Light-assisted templated self assembly using photonic crystal slabs

Camilo A. Mejía*, Eric Jaquayb, Luis Javier Martínezb, Avik Duttc, and Michelle L. Povinelli

aDept. of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089, USA
bMing Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA
cDept. of Electronics and Electrical Communication Engineering, Indian Institute of Technology, Kharagpur, India

ABSTRACT

We calculate optical forces on colloidal particles over a photonic crystal slab. We show numerically that exciting a guided resonance mode of the slab yields a resonantly-enhanced, attractive optical force. Optical forces in the lateral direction result in a two-dimensionally periodic pattern of stable trapping positions. Trapping patterns can be reconfigured by changing the wavelength or polarization of incident light. We study the dependence of optical forces on particle size, particle dielectric constant, and photonic-crystal slab parameters. Finally, we describe the fabrication and measurement of a photonic crystal slab with a $Q \sim 370$.

1. INTRODUCTION

It is well established that the force of light can be used to manipulate nanoscale objects. Optical tweezers\(^1,2\) provide a well-known example. Recent research has studied the use of structured light fields to form arrays of optical tweezers, or traps, and demonstrated various applications in physics and biology.\(^3,4\) While much of this work uses holographic techniques and/or free-space optics to shape the light field, an alternate approach employs microphotonic structures. Previous work has shown that large optical forces can be achieved by using the strong electromagnetic fields near devices such as nanoapertures\(^5,6\), gratings\(^6\), photonic crystal microcavities\(^7,8\), slot waveguides\(^9\) and plasmonic structures\(^10,11\). However, much of the work on microphotonic structures has considered single-particle traps.

In a recent paper\(^12\), we have proposed to use the guided resonance modes of a photonic crystal slab to trap arrays of particles in crystalline patterns. This process is a form of light-assisted self assembly. Laser light incident on a photonic-crystal slab is strongly enhanced by a resonant mode of the photonic crystal, magnifying the optical force on nearby particles. We have predicted that particles will be attracted to the slab and settle in an array of stable trapping locations. Changing the wavelength or polarization of the light source will yield a different pattern of trapping locations. Thus, unlike traditional self assembly methods, in which the particle configuration is determined by energetic constraints, the use of light forces should allow flexible assembly and reconfiguration of diverse particle patterns.

In this proceeding, we start by summarizing our previous theoretical work, which predicts the stable trapping locations for particles near a photonic-crystal slab. We then extend our results to show the dependence of the optical force on characteristics of the nanoparticles (radius, dielectric constant) and photonic-crystal slab template (hole size, height). Finally, we present the fabrication and measurement of a photonic-crystal slab designed for light-assisted, templated self assembly.

2. THEORY AND SIMULATION

Figure 1(a) illustrates the concept of light-assisted templated self-assembly. Light is incident on a photonic crystal slab as shown by the red arrow. The periodicity of the photonic crystal gives rise to a periodic electromagnetic field near the slab surface, resulting in a periodic array of optical traps.

For concreteness, we consider a silicon photonic crystal ($\varepsilon = 11.9$) with a square lattice of holes of radius $0.2a$ and thickness $0.6a$ resting on a silica substrate ($\varepsilon = 2.1$). The holes in the photonic crystal and the region above the crystal are filled with water ($\varepsilon = 1.77$). The incident light is an $x$-polarized plane wave propagating in the $z$ direction. Figure 1(b)
shows $|E_z|^2$ at a frequency of 0.47 c/a, where c is the speed of light and a is the lattice constant of the photonic crystal. Calculations are performed using the MIT meep package.

The transmission through the photonic crystal in the absence of particles is shown in Figure 2(a). The transmission exhibits characteristic guided resonance peaks at frequencies 0.472, 0.496, and 0.501 (c/a). We refer to the three resonances as R1, R2, and R3 respectively.

The force on a polystyrene sphere ($\varepsilon = 2.28$) of radius 0.1a at a height of 0.25a above the slab surface was calculated from the Maxwell stress tensor. We plot the dimensionless quantity $F_c/\phi$, where $\phi$ is the incident power per unit cell, for a sphere positioned equidistant from the four closest holes (Figure 2(b)). For each of the three resonances, we observe an enhanced force peak at the same frequency. The force attracts the sphere toward the slab. For comparison, we calculate the radiation pressure of a plane wave on a spherical particle in the absence of the photonic crystal and obtain a value of $F_c/\phi \sim 1 \times 10^{-5}$. The sign is positive, corresponding to a pushing force. The photonic crystal slab produces a force that is four orders of magnitude larger than radiation pressure.

Figure 1 a) Light-assisted templated self-assembly using a photonic crystal slab. b) $|E_z|^2$ on a plane right above the surface of the photonic-crystal slab for normally incident, x-polarized light at a frequency 0.47 c/a. Dashed lines indicate hole positions.
We now look at the spatial dependence of the force on resonance. Figures 3(a-c) show the intensity of the electric field for R1, R2 and R3 respectively. Figures 3(d-f) show the force on a vertical (x-z) slice at y = 0. The vertical forces are attractive. Figures 3(g-i) show the forces on a horizontal (x-y) slice 0.25a above the slab surface. The circles indicate hole positions. The length of the arrows next to the graphs represent the value of \( Fc/\phi = 0.2 \), and the red circles represent the stable points to which the particles are attracted. As we can see, R1, R2 and R3 produce different stable patterns. Figure 3(g) has an additional stable point at the center of the unit cell, but it is not labeled with a red dot because it has a weak lateral force compared to other trapping points. Similarly, Figure 3(h) has two additional weakly stable points at the bottom and top edges of the unit cell.

The stable patterns depend on polarization, as shown in Figure 4. Due to the symmetry of the photonic crystal, y-polarized light produces the same trapped patterns as x-polarized light, but rotated 90° (Figures 4(a) and 4(b)).

We have estimated\(^2\) the power density required for trapping to be approximately 1 mW/unit cell for R1, which has a modest \( Q \) of ~260. The required power decreases with increasing \( Q \).

The lattice constant of the photonic crystal can be scaled to place a given guided resonance at a particular wavelength of interest. For \( a = 760 \) nm, for example, R1 occurs at \( \lambda = c/\nu = 1609 \) nm, while R2 occurs at 1532 nm. For \( a = 375 \) nm, R1 is at 794 nm and R2 is at 748 nm.

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**Figure 2.** (a) Normalized transmission through a silicon photonic crystal slab with hole radius 0.2a and height 0.6a, resting on silica and covered by water (b) force in the z-direction for a sphere of radius 0.1a placed 0.25a above the slab surface equidistant from the four closest holes.
Fig. 3. (a-c) Intensity for normally incident x-polarized light for R1, R2, and R3, respectively. White circles indicate hole positions, (d-f) force in the x-z plane at y = 0, (g-i) force in the x-y plane at z = 0.25a for R1, R2, and R3, respectively. The red dots represent stable trapping points and the black circles indicate hole positions.

Figure 4. (a) Pattern for x-polarization, (b) pattern for y-polarization.
Figure 5(a) shows the vertical force as a function of the dielectric permittivity of the sphere, $\varepsilon$, for a sphere of radius $0.15a$. The magnitude of the force increases with $\varepsilon$, and no shift is observed in the resonance peak. Similarly, Figure 5(b) shows the vertical force as a function of sphere radius for a particle with $\varepsilon = 3$. The force increases with increasing sphere radius, and no shift is observed in the resonance peak. For larger sphere radii, increasing $\varepsilon$ will increase the force and shift the resonance peak, as shown in Figure 5(c). The figure shows the region of the spectrum near R1 for a sphere radius of $0.35a$.

![Figure 5](image1)

Figure 5. (a) Vertical force as a function of $\varepsilon$ for a sphere with radius $0.15a$, (b) vertical force as a function of sphere radius for $\varepsilon = 3$, (c) Vertical force for R1 as a function of $\varepsilon$ for a sphere radius of $0.35a$.

Changing the template will change the frequencies and quality factors of the resonances, changing the optical force. Figure 6(a) shows the change in force due to changing hole diameter for R1, $\varepsilon = 2.28$, slab thickness $0.6a$ and sphere radius of $0.1a$. The force peak shifts to higher frequencies as $d$ is increased. The force peak widens, and the peak amplitude decreases, corresponding to a decrease in the resonance quality factor. Figure 6(b) shows the change in force with slab thickness for R1, $\varepsilon = 2.28$, hole diameter of $0.4a$, and sphere radius of $0.1a$.

![Figure 6](image2)

Figure 6. (a) Vertical force as a function of hole diameter for R1 and $\varepsilon = 2.28$, (b) vertical force as a function of slab thickness for R1 and $\varepsilon = 2.28$. 
3. FABRICATION

The photonic crystal slabs studied here were fabricated in a silicon-on-insulator wafer (manufacturer: SOITEC) with a device layer of 250 nm and a buried oxide layer of 3 μm. The patterns were written in a Raith 150 e-Line electron beam lithography system using PMMA 950K A-4 as a resist. The patterns were transferred to the Si layer in an Oxford 100 DRIE system using a pseudo-Bosch process in which both the etchant (SF6) and the polymer (C4F8) gasses were flowed in the chamber simultaneously. Figure 9(a) shows a representative device.

Measurements were performed with an HP 81689A tunable laser with a tuning range of 1525 to 1575 nm. Incident light was focused onto the sample plane using a microscope objective, collected using a microscope lens and focused onto a photodetector. Two crossed polarizers were placed at the input and output so that the guided resonance mode appears as a peak in the transmission spectrum. Figure 9(b) shows a measured transmission spectrum as a function of wavelength for a representative device with $a=760$ nm. The spectrum shows the characteristics of a guided resonance mode. A quality factor of 370 was extracted by fitting the spectrum to a Fano resonance formula. The peak occurs at $a/\lambda = 0.4935$, corresponding to a physical wavelength of 1540 nm.

![Figure 9. (a) SEM micrograph of a photonic crystal square lattice, (b) Transmission spectrum for a photonic crystal square lattice showing a characteristic guided resonance feature.](image)

4. CONCLUSION

In summary, we predict that optical forces above photonic crystal slabs can be used to assemble crystalline arrays of particles. Tuning the incident wavelength to a guided resonance of the photonic crystal enhances the force by up to four orders of magnitude compared to radiation pressure. Each guided resonance corresponds to a particular array of stable trapping points. We predict that different patterns of particles can be assembled by tuning the wavelength or polarization of the light source. We term this process “light-assisted templated self assembly.”

For low-$\varepsilon$ particles and small particle radius, the particles do not shift the resonance of the photonic crystal slab. The force increases with particle $\varepsilon$. The position and magnitude of the force at resonance are sensitive to the photonic crystal slab thickness and hole diameter. These parameters can be optimized for a given application.

We have demonstrated the fabrication of a photonic-crystal slab device and measured a resonance with a quality factor of 370 near a wavelength of 1550 nm.

We expect the approach of light-assisted self-assembly described here to be of broad utility for fabrication of complex photonic materials, sensors, and filters. It is intriguing to consider whether metamaterials based on metal nanoclusters, for example, could be assembled in the manner we describe, using the optical response of the nanoclusters to tune or adjust assembly.
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REFERENCES