Constructing an Optimized Optical Tweezers

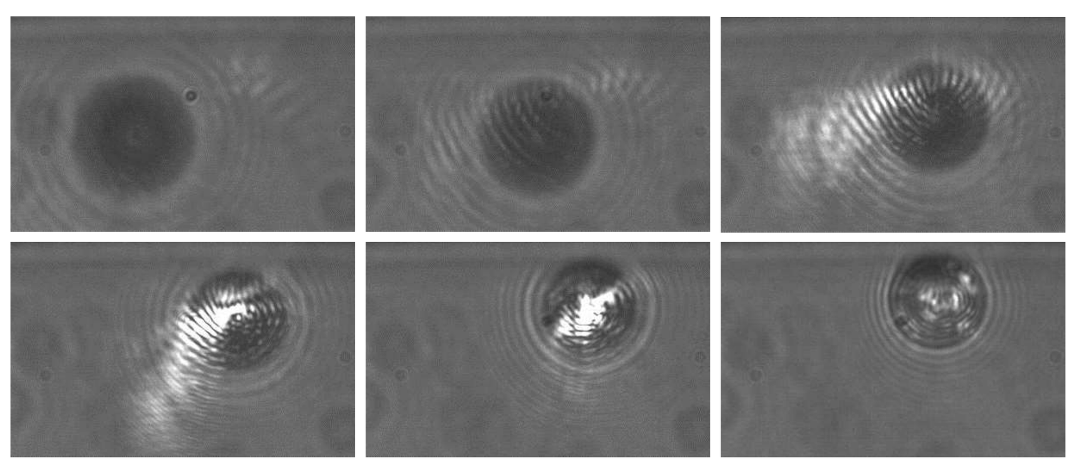
Kathy Camenzind[1,2], Martin G. Cohen[2] and John Noé[2]
1. California High School, San Ramon, CA
2. Laser Teaching Center, Stony Brook University

Simons Foundation

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), since 1986 it has been known that particles can be trapped by using a tightly focused single laser beam. Such devices are called optical tweezers. They are often applied in biological sciences as a means of noninvasive particle manipulation.

Our research involved constructing an optical tweezers to trap particles in three dimensions, using a low-power laser and generic 50X microscope objective. We attempted to optimize trap efficiency by altering the trapping beam's intensity profile. The drag- force method was used to quantify trapping forces .



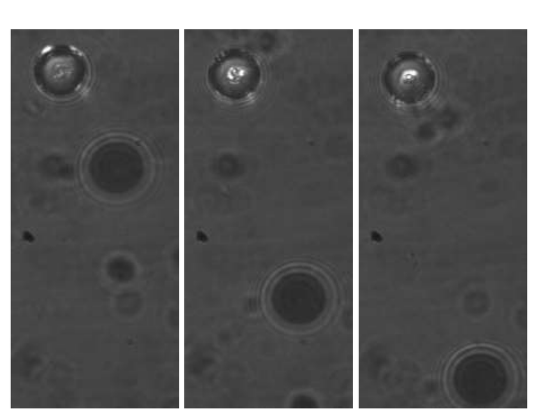
Latex sphere falling into a vortex trap.

Quantifying Forces: Drag Force Method

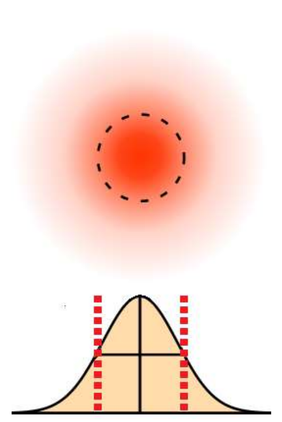
Stokes' Drag Theorem: $F = 6\pi\eta r v$

A video was analyzed for the velocity at which the particle 'fell out" of the trap. For lower trap forces, the percent error increased. The viscosity of water (η) was taken into account, as it has a strong inverse dependence on temperature, which increases under the heat of the illumination source.

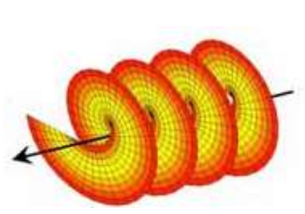
Below is an image sequence of a trapped particle (top left corner) as the stage is translated beneath it.



Trapping Efficiency is defined by the Q parameter $Q = Fc/nP$ and can increase with:

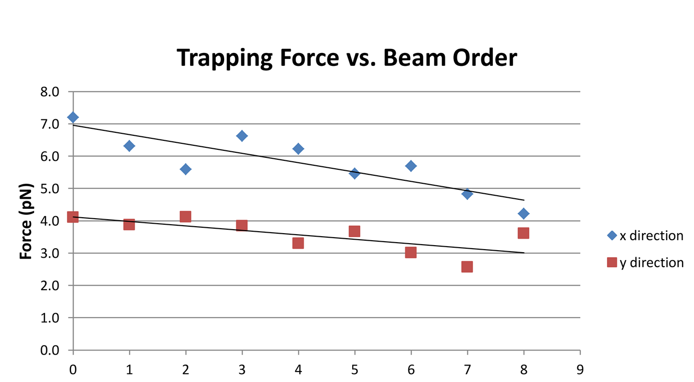


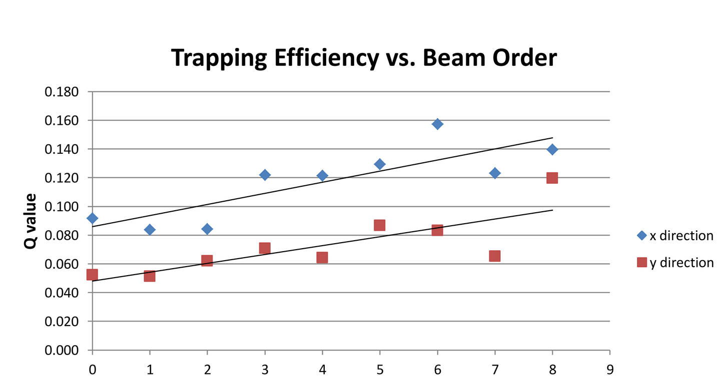
Overfilling: expanding the beam to a greater width than the objective. This truncates the low-intensity outer beam (shown to the right by dotted lines).



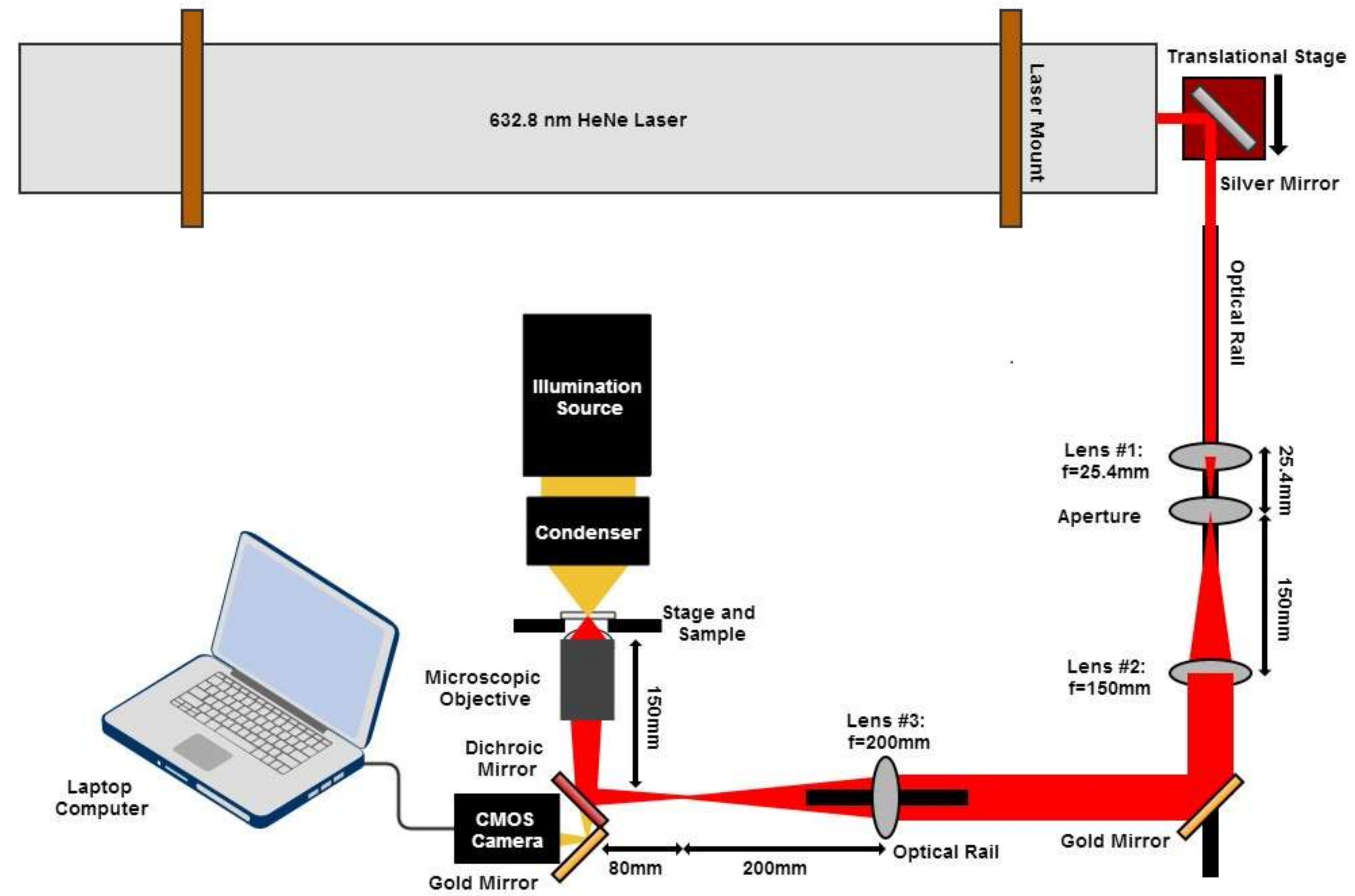
Optical vortices have a phase singularity at the center, reducing intensity of central rays and increasing intensity of outer rays.

Typical quantified trapping forces and trapping efficiencies on a latex sphere:





Optical Tweezers Setup

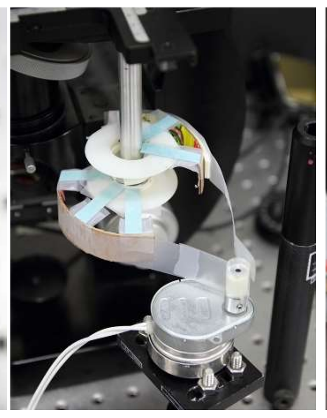


Laser: Relatively low power 633 nm laser (38 mW) with a maximum trapping power at the trapping plane of 10 mW.

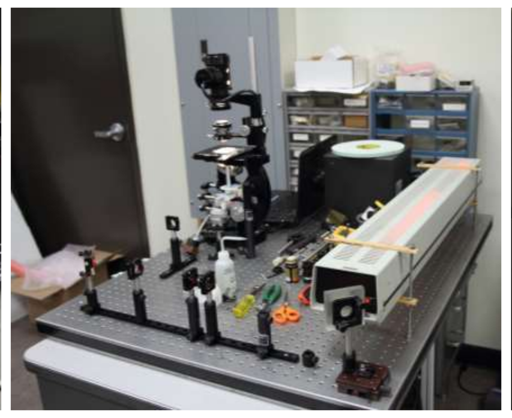
Microscope Objective: Generic 50X air objective, with a relatively low numerical aperture (NA = 0.85).

Trapped Particles: Yeast cells (~5 μm) and polystyrene latex spheres (10 μm) were successfully trapped in 3D.

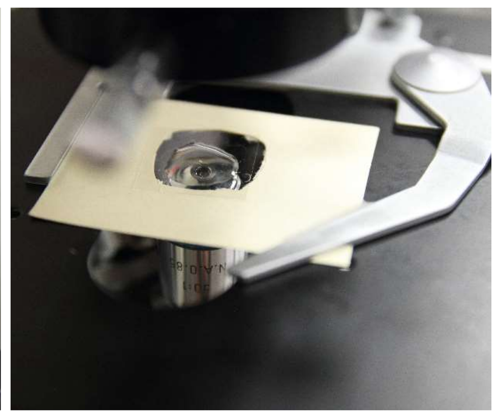
Motor



Pulley



Full Setup

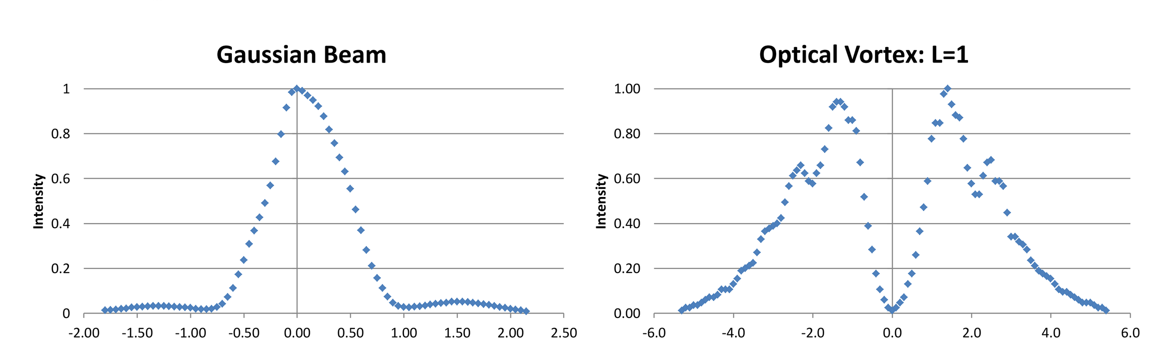


Sample plane

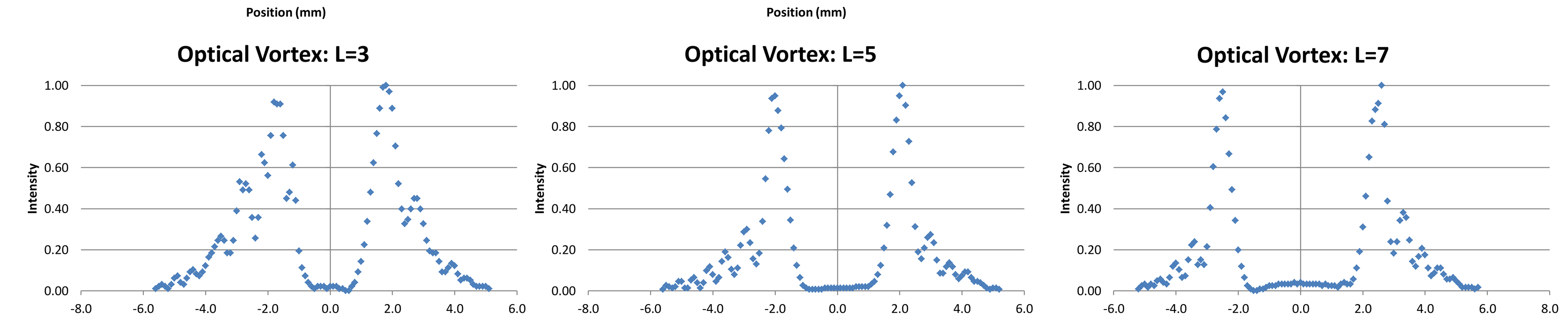
Motorized Stage Design

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

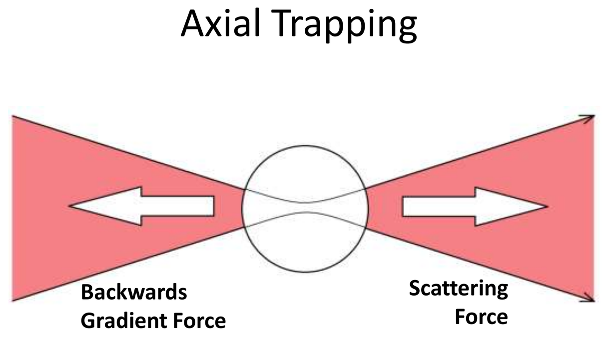
Trapping Beam Intensity Profiles

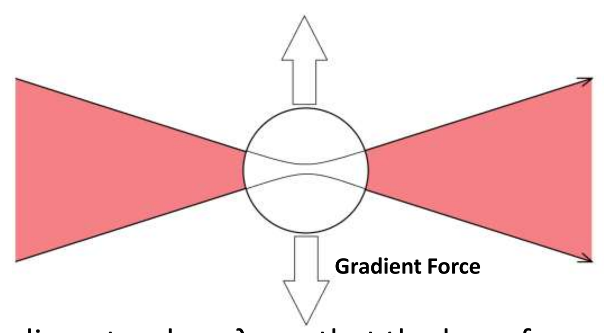


Beams (orders ℓ=0-8) were expanded to 3 widths.

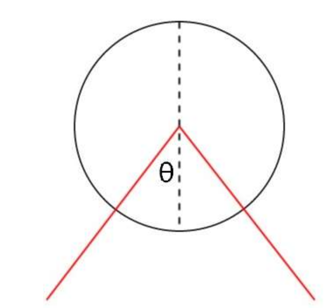


Modeling Trapping Forces

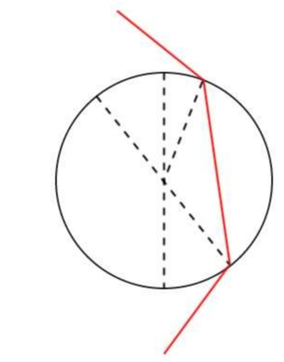




Transverse trapping forces were modeled for particles with diameter d > > λ , so that the laser focus was much smaller than the particle. This is based on the ray-optics trapping theory (Ashkin, 1992).

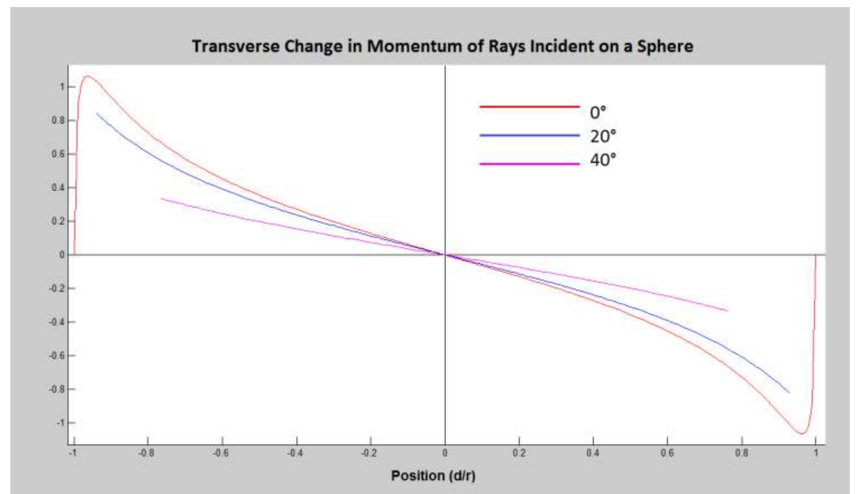


Beams strike the particle in ray pairs of equal and opposite angles. The rays converge towards the beam focus, which is treated as a point.

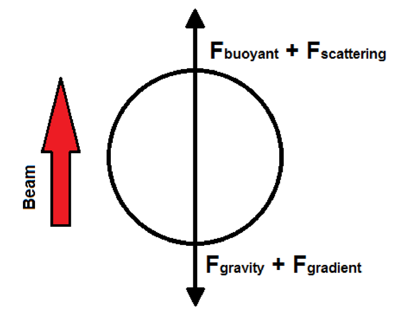


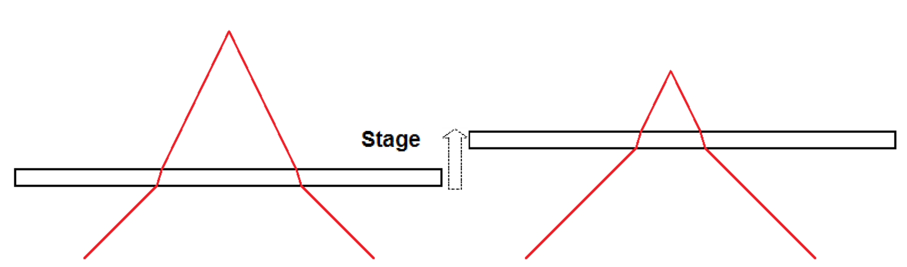
A ray's change in momentum after refraction and reflection can be calculated using Snell's Law and the Fresnel Equations.

A simplified 2D model of transverse trapping forces. Three incident rays of different angles and their changes in momentum are shown as the beam focus moves in the transverse direction d/r from the center.



Hooke's Law: Optical traps act as a spring. This model demonstrates this linear F=-kx behavior near the particle center. The harmonic motion of the particle is damped by the fluid trapping medium.





Axial trapping is more difficult to quantify than transverse trapping. This is because of the many axial force components in an inverted optical tweezers (left) and the movement of the trap focus when the stage is translated vertically (right).

References

Ashkin, A. (1970). "Acceleration And Trapping Of Particles By Radiation Pressure," Physical Review Letters **24**(4), 156-159.

Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E., & Chu, S. (1986). "Observation Of A Single-beam Gradient Force Optical Trap For Dielectric Particles," Optics Letters **11**(5), 288

Ashkin, A. (1992). "Forces of a Single-beam Gradient Laser Trap on a Dielectric Sphere in the Ray Optics Regime," Biophysical Journal **61**(2), 569-582.

O'Neil, A., & Padgett, M. (2001). "Axial and lateral trapping efficiency of Laguerre–Gaussian modes in inverted optical tweezers," Optics Communications **193**(1-6), 45-50.

Sridhar, H. (2007). "Development of an inverted optical tweezers with full motional control," Laser Teaching Center, Stony Brook University, NY (unpublished internet report).

Acknowledgements

This work was supported by the Laser Teaching Center and the Simons Foundation. We also thank RPC Photonics, Inc. (Rochester, NY) for providing the spiral phase plate.