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Dynamic control of photonic crystal nanocavities for photon manipulation

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Abstract– Photonic crystal nanocavities can confine photons for long time (~ns) into a tiny region and thus it is expected to be applied to various fields including slowing and/or stopping of light and quantum-information processing. In this talk, we present the demonstration of photon manipulations by dynamic control of the photonic crystal nanocavities, which is induced by ultrafast non-linear optical responses.

1. Introduction

High-quality (*Q*) factor photonic crystal (PC) nanocavities [1-3] are currently the focus of much interest because they can strongly confine photons in a tiny space. Nanocavities have been realized with ultra-high *Q* factors of ~ 4 million and modal volumes of a cubic wavelength [3]. Due to such characteristics, these nanocavities are expected to be applied to various fields including nonlinear optics [4], where confining short pulses with high peak powers could lead to enhanced the nonlinear effects; slowing/stopping light [5] for all-optical communication; and cavity quantum electrodynamics [6,7]. However, once the PC nanocavities were fabricated, the characteristics of the PC nanocavities were determined by their configurations, and the characteristics were fixed. This restricts the controllability of photons by using PC nanocavities.

In 2005, we proposed that this limitation could be overcome by introducing the concept of a dynamic control of PC by using optical nonlinear effects in the materials consisting of PC[8]. In 2007, we have demonstrated dynamic control of *Q* factor in PC nanocavities and pulse capture/holding/release operations[9]. In this paper, we will review the dynamic control of PC nanocavities for photon manupulations.

2. Dynamic control of nanocavity *Q* factors

We have realized nanocavities with *Q* factors of more than 4 million. The corresponding photon lifetime is as long as 3 ns, which means photons can be confined for 3 ns in the very tiny region. Unfortunately, their resulting ultra-narrow resonant spectra dictate that only optical pulses of temporal duration as long or longer than the cavity’s photon lifetime can be effectively coupled to them. Therefore a method to efficiently capture relatively short pulses in high *Q* cavities would be expected. To realize this, the following functions are required: (i) when we first introduce photons into the nanocavity, *Q* should be low to facilitate coupling. (ii) Once the photons are introduced into the nanocavity, *Q* should be rapidly increased, which leads to pulse trapping. (iii) Finally, when we release photons from the nanocavity, *Q* should be rapidly decreased, which leads to pulse releasing. In this section, we describe the concrete design and method for realizing these function, and the experimental results for such *Q* factor control.

2.1. Method for dynamic control in *Q* factor

We proposed a system shown in Fig. 1 for dynamic control in *Q* factor[8-10]. The system consists of a nanocavity, a waveguide, and a mirror using a hetero interface set on one end of the waveguide. In this system, the *Q* factor is determined by two factors: (i) the vertical optical coupling between the nanocavity and free space, and (ii) the in-plane optical coupling between the nanocavity and the waveguide. When the individual *Q* factors determined by (i) and (ii) are denoted by Q_{v} and Q_{in}, respectively, the total quality factor (Q_{total}) of the nanocavity can be expressed as

$$\frac{1}{Q_{\mathrm{total}}} = \frac{1}{Q_{\mathrm{in}}} + \frac{1}{Q_{\mathrm{v}}} \qquad (1)$$

The value of Q_{v} is fixed by the structure of the cavity and is mainly determined by the total internal reflection condition for the vertical direction. The value of Q_{in} is decided by the amount of the loss to the waveguide. In this system, since a mirror is placed at one end of the waveguide, Q_{in} is affected by the interaction between the lightwaves emitted from the nanocavity to the backward direction (solid blue line) and to the forward direction, which are then reflected backward by the mirror (dashed blue line). When this interaction occurs constructively, Q_{in} is reduced. Conversely, Q_{in} is significantly increased when the interference is destructive. The total Q factor of the nanocavity is then derived as

$$\frac{1}{Q_{total}} = \frac{1}{Q_{in0}/(1+\cos\theta)} + \frac{1}{Q_v}, \qquad (2)$$

from coupled mode theory[15], where θ is the phase difference between the two lightwaves, and Q_{in0} is the in-plane quality factor in the absence of a mirror. If it is assumed that $Q_v >> Q_{in0}$, Q_{total} can be changed from $Q_{in0}/2$ to Q_v by changing θ from 0 to π. The value of θ can be changed by irradiating an optical pulse onto the waveguide to generate free carriers, which reduces the refractive index by the carrier plasma effect. If the duration of the optical pulse is several picoseconds, the refractive index changes on the same time-scale. Moreover, in silicon-based photonic crystals, where the carrier lifetime is several nanoseconds[18,19], the refractive index change can be preserved for a similar length of time, long after the irradiation of the control pulse.

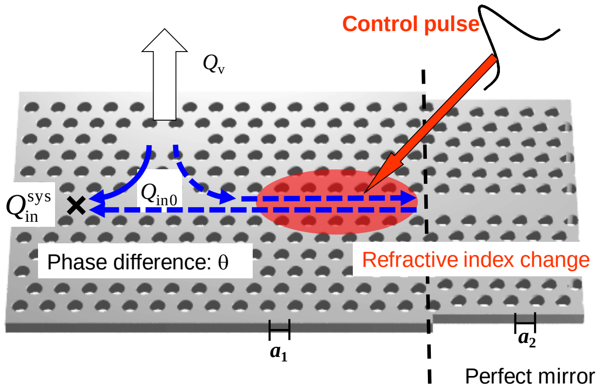

Fig. 1 Schematic image of proposed system for dynamic Q factor control

2.2. Experimental demonstration

We have fabricated PC samples which were made from air-suspended 250 nm silicon slabs with a triangular lattice of air holes with lattice constant a = 407.5 nm and hole radius r = 118 nm. L3 nanocavities with 3 shifted edge holes are introduced into the PC and their Q_V and resonant wavelengths are measured to be ~50,000 and 1550 nm, respectively. The nanocavities and the waveguide are separated by five rows, which determines Q_{in0} to ~3000.

We set up a measurement system for realizing the dynamic Q factor control and the observation of pulse capture/release operation[11]. Schematic image of the system is shown in Fig. 2. Pulses from an optical fiber-based, tunable, passively mode-locked laser (operating wavelength 1535-1555 nm, pulse width ~4 ps) are split. One portion producing signal pulse input into the PC waveguide, while another is converted to 775 nm pulses by a second harmonic generation (SHG) crystal and used as control pulses to change the refractive index of the waveguide. In order to measure the operations in time domain, we established a cross-correlation measurement system, with a resolution of ~4 ps (same as the original pulse width).

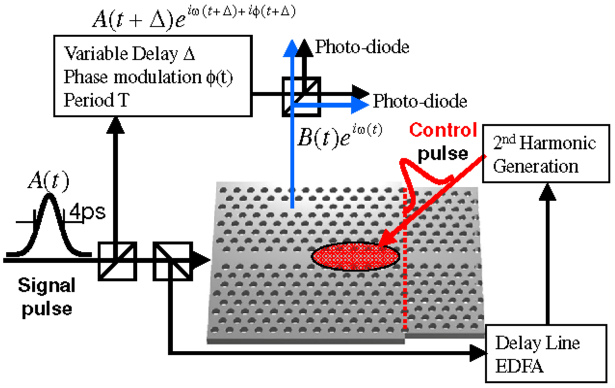

Fig. 2 Schematic image of our measurement system

We demonstrated the pulse capture operations. Figure 3 shows the time-resolved light energy in the nanocavities for the samples. Two cases are measured for the sample: (1) Only the signal pulse enters the nanocavity without a control pulse (black curve). In this case the phase difference remains θ~0, therefore the curve describes the static, low Q state of the device. The signal pulse easily couples into the nanocavity, but the coupled pulse also easily leak in the waveguide. (2) When the control pulse arrives just as the light coupling into the nanocavity reaches a maximum (blue curve). Here the light couples into the nanocavity while Q is low, then experiences a dynamic increase of Q due to the dynamic change of θ from ~0 to ~π. In this case the signal pulse easily couples into the nanocavity. After the coupling the pulse remains in the nanocavity for longer time, because the pulse cannot leak in the waveguide due to the dynamic increase of Q factor. This result clearly shows the pulse capture operation into the PC nanocavity.

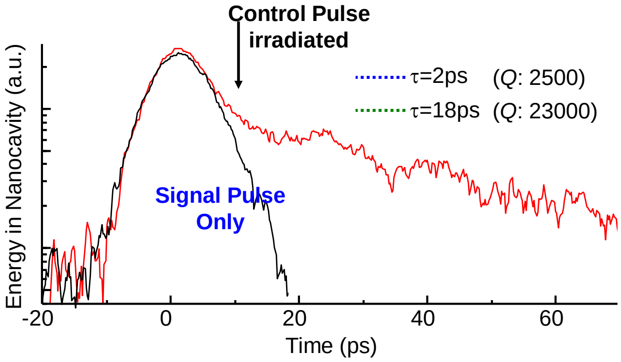

Fig. 3 Time resolved measurement result for pulse capture

We also carried out the pulse releasing measurements. After the pulse capture described before, another control pulse is irradiated, which changes θ from ~π to ~2π. This reduces Q_{in} dynamically, and the captured pulse is released to the waveguide. The measurement results are shown in Fig. 4. The black curve indicates the case where only a control pulse for capture is irradiated. The other curves indicate the case where control pulses for both capture and release are irradiated. The timing of release pulse irradiation is changed. This figure clearly shows that the captured pulse is released when the additional control pulse is irradiated.

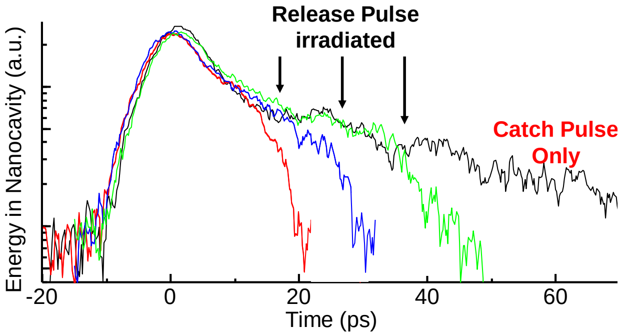

Fig. 4 Time resolved measurement result for pulse release

3. Conclusion

We have succeeded in the dynamic control of PC nanocavity Q factor by using optical non-linear effects. The Q factor can be increased from 2,500 to ~23,000 in few picoseconds, and the pulse catch operations by using this Q factor increase can be observed in the time domain. The dynamic decrease and pulse release operations can be also successfully observed. Recently, we have also demonstrated a dynamic control of strongly coupled nanocavities[12]. In the conference, we'd like to talk about this issue.

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