High- *Q* Air-Slot Photonic Crystal Cavities

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***Abstract*- We analyze photonic crystal based optical nanocavity structures. The result indicates that the photonic crystal based cavity structure has the promising application toward optomechanics. The structure also has a potential application for cavity-QED due to large *Q*-factor and small modal volume.**

I. INTRODUCTION

Photonic crystal (PhC) cavities with high quality factors (Q) have been of much interest in the recent past due to their potential applications in optoelectronics, sensing, silicon-based light emitters and optomechanics [1]. Especially, air slotted structures are attracting a growing interest due to potential ability to confine light in extremely low volumes and to extend the possibility of the application. We recently reported that the width-modulated line defect PhC nanocavity with air slot exhibit very high Q (>10^6) [2,3,4]. Another attractive topic is a dynamical wavelength conversion using a PhC cavity structure. We dynamically change a refractive index of PhC nanocavity by injecting an optical pulse and demonstrated the wavelength conversion [5,6,7]. We use optical nonlinear effects to modulate a refractive index. However, an amount of refractive index change of optical nonlinear effects is not so large and as a result an amount of wavelength shift is small. This limitation can be overcome by combining optical nanoelectromechanical system (NEMS) techniques with optical cavities [8,9].

In this paper, we present PhC cavity structures, which are suitable for applications of optomechanics. We also show that the air-slot PhC nanocavity have a potential application of cavity-QED [10,11]. We use the 3D finite-difference-time-domain method for the numerical calculation.

II. OPTOMECHANICS

We study two types of cavity structures. Schematic illustration of a width-modulated line defect PhC nanocavity coupled to the waveguides is shown in Fig. 1. Since a line defect with shifted holes have a mode edge at a lower energy, which constructs optical cavity. The EM field is confined in the cavity by both the photonic band gap and the waveguide mode gap. In the structure, a linear air-slot is introduced to the center of the line defect of a nanocavity. We also consider a double-layer PhC nanocavity, which is shown in Fig. 2 schematically. It consists of two hexagonal air-hole PhC slabs with identical five-hole cavities and shifted end-hole positions [12].

Figure 3 shows the calculated resonant wavelength of these two types of nanocavity structures as a function of separation of two slabs and a width of air-slot. For both structures, the resonant wavelength varies greatly with changing the separation, which cannot be achieved by modification of refractive index with optical nonlinear effect. This indicates the possibility of realizing large wavelength conversion with using the NEMS technology. The amount of wavelength change shown here is around 300 nm for both types of structures. The Q factor for a cavity is the same as that for the width modulated line-defect cavity, that with s=0 is about 10^7 and remains larger than 10^5 for a separation smaller than s=100 nm [11].

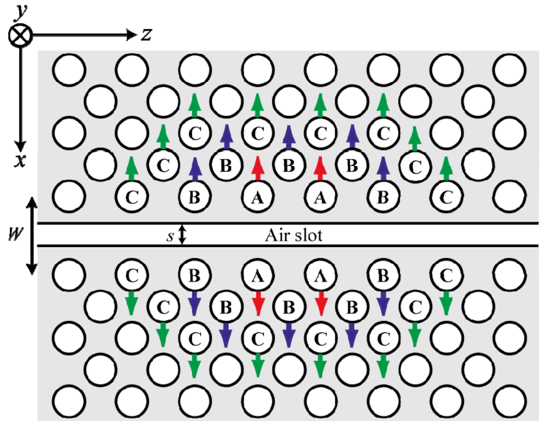

Fig. 1. Schematic of an air-slot cavity. A linear sub-wavelength-wide air slot is introduced to the center of the line defect of the width-modulated photonic waveguide cavities. Air holes labeled A, B, and C have the same radius with their position shifted outward.

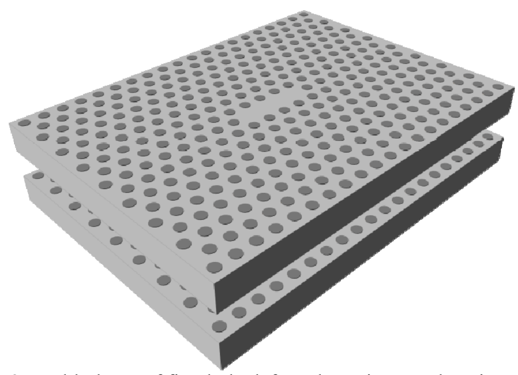

Fig. 2.Double-layer of five-hole defect photonic crystal cavity. The cavity consists of five missing holes with shifted side holes. Two slabs are located with a separation *d*.

Figure 4 shows the strength of the force acting on the slabs. The results indicate that the induced force is large so that it can be practically observed. The induced force is closely related with the variation of the resonant frequency as the func-

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tion of the slab separation or the air-slot width. The strength of the force does not depend on the Q factor of the cavity; however, a sufficiently high Q is preferable for practical experiments. The difference between the characteristics of two types of cavity structures is attributed to the physical origin of their cavity modes. The air-slot structure does not retain its cavity property with a large separation, while the double-layer cavity structure still has a cavity in each slab.

III. CAVITY QED

Because of the electric-field continuity condition at the dielectric boundaries, the cavity mode can be locally enhanced inside the slot. We numerically investigated this field concentration effect on the cavity. Figure 5 shows the calculated electric-field distributions of the resonant mode for the x-z plane. The mode distribution is quite sensitive to s and the electric field is strongly enhanced in the air slot. The cavity exhibits Q=5.7×10^6 and V=0.017 at s=49 nm. The resultant Q/V=3.3×10^8. Compatibility between high Q/V and field concentration in free space is a distinguished feature of our air-slot cavities, which is suitable for the study of cavity-QED. We estimate cavity-QED parameters with our cavities and the $5P_{3/2} - 4D_{5/2}$ transition of ^{87}Rb atoms. We obtain large one-photon coupling constant $g_0=2\pi\times13$ GHz.

IV. SUMMARY

We study photonic crystal based optical cavities and show that the double-layer of PhC cavities and the air-slot cavities generates the large radiation force by an electromagnetic field stored in the cavities and large wavelength conversion can be achieved by varying the separation of slabs. We then show that the air-slot photonic crystal cavities are promising for the cavity-QED applications due to their extremely high-Q and confinement of light in small volumes.

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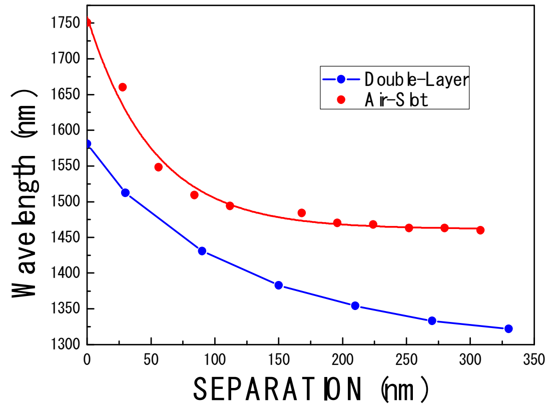

Fig. 3. Resonant wavelength of air-slot cavities and double-layer cavities.

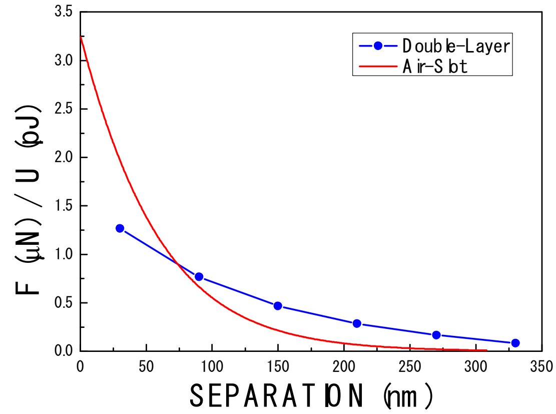

Fig. 4. Radiation force of air-slot cavities and double-layer cavities. The calculated value of the force is normalized for a stored EM field energy of 1pJ.

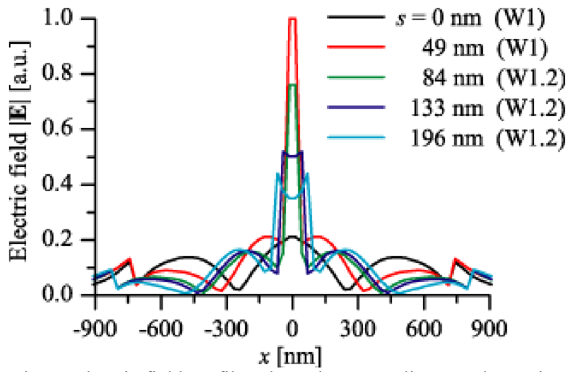

Fig. 5. Electric field profiles along the x-coordinate at the cavity center for W1 and W1.2.