Trapping Nano-Particles with Azimuthal and Radial Polarization Modes

Suzanne Leslie, Anirban Mitra, University of Rochester

Abstract

We compare the trapping capabilities of focused radial and azimuthal doughnut modes with those of a focused linearly-polarized Gaussian beam. Polystyrene beads (500nm and 1µm in diameter) in aqueous solution were sent through a microchannel formed by a pair of glass coverslips. Light from a 532nm laser was focused at the interface of the microchannel and nano-particle solution. The optical gradient forces produced and the trap lifetimes are presented for the three polarization modes.

Introduction

Recent advancements in the creation and understanding of exotic polarization modes have given the scientific community a new set of tools for the detection and characterization of nano-particles. Current work in nano-particle manipulation has been focused in areas such as optical tweezers and real-time detection, two fields that exploit subtleties in the interaction of matter and focused light. Radial and azimuthal doughnut modes are known to have unique characteristics that lead to very different magnetic and electric field densities when tightly focused. In this project, we compare the trapping of polystyrene beads by radial and azimuthal polarization modes to that of linearly polarized light.

Theory

There are two forces that act on a particle in a liquid as it passes through a laser focus: the Stokes force that pulls the particle along in the stream, and the optical gradient force which pulls the particle towards the center of the focus. In addition to these two forces, there is also a random force due to the fluctuating environment (Brownian motion). The Newtonian equation of motion for such a situation is (for a particle size small compared to the wavelength of the laser):

\[ m \ddot{r}_p = 6\pi \eta R (\dot{r}_p - \dot{v}_o) + \frac{\alpha}{2} \nabla |E(r_o)|^2 \]

(1)

where \( m \) is particle mass, \( R \) is the radius of the particle, \( r_p \) is the coordinate of the particle, \( \eta \) is the viscosity of the liquid, \( v_o \) is the velocity of the liquid, \( \alpha_p \) is the polarizability of the particle and \( E(r_o) \) is the electric field due to the laser beam.[6] The first term on the right is the Stokes
component, and the second term is the optical gradient force, neglecting Brownian motion for the time being. The force exerted by the liquid (water in our case) on a nano-sized polystyrene bead is on the order of a pico-Newton and it gives rise to an almost instantaneous acceleration ( for a time $\sim 1 \mu s$). Since the experiment is conducted for time lengths on the order of several milliseconds, we can disregard any acceleration due to such a force, i.e. $\ddot{r}_p = 0$. The equation of motion for the particle can then be written as:

$$\dot{r}_p = v_0 - \frac{\alpha_p}{12\pi\eta R} \nabla |E(r)|^2$$

(2)

Thus we can say that the particle velocity at any point of time can be expressed as the ratio of the optical force and the Stokes force. The gradient force can then be written as:

$$F_g = \frac{\alpha_p}{2} \nabla |E(r)|^2 = 6\pi\eta R(\dot{r}_p - v_0)$$

(3)

In the absence of flow, Brownian motion is the dominant source of particle motion toward the trap. The effect of Brownian motion is random and therefore cannot be deterministically predicted. If, for simplicity though, we assume that the particle is only allowed to move along the x-axis, then the one-dimensional motion can be modeled as a random walk. In addition to the linear motion, the particle steps forward or backward with a probability of 0.5 during each time interval $dt$ that we consider. The magnitude of these steps is given by:

$$dl = \sqrt{\frac{2kT}{6\pi\eta R} dt}$$

(4)

where $k$ is the Boltzmann constant, $T$ is the temperature of the system, $\eta$ and $R$ are as defined before, and $dt$ is the calculation time-step. This model converges to actual Brownian motion in the limit $dt \to 0$. 
The exotic polarization modes shown above in Figure 1 and used in this experiment have distinct features when tightly focused. Vectorial diffraction theory predicts that when focusing with a high numerical aperture, a radially polarized field has a strong longitudinal electric field component near the focus.[1] This is in contrast to an azimuthally polarized field, which has a strong axial magnetic field near the focus, but its electric field is purely transverse and zero at the center.[1] The differences in the intensity distributions of the two polarization modes can be seen in Figure 2.[1]

The magnetic energy density distribution for a radially polarized beam is the same as the electric energy density distribution for an azimuthally polarized beam, and vice versa.[1]

It has also been shown that the minimum spot size of just the longitudinal mode for a radially polarized beam is smaller than that of either an azimuthally or linearly polarized beam.[1] Thus, we would expect that a radially polarized beam would be better-suited for trapping.
Experimental set-up

In our experiment, we used a Compass 315M diode-pumped CW laser, emitting horizontally polarized light at 532 nm, with 100 mW maximum power output. The beam was first expanded and then collimated before passing through the polarization mode converter. This optical element consists of four half-wave plates that have been joined together with their fast axes oriented according to Figure 3.

Figure 3. Orientation of the fast axes of the four pieces of a half-wave plate that make up the mode converter.

The unions of the half-wave plates are discontinuities that introduce spatial frequencies corresponding to undesired polarization modes, and so the beam was next sent through a spatial filter. Depending on the orientation of the mode converter, after passing through the spatial filter the beam is either radially or azimuthally polarized, and is then sent to an inverted microscope objective (Nikon 60X, 1.4 N.A., oil immersion), which brings the laser beam to a tight focus.

A microchannel created by vacuum grease and two cover slips sits on top of the objective. The backscattered light from the solution in the microchannel is then diverted to a CCD camera which is connected to a monitor for easy viewing and data acquisition. A small white light placed directly above the objective is also used to better illuminate the sample area so that the flow of the particles can be observed on the monitor. The flow rate was controlled with a pair of gold electrodes placed on opposite ends of the microchannel.

Experimental method

The solutions were made from either 500nm or 1000nm particles taken from standard Duke Scientific polystyrene beads, and then diluted (with DI water + 0.02% Tween-20 surfactant) to
obtain the desired concentrations. Two thin lines of vacuum grease were applied to a rectangular glass cover slip to form the microchannel and a smaller square cover slip was placed on top.

The spatial filter had to be repeatedly adjusted to produce a quality doughnut mode at the desired power. After the quality and power of the mode were confirmed, the microchannel was placed on top of the objective and the two electrodes were placed on opposite sides. One 20μl-drop of the polystyrene bead solution was placed in the vicinity of each electrode, and the focus of the objective was adjusted. The position of the focus as seen on the CCD monitor was noted.

For trapping lifetime data, a voltage of ~10 V was applied across the electrodes in order to induce a moderate flow speed. We then waited for a particle to be trapped at the focus. Once trapped, a stop-watch was used to record the time until the particle left the trap.

To calibrate the flow rate, the voltage was first set to ~10 V and the time for 1 particle in the objective focal plane to cross half of the length of the monitor screen was recorded. These times were recorded for 20 particles at a given voltage, and then the applied voltage was increased by 5-10 volts (up to 40V) and the measurement was repeated. This gave us a calibration of the flow rate in arb./sec. for a given voltage across the electrodes. In order to calibrate the flow rate in SI units, a nanochannel with known width was placed in the objective focus, and its width on the monitor screen was measured. In this way, we were able to calculate the average velocity of the particles for a given applied voltage.

To measure the trap stiffness, we again began by applying a voltage of ~10 V and then waited for a particle to be trapped in the beam focus. The voltage was then slowly increased in steps of 3-5V, and the voltage at which the particle left the trap was recorded.

Data

The flow rate calibration data was used to calculate the trap stiffness. The mean escape voltage for each polarization and power setting was calculated, and this value was inserted into the equation for the linear fit curve on the flow rate graph in Figure 4.
This gave us a mean escape velocity for the trapped particles, from which we calculated the trap stiffness according to Eq. (3). These results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Beam polarization</th>
<th>Particle Size</th>
<th>Power (mW)</th>
<th>Force (pN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>500 nm</td>
<td>3.6</td>
<td>0.36</td>
</tr>
<tr>
<td>Radial</td>
<td>500 nm</td>
<td>2.2</td>
<td>0.30</td>
</tr>
<tr>
<td>Azimuthal</td>
<td>1 um</td>
<td>2.2</td>
<td>0.84</td>
</tr>
<tr>
<td>Gaussian</td>
<td>1 um</td>
<td>2.0</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Table 1. Optical Gradient force**

The mean trap lifetime for each polarization and power setting was also calculated. The results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Beam polarization</th>
<th>Particle Size</th>
<th>Power (mW)</th>
<th>Mean trap lifetime (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>500 nm</td>
<td>3.6</td>
<td>289</td>
</tr>
<tr>
<td>Radial</td>
<td>500 nm</td>
<td>2.2</td>
<td>42</td>
</tr>
<tr>
<td>Azimuthal</td>
<td>1 um</td>
<td>2.2</td>
<td>184</td>
</tr>
<tr>
<td>Gaussian</td>
<td>1 um</td>
<td>2.0</td>
<td>29</td>
</tr>
</tbody>
</table>

**Table 2. Mean trapping lifetime**
Histograms of the escape voltages were plotted and fitted with a normal distribution curve. They are presented in the attached appendix, Figures 6-9.

**Discussion**

Throughout the experiment, it became clear that the trap was sensitive to several parameters in the set-up. The most important of these being: the beam power, the stability/purity of the polarization mode, and the tightness of focus. These parameters had to be constantly monitored and adjusted to ensure consistent control conditions.

To better understand the source of flow in the microchannel, some basic electrokinetic concepts should be discussed. The important parameters for the motion were: the negatively-charged polystyrene beads, the distilled water in which they were suspended, the two glass cover slips that formed the channel, and the electric field provided by the electrodes. These variables created two competing phenomena: electrophoresis and electrosmosis. In short, electrosmosis is the motion of the bulk liquid in response to the applied electric field, while electrophoresis is the motion (relative to the bulk liquid) of the charged colloidal particles.[4] Cations in the water are drawn to the glass cover slips that form the top and bottom of the microchannel. Electrosmosis then, causes the bulk liquid to be dragged along this boundary toward the negative electrode. This is demonstrated schematically in Figure 5.

![Figure 5. Electrosmosis vs. electrophoresis in our set-up](image)

In our set-up, we observed that when the voltage was applied, the particles that were in the focal plane moved toward the negative electrode, while those deeper in the microchannel were seen to be moving in the opposite direction. We thus determined that electrosmosis was the
dominant force in moving the particles to the focus, and the source of the flow rate. The out of focus particles were moving toward the positive electrode due to electrophoresis, since at that distance they were far enough from the glass boundary to resist the pull of electrosmosis.

A few points on the data-taking method deserve mentioning. At times the concentration of the solution used was changed, which obviously affected the number of particles that approached the focus. This would have affected the trap lifetime and stiffness measurements since particle collisions were one cause of a particle leaving the trap. This was accounted for by neglecting the data corresponding to the particles that appeared to leave the trap collisionally. Instead, trapping lifetime and stiffness data were only recorded for those particles which did not appear to come into contact with other particles during their time in the trap.

Another important issue dealt with the appearance of the doughnut mode vs. its power as measured by a power meter placed after the spatial filter. It was thought that the mode often looked purer and more symmetric at lower powers. This was one factor that influenced the decision to take more data at the lower power level (~ 2 mW) rather than at a higher power (3 - 4 mW). The higher power setting had the advantage of a stiffer and more robust trap, but didn’t seem to give as pure of a doughnut mode as was found at the lower power position.

**Conclusions and Future Plans**

As can be seen in Tables 1 and 2, the radial polarization mode was able to trap smaller diameter particles and hold them longer in a stiffer trap than either the azimuthal or the linear polarization mode. The azimuthal mode was barely able to trap 500nm particles, but trapped 1um particles better than linear polarization at same power and concentration. This confirmed that exotic polarization modes such as the radial and azimuthal ones created by our set-up offer unique advantages in trapping nano-particles when compared to linearly polarized Gaussian beams.

There are many improvements that could be made to the current experiment and set-up, though, to make it easier to compare these modes and arrive at conclusive quantitative results. The purity of the polarization mode in terms of wavefront aberrations was never measured in this experiment, and it seems that this information could help to better characterize the sensitivity of the trap efficiency on this parameter.
The radial and azimuthal modes were relatively easy to make with the mode converter and spatial filter, but the sensitivity on the exact location of the spatial filter led to mode stability issues with time. The complexity of the microchannel set-up could be also reduced a great deal if the electrodes were replaced with another means of providing flow, such as piezo-transducer or motorized stage. This would also increase the amount of time that a microchannel could be used to take data. With the current set-up, the microchannels had to be replaced approximately every 20-30 minutes, as the solution would have dried such that the electrodes were no longer making good electrical contact with the channel.

The laser power was a very sensitive parameter that we weren’t able to control as much as we would have liked in our set-up. It would be interesting and useful to perform a similar experiment employing a greater variability in the beam power to be able to better characterize the trap dependence on that parameter.

References


Appendix

Escape Voltage for Radially polarized doughnut beam

Particle Size = 500 nm
\( P = 2.2 \text{ mW} \)

Figure 6. Radial Polarization Escape Voltage for \( P = 2.2\text{mW} \)

Escape Voltage for Radially polarized doughnut beam

Particle Size = 500 nm
\( P = 3.6 \text{ mW} \)

Figure 7. Radial Polarization Escape Voltage for \( P = 3.6\text{mW} \)
Figure 8. Azimuthal Polarization Escape Voltage for $P = 2.2 \text{ mW}$

Figure 9. Linear Polarization Escape Voltage for $P = 2.0 \text{ mW}$