Photonic Crystal Nanocavities with Extremely Long Photon Lifetimes and Their Applications

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Photonic crystal (PhC) nanocavities with ultrahigh Q values are reviewed. The demonstrated Q for a width-modulated PhC nanocavity is extremely high at 1.2×10^6, which corresponds to a photon lifetime of ~1 ns. In addition, an ultrahigh Q of 3.2×10^5 is demonstrated using a point defect type hexapole cavity. The extremely long photon lifetime enables us to fabricate devices, such as photonic DRAMs, chip integrated slow light materials, and novel wavelength converters.

Key Words: Photonic crystal, High-*Q* nanocavity, Photonic DRAM, Silicon photonics

1. Introduction

Cavities with an ultrahigh quality factor (Q) and an ultra small modal volume (V) yield a high photon density even at an extremely low input power.[1)] Of the various types of micro-cavities, such as toroid cavities, micro-disk cavities, micro-ring resonators and micro pillars, photonic crystal (PhC) nanocavities can achieve the smallest V[2)] and an extremely high Q.[3,4)] Therefore, ultrahigh-Q PhC nanocavities are considered to be promising candidates for low energy switches[5, 6)] or cavity quantum electro-dynamics devices,[7)] the operation of which requires efficient optical nonlinearity. This paper describes the ultrahigh Q of two different types of PhC nanocavities, and discusses various applications that became possible as a result of the ultrahigh Q of the PhC nanocavity.

The paper is organized as follows. First, we discuss two different approaches to obtaining an ultrahigh Q in PhC nanocavities; one employs a point defect and the other employs a width-modulated line defect. In section 3, we explain how the Q of a PhC nanocavity can be dynamically tuned within the photon lifetime, thus enabling the fabrication of future photonic DRAM circuits. Section 4 describes the demonstration of a large pulse delay using a single cavity that can be employed as a basic element of a coupled resonator optical waveguide (CROW). Finally, an example of an ultrahigh-Q cavity application is shown, where optical wavelength conversion via adiabatic control is demonstrated numerically.

2. Ultrahigh-*Q* PhC nanocavities

2.1 Hexapole cavity

A single point defect cavity exhibits a hexapole mode as shown in Fig. 1(a).[8-10)] Rotational spatial symmetry significantly reduces the out-of-slab radiation due to the far field interference effect, and this enables us to achieve an ultrahigh Q. By optimizing the position of the six holes closest to the cavity, we have achieved a theoretical Q of 1.6×10^6 and a measured value of 3.2×10^5, both of which are the highest yet demonstrated for point defect type PhC nanocavities.[10)] The extremely large Q/V of this cavity makes it possible to generate carriers by two-photon absorption (which yields optical bistability[11)]) at an input power of just a few 100 μW.[6)] This may allow us to fabricate all-optical switches and logic gates[12)] operating at an ultra-low power.

2.2 Width-modulated line-defect PhC nanocavity

The width-modulated line-defect PhC nanocavity [Fig. 1(b)][13)] also yields an ultrahigh measured Q of 1.2×10^6 as shown in the inset of Fig. 1(c).[3)] This type of nanocavity employs the modegap to confine the light. Since the spectral transmittance width is extremely small (1.3 pm), we used an optical single-sideband modulator for a wavelength scan to confirm the accuracy of the measurement.[14)] By contrast, time

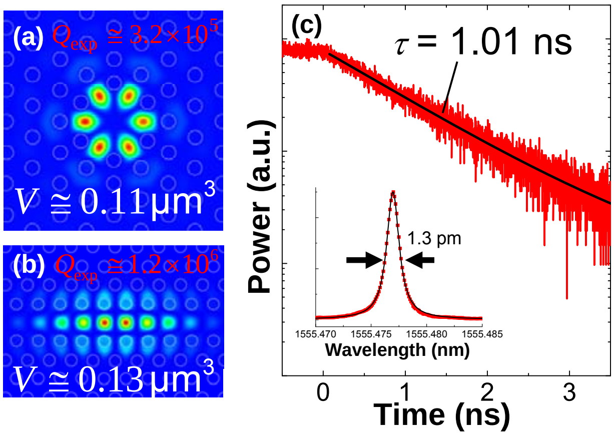

Fig. 1 (a) Mode profile of a hexapole cavity. (b) Mode profile of a width-modulated line-defect cavity. Although it is difficult to discern, the holes at the cavity are slightly shifted towards the outside to enable modegap confinement. (c). Discharge signal of the ultrahigh-Q PhC nanocavity when the input light was turned off at 0 ns. The inset shows the transmittance spectrum.

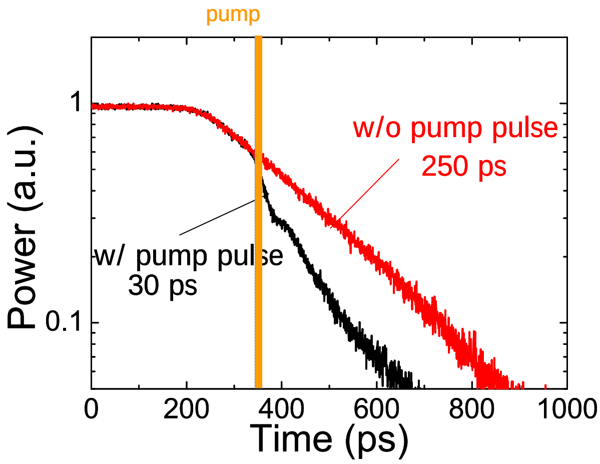

Fig. 2 (red line) Discharge signal from a PhC nanocavity with a Q of 2.7×10^5. (black line) Discharge signal when a 1-ps pump pulse at a wavelength of 800 nm is irradiated at t=350 ps from the top of the slab to generate free carriers.

domain measurement is an alternative and sophisticated way of characterizing an ultrahigh-Q PhC nanocavity. Here we successfully obtained an extremely long photon lifetime of 1 ns [Fig. 1(c)]. [3]

3. Dynamic tuning of cavity *Q*

3.1 Experimental demonstration of the dynamic tuning of the intrinsic *Q within the photon lifetime*

Although a high-Q cavity can trap photons for a long period of time and so may be used as a photonic memory, the operating speed will be limited by the photon lifetime. However, if we can change the cavity Q within the photon lifetime, we can overcome the bandwidth limit of the high-Q cavity systems. Figure 2 shows an experiment in which we undertook the dynamic tuning of the intrinsic Q of a PhC nanocavity. The red line is the discharge signal from the nanocavity. We obtained a photon lifetime of 250 picoseconds. Then we launched a pump pulse into the top of the slab. This generated carriers and changed the cavity Q by free-carrier absorption. Then, we obtained a very short photon lifetime of just 30 picoseconds immediately after the pulse. This demonstrates that it is possible for photons to be eliminated faster than the lifetime determined by the original Q of the cavity.[3]

3.2 Dynamic tuning of the in-plane Q: Controlling the coupling strength of the cavity / waveguide system

Although Fig. 2 shows a demonstration of the dynamic tuning of the Q, it is simply the modulation of the intrinsic Q. If we wish to obtain useful devices, such as photonic DRAMs, we have to control the in-plane Q. In other words, we have to change the coupling between the waveguide and the cavity system. To accomplish this, we propose a system[15] composed of two cavities, cavities A and B, as shown on Fig. 3(a). The basic idea of the operation is to use cavity B as a gate. Since cavity B is placed much closer to the I/O waveguide, the light couples strongly with the waveguide (hence the low Q) when the resonant modes of cavities A and B are the same. This constitutes an open cavity mode. On the other hand, if the resonance of cavity B is different from that of cavity A the light is localized and trapped in cavity A, which yields an ultrahigh-Q mode. This enables us to realize a closed mode. Figure 3(b) shows 2D finite difference time domain (FDTD) calculation results. At first, the resonance of cavities A and B is the same. After the cavity has been charged, the resonance of cavity B is changed to close the gate. A resonant shift can be obtained by using, for example, carrier-plasma dispersion or the Kerr effect. After a while, the gate is re-opened by changing the resonance of cavity B. This demonstration is regarded as corresponding to the realization of a photonic DRAM. However, the Q of the closed mode is 1.0×10^5, which may not be sufficiently high for this device to be employed in useful applications. So, we attempted to find another scheme that could exhibit a higher Q in the closed mode. Figure 3(c) shows a good candidate that achieves a closed mode via the interference effect. When cavities A and B have different resonances, the light will localize in cavity A. Since the coupling between cavity A and the waveguide is high, it yields a low Q (open mode). On the other hand, if the resonance of cavity B is set at the same value as cavity A, cavities A and B exhibit a coupled mode that has an ultrahigh Q. The ultrahigh Q of the coupled mode can be explained by the interference effect between the two cavities. Since the coupled mode exhibits opposite phases for cavities A and B, the light interferes destructively at the waveguide, which results in very small coupling of the optical modes between the waveguides. A 2D-FDTD result is shown in Fig. 3(d), where a Q of 9×10^6 is obtained for the closed mode. This corresponds to a photon lifetime of about 7.5 ns, which may be sufficiently long for various applications. Some experiments have been performed with a similar scheme using micro resonators[16] and a PhC nanocavity.[17]

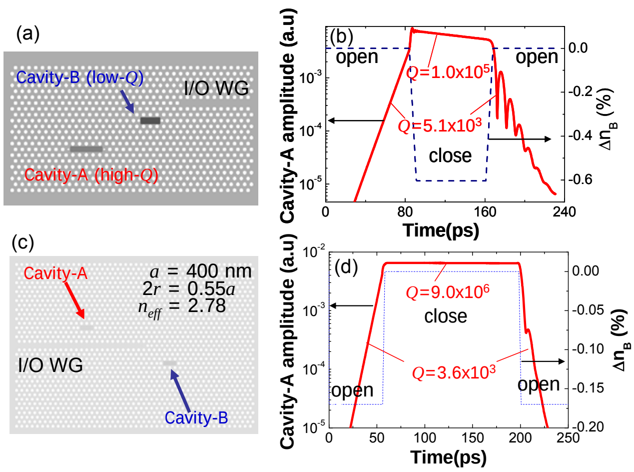

Fig. 3 (a) PhC cavity design for a photonic DRAM. Cavity B operates as a gate, which has a smaller Q owing to the strong coupling with the I/O waveguide. (b) 2D-FDTD results for the structure shown in (a). It shows the intensity in cavity A. (c) Another PhC cavity design for a photonic DRAM, which provides an ultrahigh Q in the closed mode. Two cavities provide interference, which isolates the optical mode from the I/O waveguide. (d) 2D-FDTD results for the (c) structure. The intensity in cavity A is shown.

4. Slow light on chip with ultrahigh-*Q* PhC cavity system

Slow light has been demonstrated using various materials and schemes. A PhC waveguide is a good candidate because it can be integrated on a single chip. Indeed, slow light in a PhC has already been demonstrated using a W1 waveguide[18] and coupled waveguides.[19] In these cases, the group velocity was about 0.01*c*, where *c* is the velocity of light in a vacuum. However, a pulse in the slow-light region exhibits a large dispersion, which significantly distorts the waveform. Another way to produce slow light on a chip is with a coupled-resonator optical waveguide (CROW),[20] in which high-*Q* cavities are connected in tandem.

Here, we discuss the transmission of a pulse through an ultrahigh-*Q* PhC nanocavity, which could be used as a basic element of a CROW.[3] As shown in Fig. 4(b), we compared the output pulse from the nanocavity with that from a reference waveguide and obtained the pulse delay.

Note that a pulse broadens when it propagates through a high-*Q* cavity. This is due to the narrowing of the spectral bandwidth, which can be explained in terms of the spectral intensity of the cavity, as shown in Fig. 4(a). However, bandwidth narrowing does not explain the pulse delay. Since the slope of the dispersion curve gives the delay, the maximum group delay should be about two times the photon lifetime for a relatively long input pulse. In other words, the pulse delay is one aspect of the phase of the cavity system.[21] The black curve in Fig. 4(c) shows the output from the reference waveguide and the red line is the output of the PhC nanocavity. The obtained delay was 1.45 ns. The corresponding group velocity is 5.8 km/s, which is the smallest value ever reported for a dielectric slow-light material.[3] When the cavities are connected in tandem, roughly speaking, the pulse delay is multiplied by the number of cavities. In other words, if CROW consists of *N* cavities, the maximum delay will be *N* times greater than that of a single cavity. However, the resulting velocity is the same because the device is *N* times longer. Therefore, the group velocity demonstrated in a single cavity corresponds to the minimum value that can be obtained in an ideal CROW system. Currently, we are investigating a large scale PhC CROW system composed of more than 60 cavities.[22]

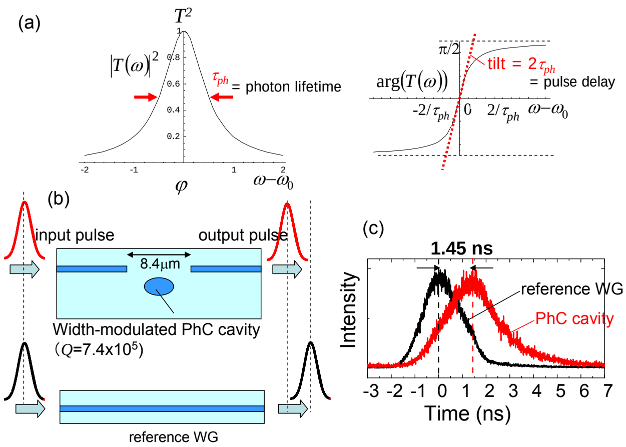

Fig. 4 (a) Spectral intensity and dispersion property of a cavity system. (b) Experimental setup for a pulse delay experiment with a PhC nanocavity. (c) Results of pulse delay experiment shown in (b).

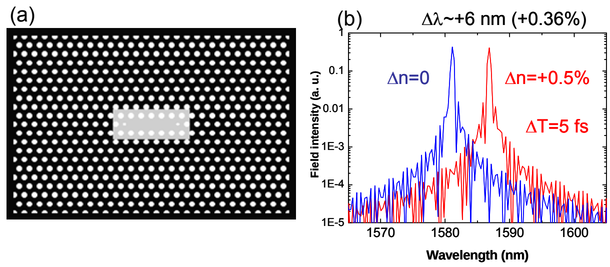

Fig. 5 (a) Structure of the PhC nanocavity used for the classical wavelength conversion of light. The refractive index of the silicon in the gray zone is changed rapidly. (b) The blue line is the spectrum of the trapped photons before the cavity resonance is changed. The red line is the spectrum of the light that was wavelength converted by the dynamic tuning of the cavity resonance.

5. Adiabatic control of light with an ultrahigh-*Q* PhC nanocavity

In this section, we discuss the fact that the classical wavelength conversion of light can now be achieved by using an ultrahigh *Q* PhC nanocavity system.[23] This is different from the well known wavelength conversion techniques that employ nonlinear effects, such as second harmonic generation or Raman conversion. Imagine plucking the string of a guitar. If we then change the tension of the string the pitch will change. How does this relate to optics? If we trap photons in an ultrahigh-*Q* cavity and rapidly change the cavity length, the wavelength of the light should follow the cavity resonance, because the photons cannot escape from the cavity. This is analogous with the example of the guitar. Such classical wavelength conversion has not been considered for optics, because the photon lifetime was not sufficiently long. However, PhC nanocavities now have an ultrahigh *Q*, and therefore, the resonant wavelength can be dynamically tuned within that period of time, by utilizing, for instance, the carrier plasma dispersion effect. The structure shown in Fig. 5(a) is a PhC cavity with a *Q* of 2.4×10^5. The refractive index of the regions shown in gray has been changed rapidly (5 fs) by 0.5 %. The 3D FDTD result is shown in Fig. 5(b). It is shown that the light spectrum is sufficiently converted. According to the calculation, the conversion efficiency is nearly 100 %, and the wavelength shift is independent of the light intensity, which is very different from wavelength conversion based on optical nonlinearities. In other words, it should be possible to convert the wavelength of a single photon with an efficiency of nearly 100 %.

6. Summary

We reviewed our recent work on ultrahigh *Q* values demonstrated using various PhC nanocavities. An ultrahigh *Q* of 1.2×10^6 and an ultra-long photon lifetime of 1.01 ns have been demonstrated using a width-modulated line-defect PhC nanocavity. In addition an ultrahigh *Q* of 3.2×10^5 is demonstrated using a point defect type hexapole PhC nanocavity. Those are some of the highest *Q* demonstrations yet performed in PhC nanocavities. Since the photon density of an ultrasmall cavity with an ultrahigh *Q* is high, it can enhance the light-matter interaction, which enables various active photonic operations. In this paper we discussed various applications including photonic DRAMs, slow light in CROWs, and adiabatic wavelength conversion achieved by the dynamic tuning of the cavity.

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