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# Functional Nanocavities Based on Photonic Crystals

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**Abstract**
We discuss several interesting applications of ultrahigh-Q and ultrasmall nanocavities recently realized in silicon photonic-crystal slabs: 1) All-dielectric slow-light media, 2) All-optical bistable switching elements towards all-optical logic chips, 3) Adiabatic wavelength conversion, 4) Super-efficient optomechanical energy converter.

## 1. Ultrahigh-*Q* and ultra-small nanocavities based on photonic crystals

Recently, there has been rapid progress in the quality factor ($Q$) of wavelength-sized nanocavities based on semiconductor photonic crystal slabs owing to improvements in design and fabrication resolution. [1,2,3] We have recently proposed a novel design of photonic-crystal cavity, namely width-modulated line-defect cavity, and realized $Q$ of 1.2 million with the mode volume of $1.5(\lambda/n)^3$ by detailed spectral and time-domain measurements. We observed a long photon lifetime (~1 nsec) for this high-$Q$ cavity. [3,4,5]

## 2. Slow-light media

A cavity having long photon lifetime should exhibit a substantial group delay. If the cavity size is small, we can expect significantly small group velocity. We have measured the speed of light passing through photonic-crystal nanocavities and found that it is reduced down to $c$/50,000, which is the slowest value reported for all-dielectric slow-light media.[3,5]. To increase its operation bandwidth, we have recently realized large-scale coupled-resonator waveguides employing these nanocavities. We observed significantly high transmission up to N=200 (N is the number of cavities). [6]

## 3. On-chip all-optical logic processing

One of the most important aspects for high-$Q$ nanocavities is the fact that intrinsically weak light-matter interaction can be greatly enhanced by employing high-$Q$ nanocavities. Such enhancement is expected for various optical phenomena, such as light emission, optical nonlinearity, etc. We have recently employed these nanocavities for all-optical switching based on optical nonlinearity in materials.[7,8,9,10] The device is based on high-$Q$ nanocavities having two resonant modes coupled to input and output waveguides implemented in silicon photonic crystals. We have observed all-optical bistable switching operation with significantly small switching energy (<100 fJ) and fast switching speed (~100 ps). This switching operation is based on two-photon absorption in silicon and subsequent carrier-plasma dispersion effect. Although silicon is not an ideal material for nonlinear application in comparison with III/V materials, we observed fairly low-power switching operation. This is because the switching power should be scaled as $V/Q^2$ (the switching energy should be $\sim V/Q$).[11] Although the loaded $Q$ is finally determined by the required operation speed, it is always advantageous to have smaller $V$ and larger unloaded $Q$, which is the case for photonic-crystal nanocavities.

This tiny bistable switching element has some important aspects for future application. 1) It requires very small switching energy, 2) Bistable transistor-like operation is possible, 3) It is fundamentally suited for large-scale optical integration, 4) It is based on silicon. Although there had been extensive studies for all-optical logic using optical nonlinearity, we believe that this element can potentially solve many of problems in previous works towards on-chip integration of all-optical logic processing elements. Recently, we have designed all-optical flip-flop processor consisting of doubly-coupled nanocavities, by which we demonstrate all-optical retiming circuit operation numerically.[12] Although this is just one of examples how photonic-crystal based integrated circuits can perform, we believe much complex logic function may be possible by integrating a large number of these elements.

## 4. Adiabatic wavelength conversion

In the previous section, we discuss the possibility of manipulating light propagation in a cavity via optical nonlinearity of materials. Here we show a fundamentally different way of the manipulation of light using nanocavities. If we have a sufficiently small and high-$Q$ optical cavity, it becomes possible to change the property of this cavity within its photon lifetime. Recently, we have clarified that this dynamic tuning[13] leads to very interesting optical phenomenon. Suppose that an optical pulse is stored in a cavity and we change the resonant wavelength of the cavity. Then, what will happen? We numerically computed this phenomenon by the finite-difference time-domain technique, and we found that the wavelength of light captured in a cavity is converted.[14,15,16] This conversion does not depend on the tuning rate and thus it is different from conventional $\chi^3$ process, such as self-phase modulation. The wavelength of light just follows the varied resonant wavelength of the system. This situation is exactly the same as parameter tuning of classical oscillators. For example, let us imagine that we pluck a string of a guitar and twist a peg before the generated sound is dying out. Then, we can easily change the tone of sound. What we have done for a nanocavity is physically the same. One of the proofs is that we have numerically confirmed that $U/\omega$ is preserved during the conversion process, which is a signature of classical adiabatic tuning. Such tuning is normally impractical because light is so fast and we cannot change its property within a dwell time in a system. But now it is becoming possible because high-*Q* microcavities and slow-light media are progressing very much. Very recently, this process has been experimentally observed in silicon micro-ring resonators.[17]

## 5. Coupled-nanocavity-based optical MEMS

If we apply the previous adiabatic conversion process to a certain type of coupled cavities, very interesting opto-mechanical system can be realized. We have examined [18] a double-layer cavity consisting of ultrahigh-Q cavities studies in the first section, as shown in Fig. 3. We calculated an optical force generated by an optical pulse captured in this coupled cavity by using two different methods (Maxwell's stress tensor calculation and $-\mathrm{d}U/\mathrm{d}z$ calculation), and round that the it can generate very large optical force (~1 μN/pJ). In addition, this large optical force can do mechanical work upon the slab during the system's long photon lifetime. Consequently, this system can work as a very efficient optical to mechanical energy converter. The estimated energy conversion efficiency is close to 10%, although the system is in a non-relativistic regime. Conventional opto-mechanical systems, such as optical tweezers, suffer from their poor energy conversion efficiency, which fundamentally due to mass-less nature of light. However, we clarified that we can extremely enhance this efficiency using nanocavity-based optomechanical systems. In fact, this energy conversion is a reverse process of wavelength conversion in the previous section, and thus the converged energy corresponds to the shifted wavelength. In other words, this system is also very effective wavelength converter. If we move one of the slabs faster than the photon lifetime of the cavity, very large wavelength conversion is indeed possible. We have numerically confirmed that $\Delta/\lambda/\lambda$ can be 20%.

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