Quantifying Forces on Strongly Absorbing Materials Rotating in Optical Traps

Ryan Kropas and Emily Sobel, Physics & Astronomy Department, SUNY New Paltz
Dr. Catherine Herne, Faculty Mentor, Physics & Astronomy Department, SUNY New Paltz

Abstract

Optical trapping or "tweezing" is a laser-based method of micron-scale material manipulation, exploiting the forces produced by light refracting through small particles to capture them within a particular area (the trap). Biologists and chemists use this technology to handle large molecules, mix small volumes of liquids, and even build cell-scale machinery.

In this research project, we use Laguerre-Gauss modes to create the trap and rotate the particles. A Laguerre-Gauss mode is a "donut" shaped beam that carries orbital angular momentum. Generating the Laguerre-Gauss modes is achieved through programming a spatial light modulator (SLM) with a holographic phase pattern. We work with several different combinations of particles (polystyrene latex, silica, mica, graphite, and vermiculite) and solutions (deionized water, SDS) to conduct experimental tests of the effective trapping and rotation of strongly absorbing and the strongly refracting materials. We performed theoretical calculations of torque forces in laser modes carrying orbital angular momentum (OAM).

Here, we present the results of our measurements and calculations and show the forces acting on the particles.

Scope & Methods

- The targets we tested were vermiculite, polystyrene latex, silicon/mica, and graphite, suspended in deionized water or water/sodium dodecyl sulfate (SDS) solutions. For trapping, we used a Gaussian beam, and for rotation we used a Laguerre-Gauss (donut) beam.
- To test trapping, the Gaussian beam was used. Our laser is 110 mW with a 660 nm (red) vertically-polarized output (see Figure 2).
- To test the rotational forces in the trap, we programmed a holographic pattern on the SLM that created a Laguerre-Gaussian (LG) mode for the SLM (see Figure 1); the rest of the layout remained the same. This yielded around 2 mW of power in the LG mode.

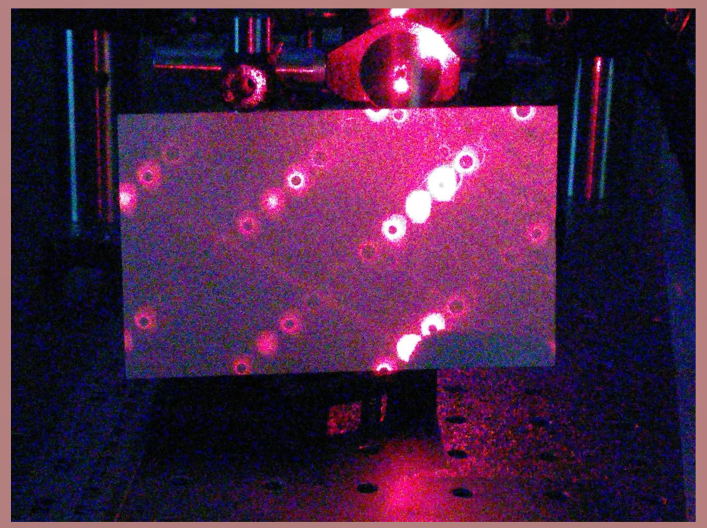

Figure 1: Image of $l = 20$ "donut" pattern created by SLM

- For trapping, we began with the focus at the coverslip (see Figure 2). Graphite absorbs momentum from the beam and moves away from it, so we blew pieces to the top to stabilize and rotate them. The next step was to switch quickly to an LG mode to begin rotation. We recorded video sequences of rotation and trapping to make calculations of forces and torques.

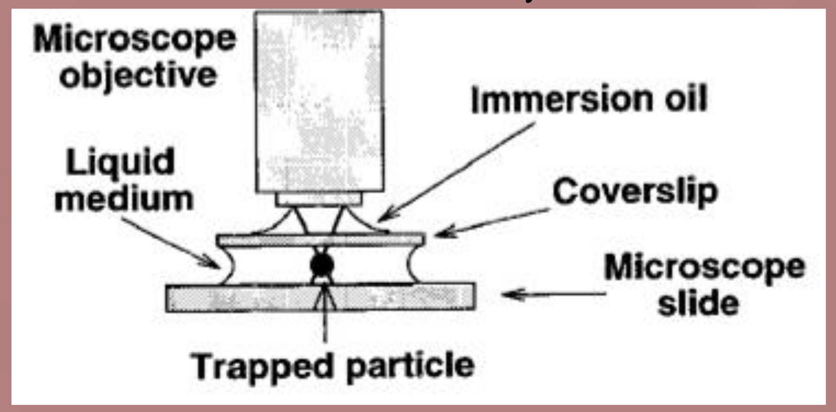

Figure 2: Diagram of optical trap (Friese et al., 1996)

Data/Discussion

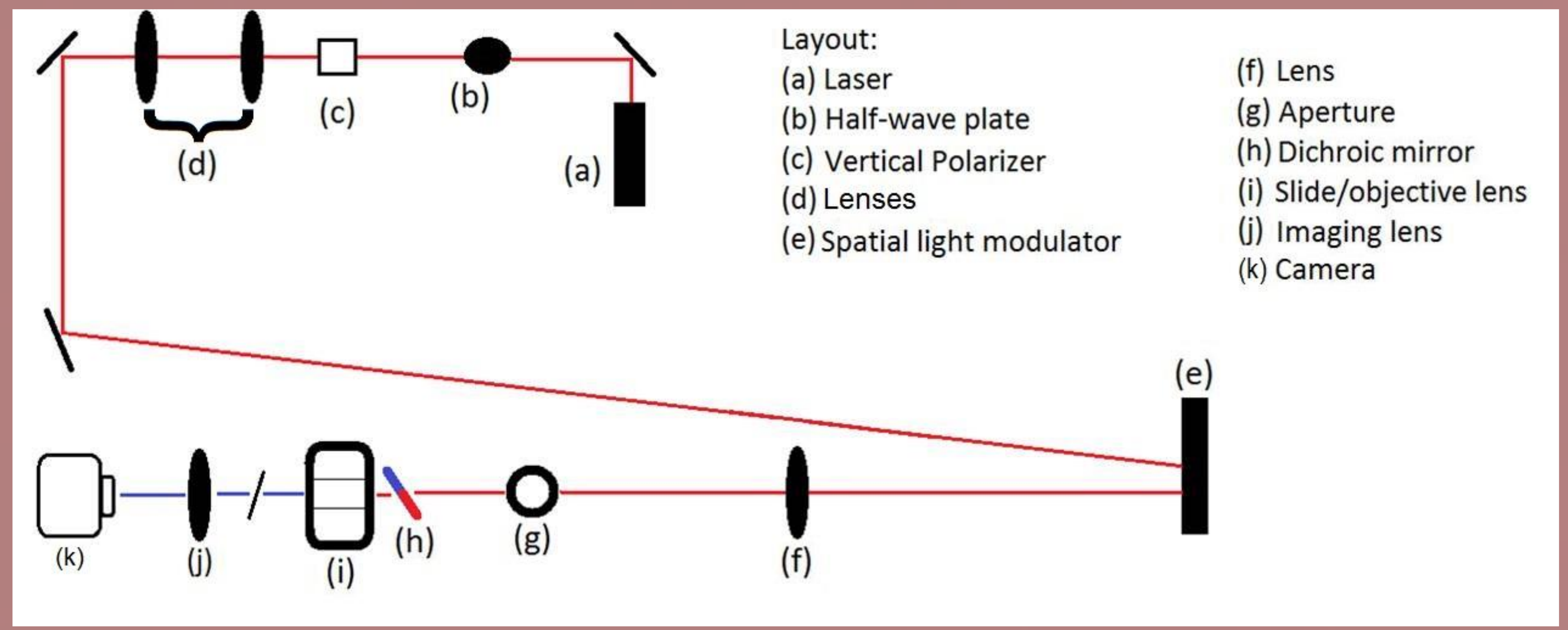

Figure 3: Diagram of the optical table layout

$$u(r,\Phi,z) = \frac{C_{lp}^{LG}}{\omega(z)}\left(\frac{r\sqrt{2}}{\omega(z)}\right)^{|l|} e^{-\frac{r^2}{\omega^2(z)}} L_p^{|l|}\left(\frac{2r^2}{\omega^2(z)}\right) e^{-ik\frac{r^2}{2R(z)}} e^{il\Phi} e^{i(2p+|l|+\zeta(z))}$$

Figure 4: Laguerre-Gauss Equation

An LG mode has a helical wavefront that carries an amount of OAM determined by azimuthal wave number, l. The size of the ring is also determined by this wave number. The azimuthal phase is given by the term in the equation about, $e^{il\Phi}$. The associated Laguerre polynomial L_p^l gives the donut shape of the beam (seen in the bottom left and center images of Figure 3). The "hole" in the donut is due to destructive interference, which is ascertained by the phase angle Φ.

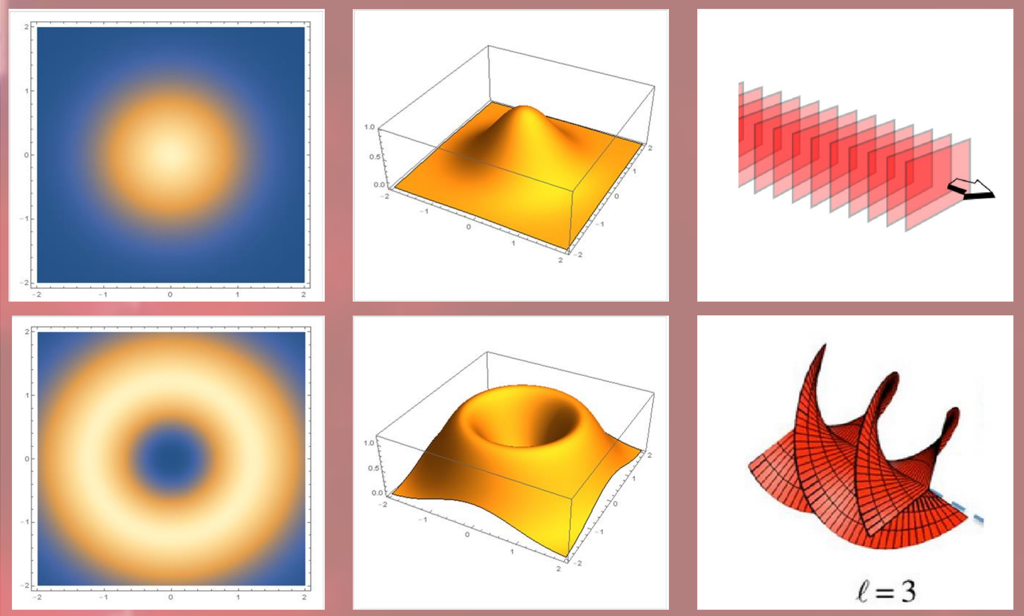

Figure 5: 2-D and 3-D representations of Gaussian and LG modes (Wolfram CDF Reader)

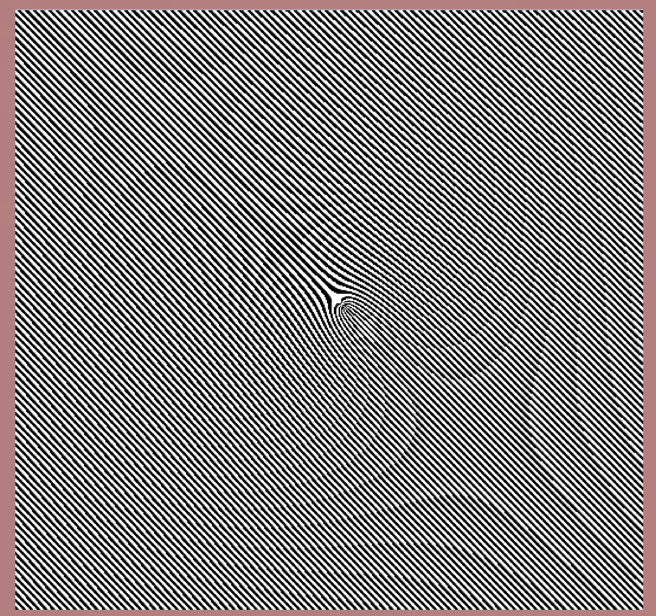

Figure 6: Example of holographic pattern used to produce LG mode via SLM

Targets and Solutions: In order to trap and rotate strongly absorbing materials, they must be attracted to the polystyrene latex spheres, which are the targets that refract incoming laser light and therefore are trapped. We initially tested vermiculite as a strongly absorbing material to take on OAM, but found that the vermiculite did not interact with the polystyrene spheres at all. There are at least two possible reasons for this; vermiculite's metal-containing sheet structure may have made it less likely to interact with the hydrocarbon-based polystyrene, and its high luster may have made the laser light reflect off the surface, instead of absorbing it. There were similar non-interaction problems using mica and silica beads.

We used graphite with the spheres in deionized water, with and without SDS. This surfactant has strong surface interactions with the benzene rings on the outside of the spheres, and thus made the spheres "stickier" (read, more effective) for the graphite.

Results

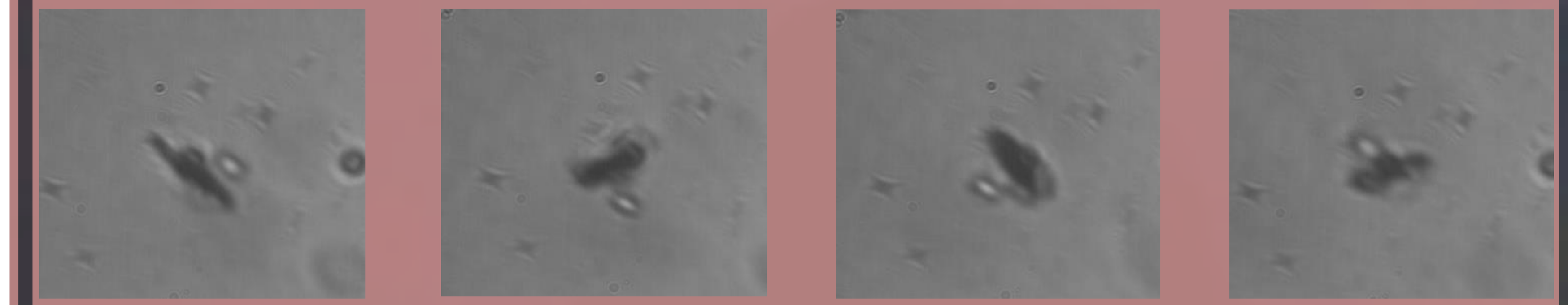

Figure 7: Rotation of graphite flake with adhered polystyrene latex beads (1 s interval between images)

The figure above shows successful rotation of a flake of graphite with polystyrene beads using an $l = 8$ mode. The clockwise rotation is consistent with what we would expect to see with our diffracted beam. Following the attached polystyrene sphere (seen above in Figure 6), we can deduce that the frequency of the objects trapped is around 0.5Hz. Using a higher l mode, we would expect to see an increase in the frequency.

The effective trapping force exerted on a sphere is modeled by Hooke's law, F = -kΔx, as seen in Figure 7. For this experiment, the expected value of this spring constant is on the order of 10^{-12} N/m.

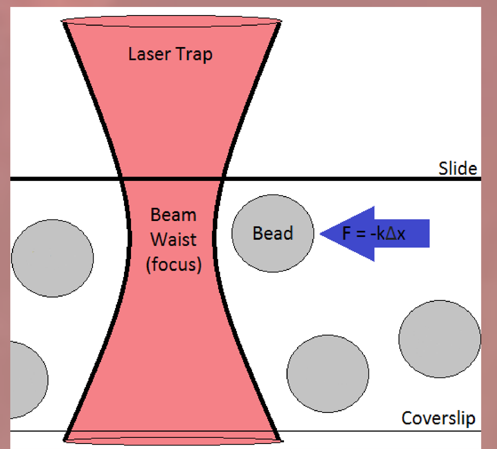

Figure 8: Model of trapping force

Conclusions/Future Work

During this project, we've confirmed the technique of trapping and rotation of strongly absorbing materials using Gaussian and Laguerre-Gaussian laser modes with graphite shavings and polystyrene latex beads.

For future experiments, a more uniformly-shaped graphite sample would be a far easier material for which to measure the trapping forces. The next step for materials would be to use a substance like graphene, as Vasi et al. have (2011). This would preserve the strongly-absorbing properties of graphite while making calculations and results more repeatable.

We also considered introducing a piezoelectric device and function generator to provide more exact data on how strong the optical trap is. Applying planar motion normal to the optical trap would help measure the horizontal component of the trapping force.

Works Cited/Acknowledgments

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Vasi, S., Monaca, M. A., Donato, M. G., Calogero, G., Fazio, B., Irrera, A., Iati, M. A., ... Jones, P. H. (December 01, 2011). Optical trapping of carbon nanotubes and graphene. Atti Della Accademia Peloritana Dei Pericolanti, Classe Di Scienze Fisiche, Matematiche E Naturali, 89.