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Photonic-crystal cavities as optical nanomachines

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A novel light source and integrated photonic device can manipulate, sort, and select complex semiconductors and/or nanoparticles.

For many years, researchers have been trying to harness the weak light force to maneuver tiny nanomachines. In addition, the driving force from a small number of solar photons may eventually provide the necessary energy for interplanetary travel.[1] Large-scale, sophisticated simulations and experiments show the great potential of linking nanophotonics and nanomechanics with high precision and accuracy by employing concentrated light to manipulate semiconductor-based objects.[2–5] However, current on-chip exploitation of the optical force still lacks a highly localized light source that could enable near-field manipulation under a range of conditions. Our research aims to partially approach this goal. We propose (and have designed) a new light source, combined with an integrated photonic device, that can be used to manipulate, sort, and select complex dielectric nanoparticles acting as nanomachines.[6]

Photonic-crystal (PhC)-slab cavities have recently become useful and popular in nanophotonics. They have been widely used in a variety of fields, such as in ultrasmall lasers, and for optical switching and chemical sensing.[7] These applications are possible because of the associated strong electric-field confinement and extremely enhanced local field.[8] PhCs are characterized by a periodic structure and a forbidden photonic bandgap, which affect the light's localization and control.

We have shown that it is feasible and of significant interest to adopt such PhC cavities to provide a link between nanophotonics and nanomechanics in the form of a fresh new design with many advantages. In particular, PhCs as operational, versatile planar light sources are urgently needed for future on-chip, integrated, nanoscale photonic circuits. We aimed to show that an all-optical coupling using light could potentially be achieved with the synthesized optomechanical potentials in our integrated system, and potentially applied in current semiconductor fabrication processes.

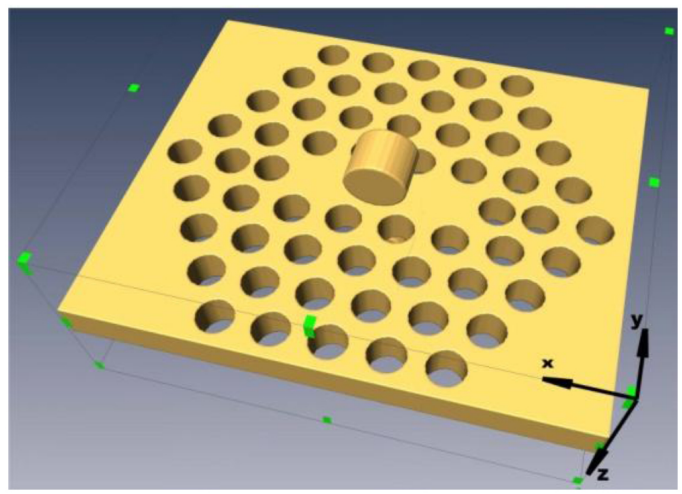

Figure 1. *Schematic showing the coupling between a nanorod and the cavity of a photonic-crystal (PhC) system.*

A strongly resonant state is first established and activated in the PhC cavity, which stores some electromagnetic energy and has a strong local electric-field gradient in its vicinity (see Figure 1). A dielectric nanorod is placed next to the cavity, causing a slight perturbation of the high-quality (high-Q) cavity. The dynamic tuning of the PhC cavity's frequency will affect the system's behavior and stability (see Figure 2). An optical force is exerted on the nanorod, pushing or pulling it into an equilibrium state. As a consequence, the interaction inside the system will change significantly, and can be analyzed using an adiabatic model (see Figure 3). The system's energy efficiency is determined by the strong electromagnetic coupling between the nanocavity and the nanorod.

Using the high-Q PhC cavity works better than traditional structured (e.g., corrugated plasmonic) surfaces. Our new system also offers numerous integrated functions on a nanosized chip, for instance in ultrasmall lasers, and for optical switching, chemical sensing, and nanoparticle micromanipulation. In

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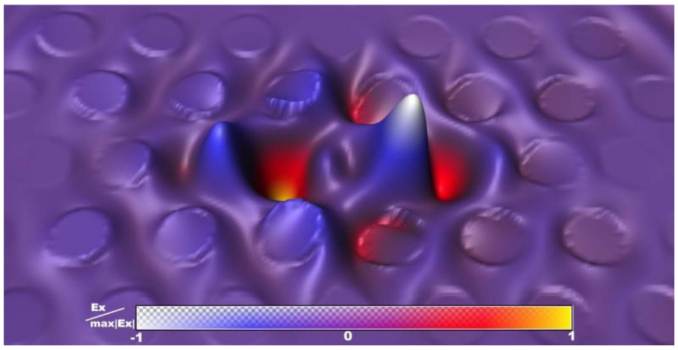

Figure 2. *Profile of the normalized electric-field component (Ex) of the fundamental cavity mode.*

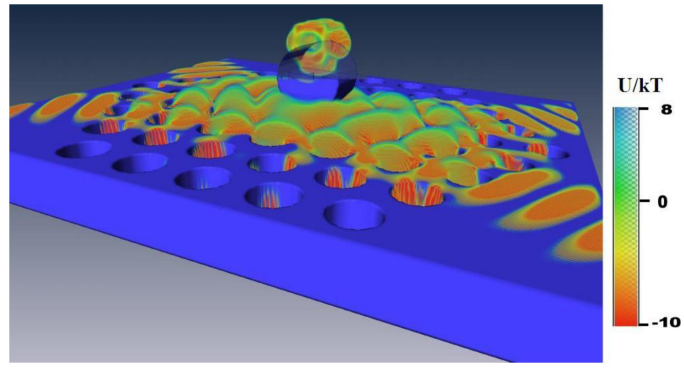

Figure 3. *Distribution of the normalized electromagnetic energy, U, in the coupled system. An attractive, optically induced potential ball is formed at the top of the nanorod. Note that the repulsive potential (light blue) dominates in the area between the bottom of the nanorod and the surface of the PhC slab.*

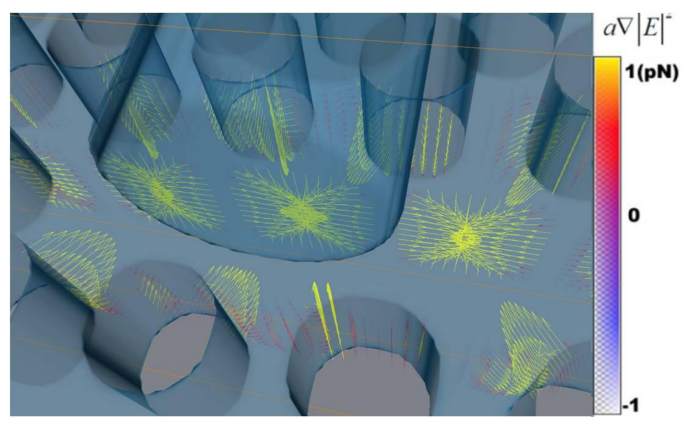

Figure 4. *Magnitude (color scale) and direction (yellow arrows) of the gradient force around and inside the PhC cavity system.*

addition, the total energy-conversion efficiency can be adjusted by tailoring the evanescent wave that passes through the strong electromagnetic-coupling mechanism, which is a unique feature among optical devices.

The new device can extend our understanding of the rapidly evolving field of nano-optomechanical systems. The variation and sign change of the optical force is of great interest for both optical trapping and manipulation, as well as for the system's control and local transduction. It also offers a platform for construction of all-optical tunable surfaces. Given its capability to locally address individual nanorods, the device is particularly useful for biosensing and cell/DNA isolation, molecule sieving, and local sample preconcentration.

This type of of near-field optical trapping is different from that associated with conventional Ashkin-type optical tweezers,[9] in the sense that it works below the diffraction limit (see Figure 4). Therefore, we have in essence developed novel optical tweezers that are easily tunable and can be fabricated using state-of-the-art technology. The light source is tunable through manipulating the spontaneous emission inside the PhC cavity. It has the advantage of strongly confined electromagnetic fields, thus enabling construction of very small lasers. The proposed cavity structure can be fabricated easily and is now one of the best options for obtaining ultrahigh-Q for certain resonances.

Based on large finite-difference time-domain simulations, we have attempted to interpret the 3D energy vector flow as well as the energy-coupling effect in the device using geometric-field and texture visualization. This technique provides a powerful aid for our intuitive understanding, which has rarely been applied in previous photonic-device research. Some detailed mechanisms and subtle system abnormalities can be demonstrated convincingly based on data visualization. Theoretical studies of the optical-coupling interaction with nanorods show that the bipolar optical-force behavior implies that a PhC cavity system could be a 'smart' new class of self-adaptive photonic devices. The sensitive optical-force response to the geometric structure in the strongly coupled system indicates that the nanocavity can adapt to its environment in a complex nano-electromechanical system. We also show the optomechanical stability of the system.

We have—for the first time—proposed the use of remarkable localized nanocavities as a general light source to synthesize optomechanical systems through exploitation of the optical force. We have shown theoretically and numerically that a high-Q PhC-slab cavity can exert different optical forces on dielectric high-refractive-index nanorods, which behave like near-field

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optical tweezers. The latter have been widely used in biological research. They exploit the concentrated gradient-potential nature of a tightly focused laser beam to trap cells. However, manipulation of nanoscale objects demands much stronger confinement of light beyond the normal diffraction limit, which is exactly what we have done. PhC-slab nanocavities provide a very compact and easily accessible optical mode at the nanoscale and have the advantages of easy design and fabrication. They are therefore promising candidates for the next generation of near-field optical tweezers.

We will next use this technology to study how different kinds of nanorods, such as metallic or gradient nanowires, nanotubes, and doped nanoparticles, will enhance the coupling efficiency through intensifying the evanescent-field strength.

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