Constructing an Optimized Optical Tweezers

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Introduction

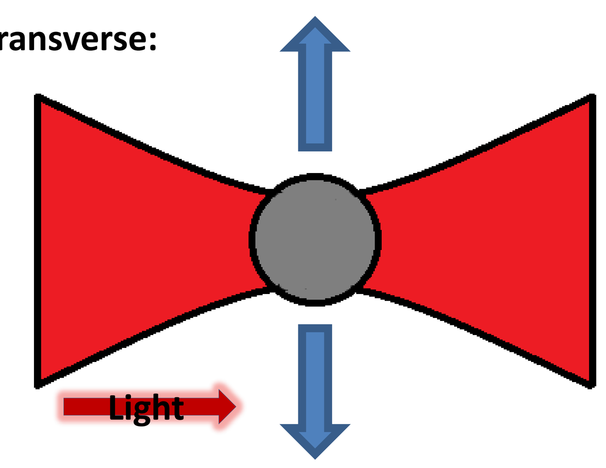
Optical tweezers utilize the radiation pressure exerted by light to trap particles in three dimensions. While the first optical trapping device was a dual-beam trap (Ashkin, 1970); optical tweezers are now created by tightly focusing a single laser beam. They are often applied in biological sciences as a means of noninvasive particle manipulation.

Our research investigated how the trapping power of optical tweezers depends on the intensity distribution of the light entering the microscope objective. We used both Gaussian beams of two widths and annular (optical vortex) beams of order ℓ = 1, 3, 5 and 7.

Theory

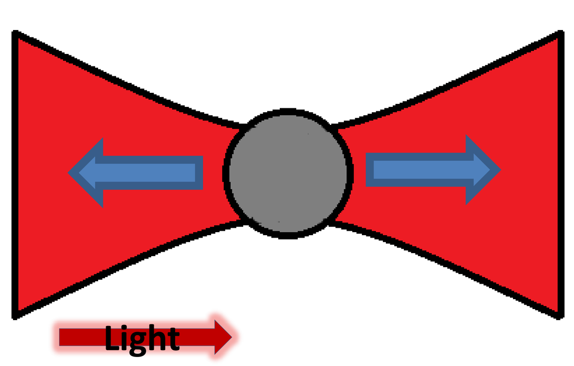
Optical traps have two trapping directions:

Transverse:



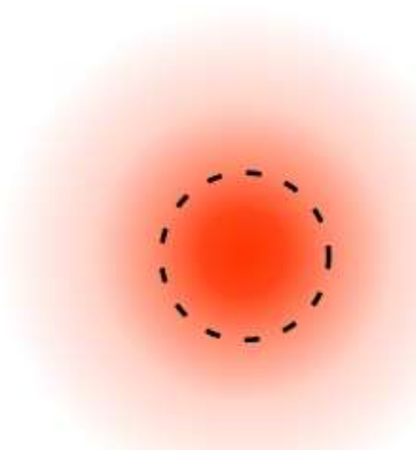
- Refracted light exerts a force on the particle
- Trapping strength depends on the intensity gradient of the light
- This "gradient force" attracts particles to the center of the light beam

Axial:



- Refracted light exerts a backwards gradient force on particles past the beam waist
- "Scattering force" acts in the direction of the light's propagation
- For a stable trap, $F_{gradient} > F_{scattering}$

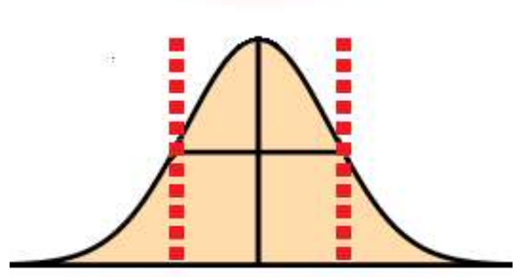
Overfilling:



The outermost light rays are refracted at the steepest angle, and contribute most to the backwards gradient force.

Central light rays have more forward momentum and therefore contribute most to the scattering force.

Overfilling the microscope aperture by expanding the beam increases trap strength because the truncated beam (see left, between dotted lines) has a higher intensity rays at the edge of the aperture and lower intensity rays in the center.

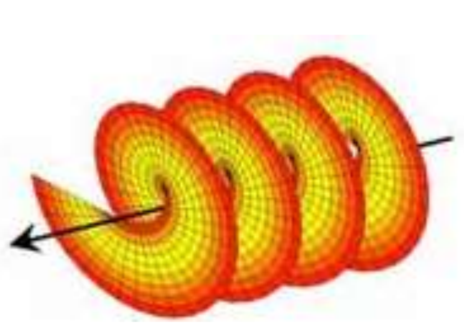


"Gaussian Beam." *ScienceNet*. N.p., n.d. Web. 4 Aug. 2013. <http://blog.sciencenet.cn/blog-292150-647761.html>.

Optical Vortices:

An optical vortex is light that travels in a helical wavefront (see left) and has a center region of no intensity.

High intensity peaks on the edge and low intensity regions in the middle mean that optical vortices improve axial trap strength.

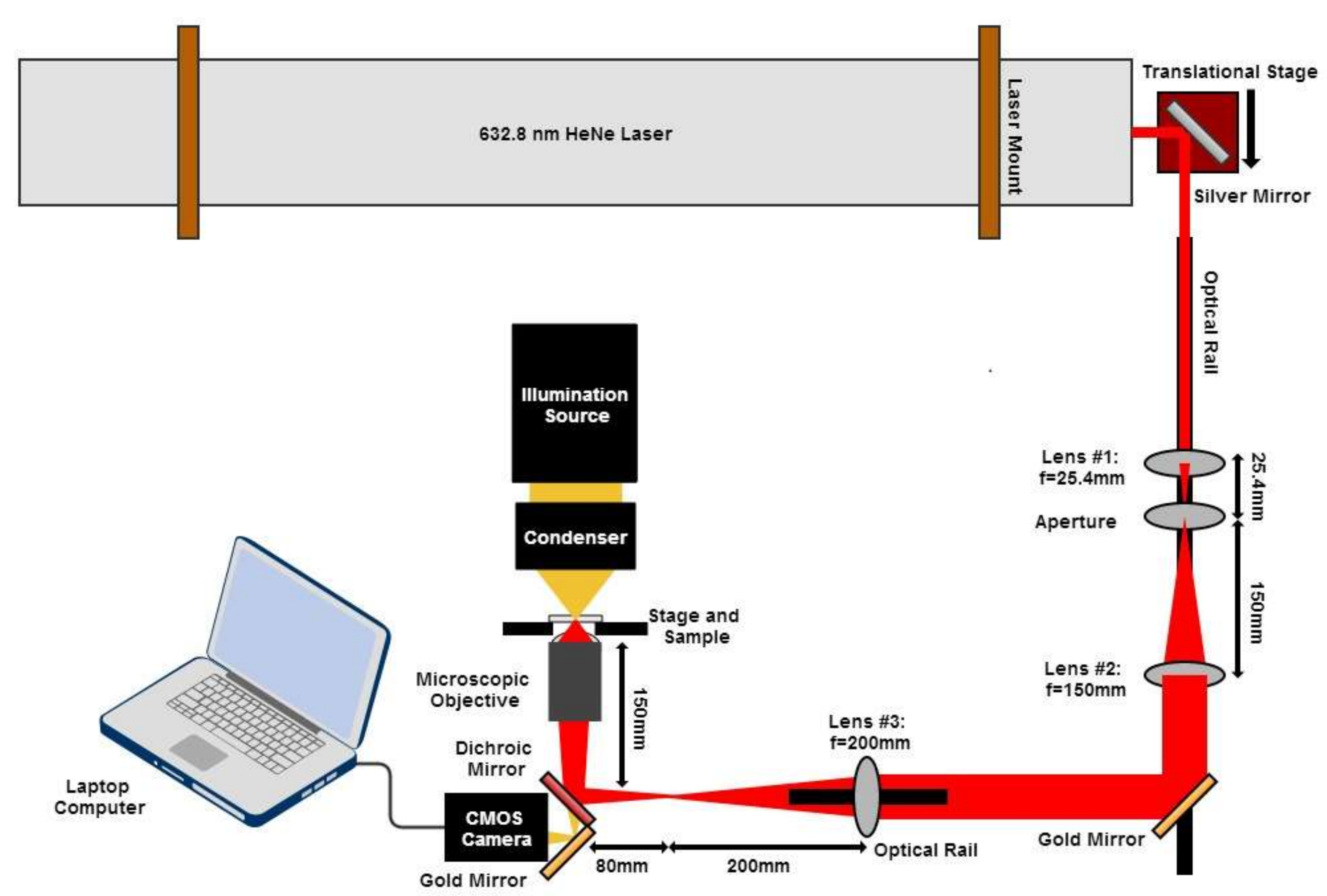


"Optical Vortices." *Raul Hernandez Homepage*. N.p., n.d. Web. 4 Aug. 2013. <http://homepages.mty.itesm.mx/raul.aranda/research.html>

Optical Tweezers Setup

My optical tweezers setup was assembled on an optical bread board (below). It was built using the following components:

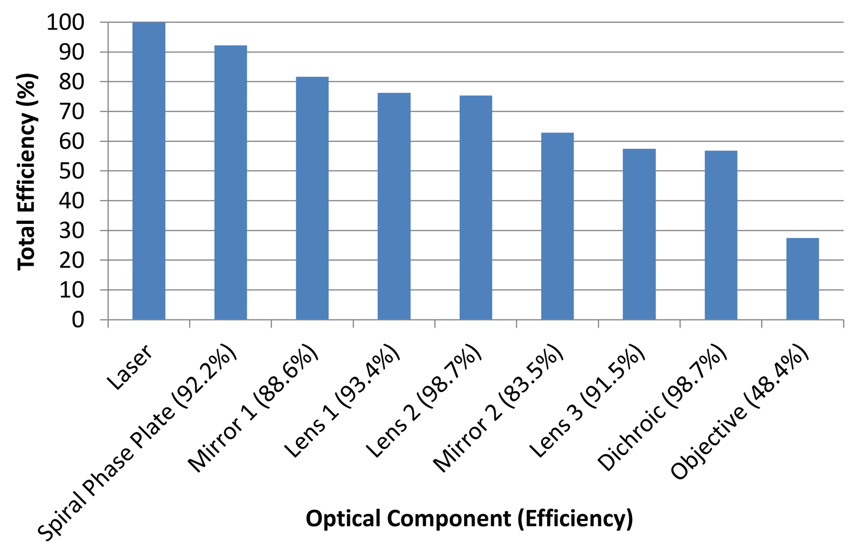
- 38 mW 632.8 nm SpectroPhysics 127 HeNe Laser
- Beam expander made of two plano-convex lenses (f = 25.4 mm and f= 150 mm)
- A 200 mm focal length lens to focus the laser light 230 mm from the objective
- Thorlabs CMOS camera for viewing and recording images on a laptop computer
- Generic 50X NA = 0.85 microscope objective with a 6.0 mm back aperture
- Nikon inverted microscope with built-in illumination source for particle viewing. Inverted microscopes have the advantage that gravity opposes the scattering force.
- A dichroic mirror and three metallic mirrors for beam turning and alignment
- Various mechanical elements such as optical rails, posts, and translation stages



Motorized Stage Design:

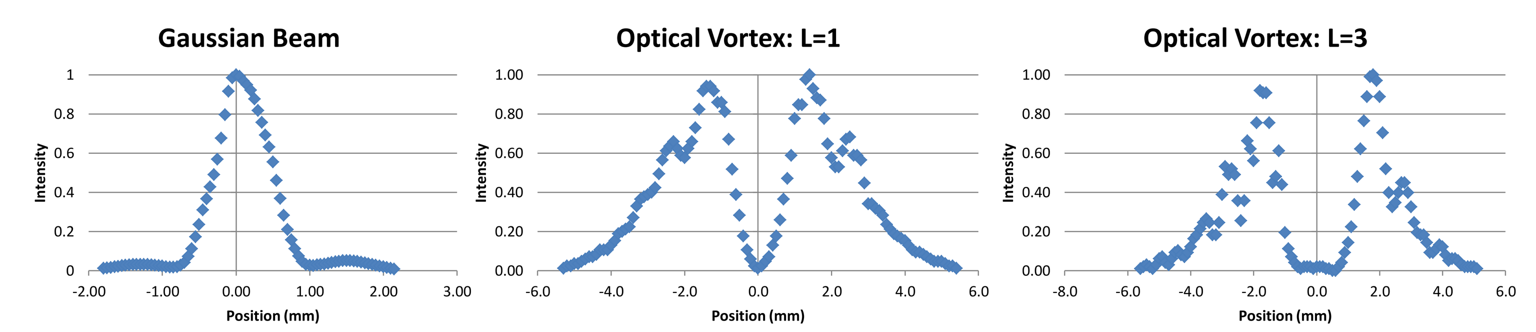
A 1 RPM motor was coupled to the translation stage mechanism through a pulley arrangement (right). The shape of the motor pulley was noncircular so that the speed of the stage motion gradually increased as the motor turned.

Optical Tweezers Setup Efficiency by Optical Component

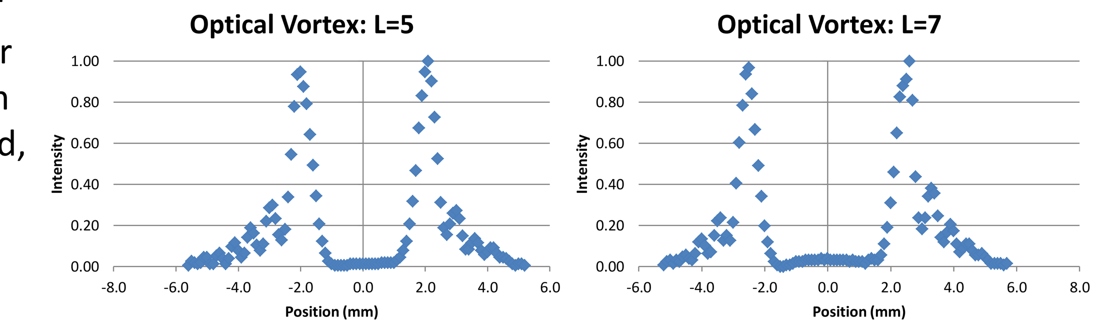


The percentage of power from the laser remaining after each listed optical component. Measurements were taken using a 3.6 mm x 3.6 mm photodiode and ammeter. We plan to improve the overall efficiency by replacing the metallic mirrors and uncoated lenses with higher quality components.

Methods and Results



Intensity distributions of the five beams tested for trapping. Gaussian beam was profiled unexpanded, while optical vortices of various orders were profiled after the final setup beam expander.



Drag Force Method

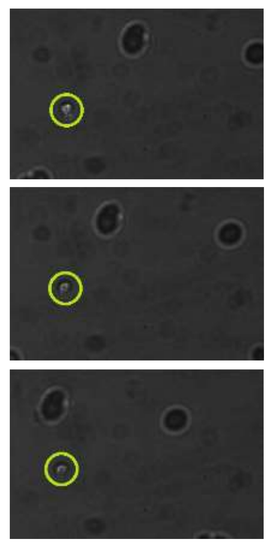
We used both yeast cells (~5 µm Ø) and latex spheres (10 µm Ø) for trapping; all the following force measurements were taken trapping yeast in the lateral directions.

In order to calculate the trap strength, the Stokes' Drag Theorem for a spherical particle of radius r moving at a constant velocity v through a fluid of viscosity η was used:

$$F = 6\pi\eta r v$$

The motion of the particle in an accelerating trap was recorded. The video was then analyzed to find the escape velocity at which the particle "fell out" of the trap.

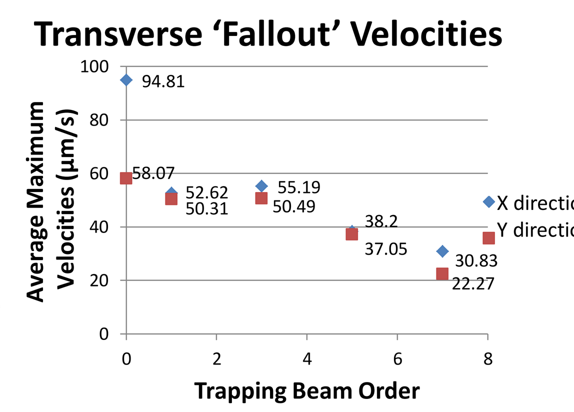
The pictures to the right show a sequence of pictures as the stage is translated to the left. Note that the yeast cell circled in green is trapped, as it does not move with the rest of the solution.

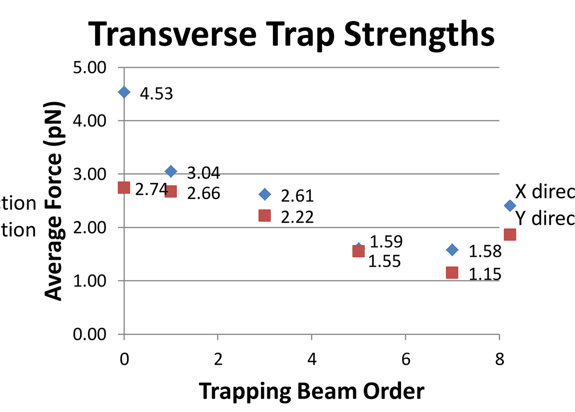


Results

We were able to readily trap yeast axially with the Gaussian beam when it was expanded to 9.5 mm, but not when it was expanded to 7.5 mm; we were also able to trap latex spheres with both beams. Measurements of the transverse trap strength for each beam revealed that optical vortices of higher modes have weaker transverse trapping forces.

The values shown to the right were attained by averaging 9-15 trials for each vortex beam order, using 3-5 different particles of varying sizes.





Conclusions

When optimizing trapping efficiency, both axial and transverse trapping must be taken into account. However, quantifying the axial trap strength is difficult. To increase trapping efficiency, one must consider the transverse efficiency losses *vs.* potential axial efficiency gains, as well as the power lost to additional optical elements. We found that optical vortices of higher orders actually decrease transverse trapping efficiency. Our results are in accordance with previous work (O'Neil and Padgett, 2001). We have also demonstrated that increased overfilling of the objective can increase axial trap strength despite power losses due to truncation.

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