NDnano
Center for Nano Science and Technology

ND*nano* Summer Undergraduate Research
2019 Project Summary

1. Student name & home university:
Alex Volk, University of Notre Dame

2. ND faculty name & department:
Dr. Gregory Timp, Electrical Engineering and Biological Sciences

3. Summer project title:
Modular assembly of metamaterials using light gradient

4. Briefly describe new skills you acquired during your summer research:
I learned the responsibility needed to function at a high level in a professional environment and the independence needed to make significant advances without frequent advising or supervision.

5. Briefly share a practical application/end use of your research:
One crucial application of my research is the improvement and development of metamaterials, intricate systems full of potential for uses such as invisibility cloaks.

6. 50- to 75-word abstract of your project:
The use of light gradient forces to manipulate and organize nanometer-scale matter is a radically new strategy for manufacturing nanosystems. A laser can be split into a 2D array for trapping particles, and by reflecting the beam off a mirror, a standing wave optical trap forms in the third dimension along which particles can stack up, creating a full 3D lattice. In this way thousands of nanoparticles can be manipulated into a complex heterogeneous voxel to form nanosystems of any size, shape and constituency.

7. References for papers, posters, or presentations of your research:
A. Ashkin, "Forces of a single-beam gradient laser trap on a dielectric sphere in the ray optics regime," Biophys. J. 61, 569 (1992).

A. Aiello and G.S. Agarwal, "Self-healing of Gaussian and Bessel beams: a critical comparison," arXiv:1501.05722v1 (2015). X. Chu and W. Wen, "Quantitative description of the self-healing ability of a beam," Optics Express, 22(6), DOI:10.1364/OE. (2014).

One-page project summary that describes problem, project goal and your activities / results:

Metamaterials are a class of materials with fascinating properties, notably a negative index of refraction. By carefully assembling precise geometries, a metamaterial's designer can manipulate light in nearly any way imaginable. These materials open the doors to a vast expanse of possibilities, including invisibility, medical imaging, a perfect antenna, and a lens that works beyond the diffraction limit. However, in order to efficiently manipulate light, a nanosystem must be very precisely assembled. The project I worked on proposes a new technique for assembling these nanosystems relying on light-gradient forces developed from standing wave optical traps.

The first part of my project was learning to de-blur existing confocal microscopy data to analyze the structure of assembled lattices. The problem is that light diffracts around the edges of particles, naturally blurring them so that even a perfect lens cannot resolve details beyond the diffraction limit. On the scale of everyday objects this effect is negligible, but on the scale of nanoparticles (we used particles ranging from 20 nm to 1000 nm) the blurring is appreciable. Fortunately, the way in which this blur occurs is systematic. The Point Spread Function (PSF) is the way in which a point source of light blurs in the instrument used to image it, under the specific conditions used in that imaging process. The actual material being imaged is convolved with the PSF to produce the blur we see in the image. Methods such as the Richardson-Lucy algorithm can be used to reconstruct an approximation of the actual object being imaged by through de-convolution of the PSF. I worked through the various degrees of freedom associated with this process and optimized the iterative application of the de-convolution algorithms (Figure 1).

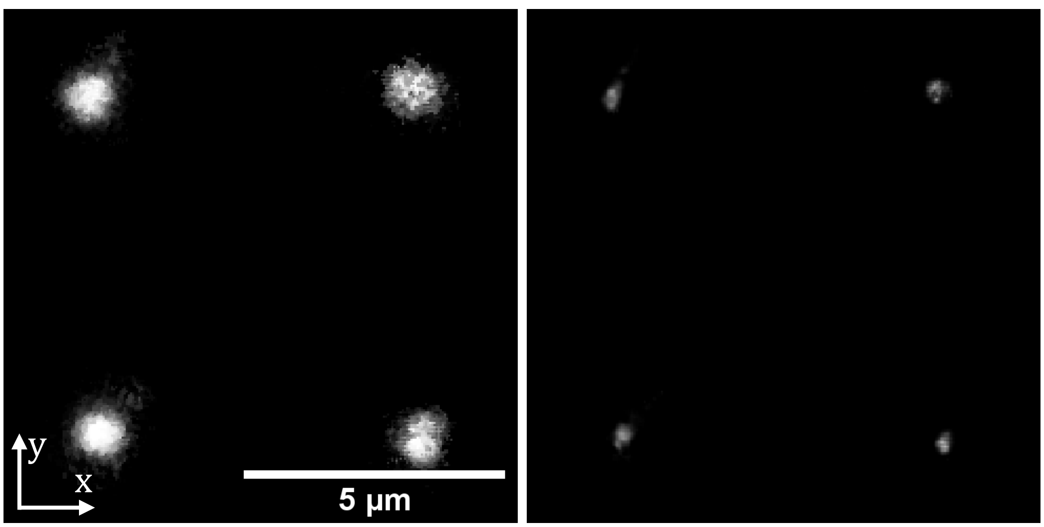

Figure 1. 2x2 array of particles. (Left) Original image. **(Right)** Image deconvolved after 15 iterations using the Richardson-Lucy algorithm.

After I was able to reliably de-blur and analyze data, I moved on to the next stage of the process: the physical assembly of the nanosystems. I worked with Dr. Koshala Sarveswaran to create arrays of optical traps. Since two-dimensional traps in the x and y directions (perpendicular to the laser beams) had already been given a good deal of attention before I began this project, I was mainly working with the structure in the z direction (i.e. along the optic axis parallel to the laser beam). Trapping in this z direction involves reflecting the in-coming laser beam back in the direction it came from so the out-going beam interferes with the incoming beam, creating a standing wave pattern of nodes and anti-nodes regularly spaced apart, making a row of individual traps along the optic axis. By creating these traps inside a gel into which we dispersed pre-fabricated nanoparticles of specific sizes, we were able to successfully trap multiple particles in the z direction.

Initially some of these traps had multiple particles in them and others had no particles in them. We developed techniques to fix this, including aligning the mirror properly with the incoming laser beam, lowering the concentration of particles floating around in the gel, and incorporating an annealing process in which the laser was flickered on and off quickly to allow for the traps with multiple particles to release their extra particles into nearby empty traps, thereby smoothing out the structure and spacing.

We have concluded that this method is, in fact, an effective way to assemble nanosystems of any size, shape, and constituency. In the future, I will be returning to the project to work on improving the structure using another beam type whose cross section is a Bessel function instead of a Gaussian function like had been used for most of the previous tests. Since the Bessel beam does not spread out as it propagates, it can be focused for a much greater distance than the Gaussian beam, allowing for longer z direction structure. It also has a “self-healing” property which allows it to reform after being partially occluded, meaning particles being trapped in the z direction won’t block as much of the light from the particles attempting to stack up behind them. Once this is all completed, this research will be essential in the fabrication of the extremely small and precise structure that defines metamaterials.