

\[ \psi_{nm} = A_{nm} \exp i\Phi_{nm} \]  

(1)

where \( \psi_{nm} \) is the wave function at each element of the device, \( A \) and \( \Phi \) are respectively the amplitude and phase at the device plane. Both SLMs and DMDs are limited by their ability to modify the wave function of light. Liquid crystal on silicon SLMs cannot modulate amplitude and DMDs cannot modulate phase. The diffraction off these devices can, however, be planned such that a particular mode amplitude is locally accessible in a plane far from the device. Combining this with spatial filtering enables only desired mode amplitudes to be transmitted and to shape the beam. Beam shaping is achieved by blending (dithering) distinct diffraction patterns with the target pattern to separate the diffracted light into the desired amplitude and phase. The most commonly used function for single-pass beam shaping is a wedge function:

\[ f_{nm} = g_n n + g_m m \]  

(2)

where \( g_n \) is a weight for the wedge in \( n \) and \( g_m \) for \( m \). Weighting of this function displayed on a SLM is a sinc in phase. On a DMD this is more straightforward simply based on the probability distribution.

Figure 1: From left to right: phase used on the SLM, simulation of diffraction, experimental realisation. Excellent correspondence can be observed.

Figure 2: From left to right: amplitude used on the DMD, simulation of diffraction, experimental realisation. Excellent correspondence can be observed.

Our theoretical and experimental analysis of the efficiency, behaviour and limitations of single-pass beam shaping methods is applied to both theory and experiment. Figure 1 demonstrates that after full characterisation of our SLM system excellent reproduction of the mode is achieved. The same is demonstrated in figure 2 for the DMD. Incident beam mode shape, aberration, and the amplitude/phase transfer functions of the DMD and SLM impact the distribution of scattered light and hence the effectiveness and efficiency of a beam shaping method. Corrections to the experimental beam shaping apparatus can be implemented by accounting for experimental parameter variations. We have several conclusions from our investigation of both devices: 1) The look up between device voltage and real phase affects the diffraction efficiency of spots and the local distribution of amplitude and phase (SLM—the separation of these modes is displayed in figure 3). 2) The optimal aberration correction changes as the look up changes (SLM). 3) Different types of target patterns have diverse properties making them more or less sensitive to physical parameters such as phase level (DMD and SLM). 4) Every wedge function has a different diffraction efficiency unless the particular device has no field effects (DMD and SLM). A good rule of thumb when implementing beam shaping is to think of it not so much as shaping but redirecting light into a target pattern.

References


The finite difference time domain (FDTD) method is a very versatile method which has seen only limited application to simulating optical tweezers. This is perhaps in part due to the abundance of other suitable methods for modelling the simpler scenarios commonly encountered in optical trapping. However, traps involving large complex structures and traps near surfaces are becoming more common, these scenarios are difficult to simulate using tools that have typically been applied to optical tweezers, due to excessive time or memory requirements. FDTD is a relatively simple algorithm that offers better scalability with particle size, thus it can be used to extend the range of optical tweezers problems that can be simulated.

First described by Yee in 1966 [1], FDTD solves Maxwell's equations in the time domain using second order numerical approximations for position and time derivatives. The method requires the electric and magnetic fields to be stored at discrete grid locations spanning the simulation space. The grid resolution is determined by the size of simulation features and illumination wavelength. As such the memory requirements scale with roughly the cube of the particle size. The numerical stability condition places a restraint on the maximum time step size in terms of the time it takes information to propagate across the simulation space. This leads to simulation time scaling roughly with the fourth power of the particle size. In comparison to other methods for simulating optical trapping, FDTD has lower memory and computational time requirements, but the use of second order accurate numerical derivatives make it less accurate in the regions where the other methods run without additional simplifications to the problem. A comparison of a few common methods is shown in Figure 1.

FDTD is already used in a variety of other fields including dosimetry and plane wave scattering calculations, but there are no dedicated implementations for 3-dimensional optical trapping simulations [2]. One might think that existing tools could be easily applied to simulating optical tweezers, however optical trapping calculations are typically only concerned with specific parameters such as the force and torque on a particle, and often require non-plane wave illumination such as tightly focussed Gaussian beams. A dedicated and configurable FDTD implementation, able to directly calculate properties of interest to optical tweezers simulations, would be a valuable addition to the computational tools available for optical tweezers simulations. The simplicity of Yee's FDTD algorithm means that a dedicated FDTD implementation for optical trapping is feasible in a relatively short amount of time. Using a new FDTD implementation written in C++ specifically for simulating optical trapping problems we intend to begin exploring various scenarios previously beyond our reach.

In this presentation I will discuss recent work using our new FDTD implementation to simulate a variety of optical tweezers related scenarios. The FDTD implementation is still under development. Preliminary results using the new implementation are shown in Figure 2 (a) and (c). Figure 2 (b) and (d) depict a couple of scenarios that could be investigated with the FDTD implementation. Other scenarios of interest include trapping of gold particles in evanescent fields using LG beams and calculations of torques on uniaxial media from tightly focused Gaussian beams, such as phase plates of different thicknesses and torques on large birefringent particles. It should also be possible to explore parameter search spaces to optimize, for example, micro-rotor or micro-machine designs.

Figure 1: Comparison of different methods used for trapping simulations including FDTD, Finite Difference Frequency Domain (FDFD), Discrete Dipole Approximation (DDA), Rayleigh Approximation and Ray Optics Approximation.

Figure 2: a) deflection of a weakly focussed incident beam by a wedge shaped particle, b) a possible micro-rotor geometry, c) force on a spherical particle displaced radially at the focus of a tightly focussed beam, d) concept for plasmonic evanescent field optical sorter.

References

Absolute calibration of optical tweezers for measurement of non-optical forces

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Optical tweezers are a versatile tool in biophysics for their ability to noninvasively measure piconewton forces within biological environments. These force measurements are typically done through the trapping of a probe particle which is calibrated. Calibration typically depends on the properties of the environment and probe particle, such as viscosity, refractive index of the environment, size and shape and refractive index of the particle. This calibration normally would need to be repeated for every probe particle and trap arrangement in the trapping medium. This becomes difficult, particularly in biological environments, where the probe particle and trapping medium are not characterised.

Absolute calibration is when optical tweezers are calibrated for a general set of probe particles, media and trap shapes. Here we present an absolute calibration of optical tweezers by synchronising force and position measurements. This absolute calibration can be used for more arbitrary probe particles, which removed the need to use a sphere as a probe particle. We also show that it is not necessary to have synchronous measurements for some purposes.

The position sensitive detector (PSD) and camera are commonly used to track probe particles in optical tweezers arrangements. The position sensitive detector is generally favoured over the camera for faster data collection rates, but it is still common to have a camera in a tweezers setup for viewing. Although they are both used to track particle position, they are measuring different quantities. A position sensitive detector measures the deflection of the trapping beam by the probe particle. Thus it is a measurement of the optical (trapping) force. A quadrant photodiode (QPD) is also commonly used to track particle position. Once calibrated, like the position sensitive detector, it measures the deflection of the trapping beam. However, the quadrant photodiode requires calibration, which requires a Gaussian trapping beam. Thus the position sensitive detector is favoured over the quadrant photodiode for our purpose of absolute calibration. A camera requires another beam, an illumination beam, and it measures the shadow of the particle. This would be a measurement of the position of the probe particle. However, we can calculate a force from these positions, and this force represents all forces that influence the particle: not just the optical trapping force.

By synchronising the force and position measurements, we can find the force when a particle is in a particular position in the trap. Although there are difficulties to do this experimentally, we find that there is fair agreement between simulation and experiment with our arrangement for collecting synchronous force and position measurements.

We also find that it is not necessary to have synchronous force and position measurements. By sorting the force and position measurements by quantiles, we are able to map out a force-position relationship for the particle in the trap.

This sorting method of calibration has the feature that it only contains the optical force of the trap, since it is the force of the deflection of the trapping beam which is measured. We can compare this solely optical force with the force calculated from the position.

The occupation probability of the positions allows us to calculate the total force acting on the probe particle. This gives us a method to measure non-optical forces that could be acting on a trapped probe particle, as demonstrated in Figure 1 where the probe particle is trapped near a wall.

![Figure 1: Force calibration curve of a simulated optically trapped probe particle near a springy wall, with two different methods of calculation. The coloured blocks show the calculated calibration curves and the lines show the inputted forces. We compare the force calibration curve mapped from sorting force and position measurements (blue) with the force calibration curve from the occupation probability (orange) and see that there is a difference (green) between these forces. This difference is the contribution of non-optical forces acting on the probe particle.](image)

We see in Figure 1 that the force calibration curves obtained through the two methods do not have the same value. The curve obtained from the occupation probability, so from the position measurements collected by the camera, has all forces acting on the particle. The curve obtained from mapping the sorted force and position measurements, where the forces were collected by the position-sensitive detector, has only the optical force acting on the particle. Thus, the difference of these two curves must be non-optical forces. In this case, it is the wall force.

By implementing this method, we can use optical tweezers to measure the non-optical forces acting on a probe particle. Examples of where this could be useful include measuring the behavior of a probe near a wall or boundary, and also the forces of a particle which has its own motion such as sperm or bacteria.
Ultra-high bandwidth tracking of micro/nano particles in fluid

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Since the discovery of Brownian motion of particle in a fluid in 1827, the hydrodynamic interactions between the particle and the fluid has been studied extensively. Later on in 1907, Einstein explained the behaviour of Brownian particle in a fluid postulating that particle in any fluid is kicked by the fluid molecules and its mean squared displacement from the initial position is an asymptotically exponential function of diffusion time [1, 2]. For Brownian motion studies, optical tweezers are the fastest available tools to measure the displacement fluctuation of optically trapped particle in any fluid [3]. In typical optical trapping systems, the measurement bandwidth of micron sized particle position is 500 kHz while higher bandwidth can be achieved by using large amount of power (>100mW) and reducing technical noise [4-6]. However, optical heating effects can alter the localized properties of the fluid and therefore, their dynamical behaviour like morphological changes and viscoelasticity cannot be measured reliably above 500 kHz [7].

In our optical tweezers, by reducing the technical noises, we demonstrate that micro/nano sized particles can be tracked at ~2 MHz bandwidth while using 6 mW of power on the specimen. Glass particles are tracked in water using optical tweezers and their diffusion is analysed using Einstein's theory of Brownian motion and generalized Langevin model. Moreover, likelihood function of particle position are approximated using Whittle's method which provides more accurate information of surrounding water properties than standard fitting of the mean-squared displacement of the particle motion. The interpreted results are then applied to fluids of different viscosity to determine the localized change in fluid properties at fast time scale. We also apply our recently discovered ENTRAPS technique using this fast detection system [8] and study the hydrodynamic interaction of particles with the fluid. This study will a step to measure the localized properties of fluids especially biological fluid at faster time scale [9].

References