Optical Trapping and Manipulation of Micron-sized Particles and Bacteria

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Introduction

Optical tweezers have become a widely used tool in biology for the manipulation of micron-sized objects. A trap is created by focusing a laser beam through a microscope objective, which is simultaneously used to view the specimen being trapped. Because the laser light carries momentum, an object that bends the beam will also recoil in the opposite direction. We have built a multi-array optical tweezers setup, and we are currently optimizing and calibrating the system. As preliminary tests, we have created micro-motors with calcite crystals, trapped latex micro-spheres, and manipulated bacteria. Micro-motors utilize angular momentum transfer from circularly polarized to the birefringent crystal, causing it to spin. This effect allows for the possibility of creating a micropump to push water in very fine amounts. The ability to precisely trap and manipulate bacteria opens the door for many possible experiments. We plan to investigate the swimming strengths of micro-organisms with flagella and to study the circadian rhythms of individual cyanobacteria. It may be possible to demonstrate that cyanobacteria synchronize their circadian rhythms when placed in close proximity using the optical tweezers.

The Physics of Optical Tweezers

Using ray optics, we can describe the scenario where the trapped particle is much larger than the wavelength of light. As shown in Figure 1, the light rays passing through are refracted as they enter and exit the particle. As the light changes direction during refraction through the particle, the light’s momentum vector changes. This change in optical momentum results in an equal and opposite momentum change for the particle.

![Figure 1. Ray optics approach of the optical tweezers. The particle seen in (a) is displaced from the center of the trap, net force exerted is toward trap center.](image)

![Figure 2. Hooke’s law comparison of the optical trap: force of trap is linear as a function of displacement from trap center.](image)

To quantify the trap strength of optical tweezers, we consider the applied force as a function of particle displacement. For a small displacement relative to the trap center, the force is linear. From this, we can compare the trap to a simple spring following Hooke’s law.

![Figure 3. The optical layout of the multi-trap tweezers design. Components aligned vertically from the CCD camera are raised vertically from the optical table. This set-up creates an inverted microscope. This layout is beneficial because particles suspended in the sample solution settle toward the trapping plane.](image)

Multi-trap Array

Using two orthogonal diffraction gratings, we created a multi-trap array capable of trapping and manipulating nine particles. As seen in Fig. 3, one arm of the set-up is devoted to creating the trapping array. With the absence of the beam splitter, each individual trap holds 6.25% of the original intensity, which is still enough to trap particles. With the beam splitter in place, we can use the second arm to move particles between positions on the trapping grid. The intensity of the beam in the second arm is much greater than that of the trapping grid.

![Figure 4. On the left, the trap is seen holding nine latex microspheres simultaneously. On the right, the trap is released and the nine particles are free from the trapping force; Brownian forces become dominant. Through rotation of the diffractive optics, the array of trapped particles can be rotated as well.](image)

Manipulation of Cyanobacteria

A large motivation for the use of optical tweezers in the past decade has been for performing biophysics research. Currently, we are adapting our experimental design for research on cyanobacteria. The trap allows us to move and manipulate individual bacteria. Using circularly polarized light, we can spin the bacteria in a controlled manner. By using an IR trap, we hope to test the properties of motile cyanobacteria and possibly study synchronization of their circadian rhythms.

![Figure 5. A single cyanobacterium has been trapped and can be translated or rotated. Stationary bacteria can be seen on either side of the trapped bacterium.](image)

Rotation of Calcite Crystals

Using circularly polarized light, we can trap and rotate micron-sized calcite crystals to create micro-motors. The polarization of the light interacts with the birefringence of the crystal, causing it to spin. We have measured rotation frequencies in the 1-100 Hz range. Trap strength can depend on the particle geometry, so only crystals of the right shape are good candidates for micro-motors.

![Figure 6. The creation of a micro-motor is shown above, the particle in the center is trapped and spinning due to incident circular polarization.](image)

Future Experimentation and References

Future experimentation includes the addition of a position-sensitive detector for more precise measurements of trap strength, an IR laser to avoid harming living organisms, and a fluorescence detection system to monitor circadian rhythms of bacteria containing fluorescent proteins.

References