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14. ABSTRACT
In this work, we successfully proposed and demonstrated a new method for making ordered arrays of nanoparticles. The technique uses a template made of silicon with small holes in it. Shining laser light at the template creates a strong optical field in the holes; these then serve as optical traps. By designing the template appropriately, we can assemble ordered arrays of dielectric or gold nanoparticles. Changing the laser wavelength allows the pattern of traps, and thus particles, to be reconfigured.

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Report Title

Final Report: Light-assisted Assembly and Reconfiguration of Complex Optical Materials using Microphotonic Templates

ABSTRACT

In this work, we successfully proposed and demonstrated a new method for making ordered arrays of nanoparticles. The technique uses a template made of silicon with small holes in it. Shining laser light at the template creates a strong optical field in the holes; these then serve as optical traps. By designing the template appropriately, we can assemble ordered arrays of dielectric or gold nanoparticles. Changing the laser wavelength allows the pattern of traps, and thus particles, to be reconfigured.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
10/24/2016	21	Shao-Hua Wu, Ningfeng Huang, Eric Jaquay, Michelle L. Povinelli. Near-Field, On-Chip Optical Brownian Ratchets, Nano Letters, ( ): 5261. doi:
10/24/2016	22	Aravind Krishnan, Ningfeng Huang, Shao-Hua Wu, Luis Javier Martínez, Michelle L. Povinelli. Enhanced and selective optical trapping in a slot-graphite photonic crystal, Optics Express, ( ): 23271. doi:

TOTAL: **2**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
09/01/2012	5	Camilo Mejia, Eric Jaquay, Luis Martinez, Avik Dutt, Michelle Povinelli. Light-assisted templated self assembly using photonic crystal slabs, Optics + Photonics, Optical Trapping and Micromanipulation VIII. 22-AUG-11, . : ,

TOTAL: **1**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
07/31/2014	14.00	LJ Martinez, E Jaquay, Jing Ma, ML Povinelli. Fabrication and optical characterization of high-Q guided mode resonances in a graphite-lattice photonic crystal slab, Conference on Lasers and Electro-Optics (CLEO). 06-MAY-12, . : ,
08/20/2013	8.00	Ningfeng Huang, Eric Jaquay, Chenxi Lin, Jing Ma, Luis J. Martinez, Camilo A. Mejia, Michelle L. Povinelli. Guided resonance modes in photovoltaics and light-assisted self assembly, THE FIFTH INTERNATIONAL WORKSHOP ON THEORETICAL AND COMPUTATIONAL NANO-PHOTONICS: TaCoNa-Photonics 2012. 24-OCT-12, Bad Honnef, Germany. : ,
08/31/2015	17.00	Eric Jaquay, L. J. Martinez, C. A. Mejia, M. L. Povinelli. Experimental demonstration of light-assisted, templated self assembly using photonic-crystal slabs, Conference on Lasers and Electro-Optics. 09-JUN-13, . : ,
08/31/2015	18.00	Ningfeng Huang, Luis Javier Martinez, Eric Jaquay, Camilo A. Mejia, Debarghya Sarkar, Michelle L. Povinelli. Light-assisted Templated Self-Assembly of a GoldNanoparticle Array, Conference on Lasers and Electro-Optics. 06-JUL-14, . : ,

TOTAL: **4**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Aravind Krishnan	0.21	
Ahmed Morsy	0.21	
Shao-Hua Wu	0.14	
FTE Equivalent:	**0.56**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ......

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ......

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Light-Assisted Assembly and Reconfiguration of Complex Optical Materials Using Microphotonic Templates

Michelle L. Povinelli, University of Southern California

Statement of the problem studied

Self-assembly methods [1] provide a widely used “bottom-up route” to making complex materials. Self assembly of colloidal particles has proven useful for making nanostructured, photonic materials such as photonic crystals [2-4] and metamaterials [6]. However, a fundamental limitation of self assembly is that only certain, energetically favorable structures are formed. To expand the range of particle patterns that can be assembled, templates can be used to guide particles into their desired locations [7-10]. However, the pattern of particles assembled in this way is static, and not easily reconfigured. Methods for on-demand assembly and reconfiguration of the particle pattern would greatly expand the range of potential applications for complex photonic materials formed by assembled nanoparticles.

In this work, we introduced a method that uses light to “assist,” or drive, the assembly process [11] (Figure 1). Our technique uses laser light incident on a patterned template to create an array of strong optical traps, which pull particles into place from solution. We studied the types of particles that could be assembled in this manner, and what patterns could be formed. We further examined how interactions between particles affect the possible patterns and their stability. The use of incident light to control assembly also provides a route to reconfiguration: theoretically, we have identified a mechanism for changing the assembled particle pattern via tuning of the wavelength of polarization of the incident laser [11]. We further assessed the ability of this assembly method to serve as the basis for (i) a nanoparticle size sorter and (ii) rectified Brownian motion, or “ratchets”.

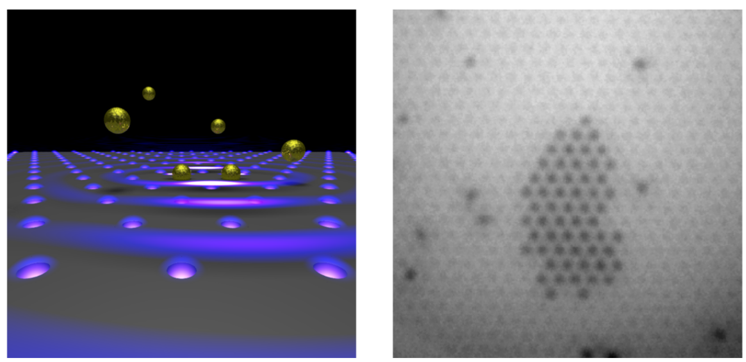

Figure 1: Light-assisted, templated self assembly. (left) Light is incident from below on a template, formed by a silicon photonic crystal slab. The slab enhances the light intensity near the holes, creating an array of optical traps for nearby particles in solution. (right) Microscope image of assembled gold particles with 200nm diameter, taken from our Ref. [5].

Summary of the most important results

Assembled dielectric nanoparticle arrays: We demonstrated the assembly of over 100 dielectric particles in a square lattice [12]. Figure 2 shows snapshots of the process. The photonic crystal template is visible in the background of each frame. When the laser beam is turned on, nanoparticles are attracted toward the slab, and begin to occupy the sites of the square lattice (Figure 2(a)). As time progresses, additional particles diffuse into the region where the intensity is high and begin to form a cluster (Figure 2(b)). Eventually, a regular array is formed (Figure 2(c)). The square symmetry of the particle arrangement is evident from the picture. When the beam is turned off, particles immediately diffuse away from the slab via Brownian motion (Figure 2(d)). These frames were recorded with a relatively dilute solution of particles for clarity of imaging, and represent an elapsed time of approximately one hour. We have verified that faster cluster formation occurs with higher concentrations, or by using particle flow, for assembly times of a few minutes.

Each site of the square lattice may be viewed as an optical trap. We obtained trap stiffness values comparable to those reported for single-particle, microphotonic near-field traps [13], which are an order of magnitude higher than standard optical tweezers. For polystyrene particles, particle interactions appeared to be minimal.

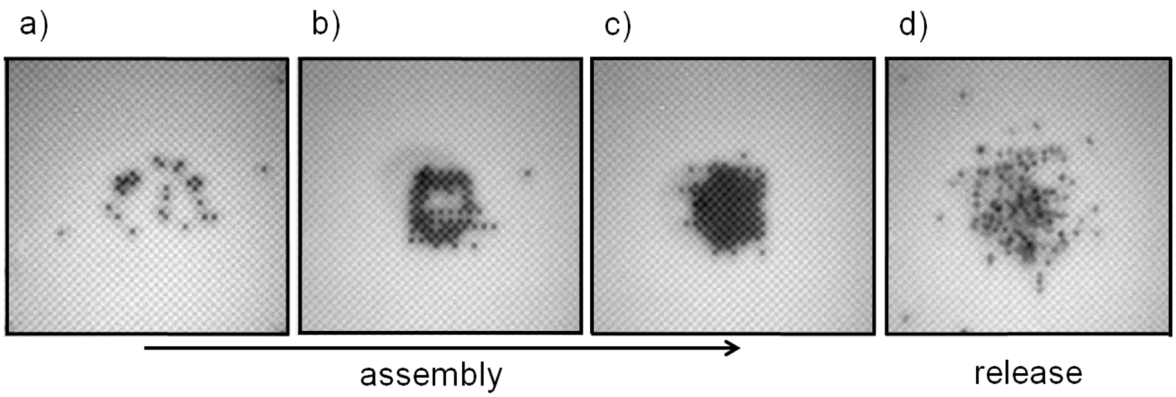

Figure 2: Snapshots of the Light Assisted Templated Self Assembly process. (a)–(c) Sequential images taken with the laser on. (d) Image taken just after the beam is turned off.

Assembled gold nanoparticle arrays: For gold nanoparticles, we observed strong interparticle interactions. Left unchecked, these can inhibit the formation of regular arrays. In our experimental work, we observed that for lattices with square symmetry, the gold nanoparticles formed chains [14]. We formulated a theoretical approach to predict the effect of interactions on the assembled pattern. Using this model, we identified a template with hexagonal symmetry that would promote the assembly of regular arrays and observed the assembly experimentally (Figure 1b) [5]. We found that in this case, the interparticle interactions act to stabilize the array, creating highly stable assemblies.

Pattern reconfiguration: Different templates support different optical field patterns, and thus trap particles in different locations. We explored and demonstrated this concept in our early simulation paper, Ref. [11]. More recently, we refined our template designs to be fully compatible with our experimental infrastructure (Figure 3).

Nanoparticle sorting: In the course of our work, we designed templates that reduce the optical power required for optical trapping. These templates tightly concentrate light in thin slots, boosting the optical trapping strength for fixed laser power [15]. We fabricated and characterized these templates [16] and used them for assembly experiments. We found that particles could be selectively trapped based on size [17], suggesting a mechanism for sorting nanoparticles out of mixtures.

Optical ratchets: Study of classical ratchet potentials has shown that for a particle subject to Brownian motion and confined to a asymmetric potential, switching the potential on and off can make the particle move in one direction [18]. The transport rate depends on particle size, leading to techniques for sorting microscale particles and DNA [19, 20]. Optical ratchets have previously been implemented using fluctuating optical lattices [21], but never with integrated microphotonic devices. We have reported the ***first integrated photonic ratchet*** in *Nano Letters* [22], using a modified version of our assembly method.

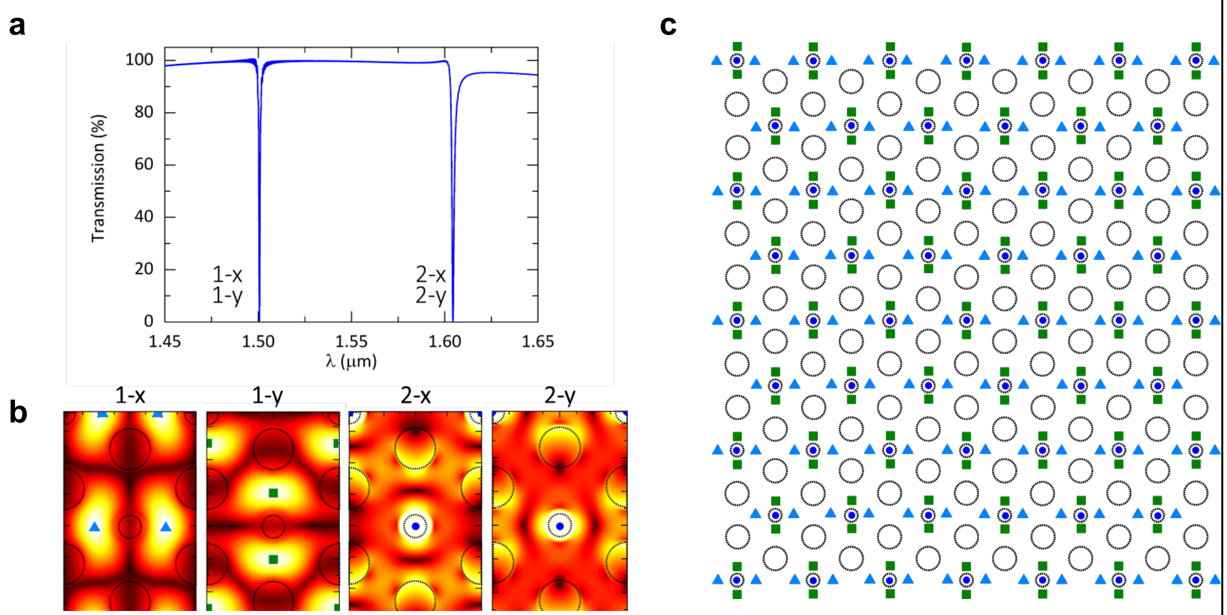

Figure 3: Predicted trapping positions for reconfiguration. (a) Calculated transmission spectrum for template. (b) Electromagnetic field intensity at each resonance, with stable trapping positions indicated by symbols. (c) Stable trapping positions in the extended lattice.

We designed a template with spatial asymmetry and calculated the resulting optical potential. We showed experimentally that modulating the incident light rectifies the Brownian motion of assembled nanoparticles, preferentially driving them in one direction.

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