High quality factor in a two-dimensional photonic crystal cavity on silicon-on-insulator

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We propose a design for high quality factor two-dimensional (2D) photonic crystal cavities on silicon-on-insulator (SOI). A quality factor of up to 1.2×10^7 with a modal volume of $2.35(\lambda/n)^3$ is simulated. A very high quality factor of 200,000 is experimentally demonstrated for a 2D cavity fabricated on SOI.

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Recently, ultrahigh quality (Q) factors have been achieved in cavities made in suspended silicon two-dimensional (2D) photonic crystals (PhCs) [1–4]. If not covered by a cladding layer [5], PhC cavities on silicon-on-insulator (SOI), for which the buried oxide layer is not removed, exhibit much lower quality factors than the membrane-type cavities [6]. Compared to the membrane approach, the SOI approach has better thermal dissipation and mechanical stability, which are crucial for the design of photonic integrated circuits. Most of the studies on SOI cavities were devoted to one-dimensional (1D) PhC wires [7–9]. Cavities embedded in 2D crystals are however necessary for integration and electrical injection or control of devices. Our previous study on 2D PhC cavities with a design similar to the one proposed by Kuramochi *et al.* [3] has attained a quality factor of 80,000 in the case of the SOI approach [10] and 2×10^6 in the suspended membrane approach [4]. In this Letter, we propose a new design of a high Q factor PhC cavity in the SOI approach, leading to an experimental Q factor of 200,000. This value is, respectively, 300 and 2.5 times higher than the one previously reported on 2D PhC cavities on SOI in [6,10] and of the same order of magnitude as those very recently reported for perforated ridge cavities [9]. Moreover, the modal volume is estimated to $2.35(\lambda/n)^3$, which is only 50% larger than that of membrane PhC cavities and 2.5 times larger than that of perforated ridge cavities.

Figure 1(a) shows the studied cavity structure. It is realized by width modulation of a W1.06 waveguide, which is ended at each extremity by a ridge-type access waveguide, in the same manner as reported in [10,11] to improve the coupling of the external light. The PhC has a lattice constant a of 416 nm and a hole radius r of 105 nm. The W1.06 waveguide corresponds to a width of $1.06\sqrt{3}\,a$. In the structures reported in [3,10] a shift is applied to several rows of holes in the direction perpendicular to the waveguide to modulate the waveguide width and create a defect mode. In this Letter, the shift is only applied to eight holes in the first row on both sides of the waveguide, as shown in warm colors in the center of the structure. The four holes (red) in the center are shifted by a distance d. The adjacent holes (orange, dark yellow, and yellow) are shifted by a distance of 3/4, 2/4 and 1/4 of d, respectively. As seen in the figure, the displacement of the holes obeys a more gradual transition than the one reported in [3,10]. This smooth transition should allow confinement of the light field more "gently," as proposed in [1]. Indeed, this smooth transition in real space should allow one to keep the Fourier components of the mode far enough from the origin to avoid leaks in the vertical direction. Because there is no gap for TM-like modes in SOI and because the perturbation of the waveguide used for creating the cavity may also couple the quasi-TE and quasi-TM modes of the waveguide, the smoother transition in SOI may also lead to higher quality factors. This smoother transition is at the expense of a slight increase of the modal volume. The barrier waveguide has a length l and the same width w_B as the W1.06 waveguide. To improve the coupling of the light from the ridge waveguide into the cavity, we have realized a coupling zone at each extremity of the barrier waveguides made with an enlarged waveguide

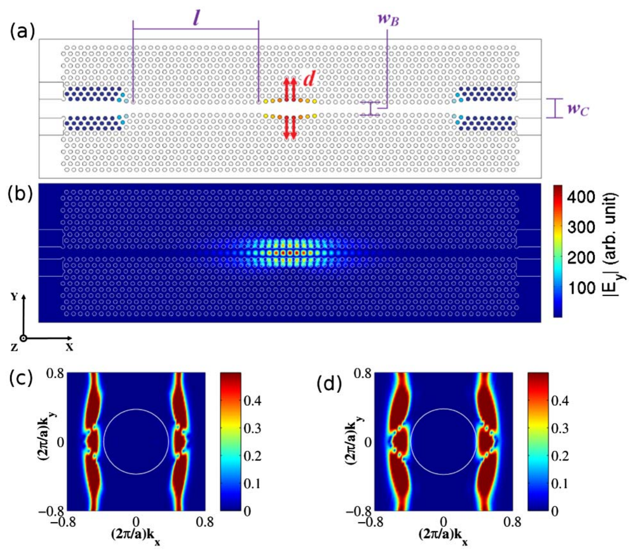

Fig. 1. (Color online) (a) Structure of the cavity: the holes in warm colors define the cavity. The blue holes show the coupling zone. All the displacements of the colored holes are exaggerated for clarity. (b) Profile of the electric field module $|E_y|$ of the resonant mode in the x–y plane calculated by 3D-FDTD. (c), (d) Fourier transform of E_y in the case of this cavity (c) and of the Kuramochi type cavity on SOI (d). The white circles represent the silica light cone.

of width w_C equal to $1.1\sqrt{3}a$ (blueshifted holes in Fig. 1 top). The electric field component E_y of the resonant mode in such a cavity is shown in Fig. 1(b). It is calculated by a three-dimensional finite difference in the time-domain method (3D-FDTD) [12,13]. The index of refraction of the buried oxide has been set to 1.45 and the one of silicon to 3.45. The respective thicknesses of the silicon layer and buried oxide are 200 nm and 2 μm. The resonance occurs at a wavelength around 1620 nm, and its modal volume is estimated to be between 1.7 to $2.4(\lambda/n)^3$, depending on different dimensional parameters as the barrier length and the hole shift, which is comparable to that reported in [3]. As seen in Fig. 1(b), the field envelop decreases slowly in the barrier despite the absence of a band gap for quasi-TE-mode in PhC waveguide made on SOI because of TE–TM coupling. In fact, calculating the symmetric and antisymmetric parts of the H field with respect to the plane passing at the center of the silicon slab, it appears that only 0.2% of the magnetic energy is in the antisymmetric part, i.e., in the TM-like part of the mode. In the case of the Kuramochi's type cavity on SOI, this ratio is 0.3%. The design of the barrier and coupling must be carefully taken into account, because the field will probe a larger volume than in the case of membrane cavities. As seen in Fig. 1(c), the smooth transition of the cavity design allows confinement of most of the Fourier components below the silica light cone, as opposed to Kuramochi-type cavities (d).

Figure 2(a) shows the quality factor calculated by 3D-FDTD as a function of barrier length l. The structure has a hole shift d of 8 nm, and the resonance occurs at around 1619 nm. As is shown, the quality factor depends on the barrier length significantly, showing the effectiveness of the barrier. We have also explored the dependence of the quality factor versus the hole shift d for cavities with a very long barrier ($l = 29$ periods) and without a coupling zone [Fig. 2(b)]. The hole shift d of 6 nm gives the highest quality factor equal to 1.2×10^7. Compared to the cavities in [3], the quality factor is slightly more sensitive with the variation of the hole shift d. However, the cavity structure designed in this work demonstrates sufficient stable quality factors, of the order of 10^6, in a large range of hole shift variation. To make a further comparison, we have calculated the same structure geometry ($d = 8$ nm) with a barrier length l of 29 periods in the membrane approach. It gives a quality factor up to 3.6×10^7 with a slightly reduced modal volume of $2.06(\lambda/n)^3$, showing the modest impact of the oxide layer on the modal volume. Moreover, in the case of the membrane approach, the extension of the mode in the x direction, $(\int x^2 \varepsilon_r \|\mathbf{E}\|^2 \mathrm{d}V / \int \varepsilon_r \|\mathbf{E}\|^2 \mathrm{d}V)^{\frac{1}{2}}$, is $2.87(\lambda/n)$ versus $3.3(\lambda/n)$ in the case of the SOI approach.

In order to confirm the FDTD simulation results, we have fabricated the samples on a SOI wafer with a 200 nm silicon layer on a 2 μm oxide layer as in the simulations. The PhC patterns and access waveguides were fabricated with the same processes as discussed in [4,11,14].

The transmission spectra are measured with an external cavity tunable laser (Agilent) with a 0.5 pm resolution and an InGaAs detector. Two polarization-maintaining lensed optical fibers are used to inject and collect light. Depending on the transmission of the sample, the injected power was between 10 and 100 nW to avoid any nonlinear effects in the cavity. The launched polarization as well as the collected light was TE only (E field in the plane of the PhC). Measurements on the vertical radiation of the cavity show that light is well localized inside the cavity.

Figure 3(a) shows the experimental measurement of quality factors for the same structures as the one simulated previously (hole shift $d = 8$ nm). The quality factors are obtained by measuring the FWHM of the transmission spectrum of the resonant mode at 1620 nm [Fig. 3(b)]. By comparing the simulation [Fig. 2(a)] with the experimental measurement [Fig. 3(a)], we obtain a good agreement for the quality factor evolution as a function of barrier length. As is shown, a very high quality factor of 200,000 has been achieved with a barrier length d of 19 periods, corresponding to a FWHM of the Lorentzian fit of 8 pm at 1620 nm. The unloaded Q factor deduced from the normalized transmission is 210,000. The modal volume V is estimated from the simulations to be $2.35(\lambda/n)^3$, resulting in a better Q/V ratio than in a previous report on PhC cavities on SOI [10].

The measured quality factors are about 2 and 14 times smaller than the simulated ones for barrier lengths l of 13 and 19 periods, respectively. We did not experimentally investigate larger barrier lengths because of the decreased transmission for large lengths. The discrepancy for long barriers is slightly larger than the one reported in our previous work in the membrane approach, where it was around a factor of 3 [4]. This fact can be explained by the higher sensitivity of SOI PhCs to fabrication-induced disorder and hole roughness [15]. Indeed, because the hole shift step between the adjacent holes in the cavity

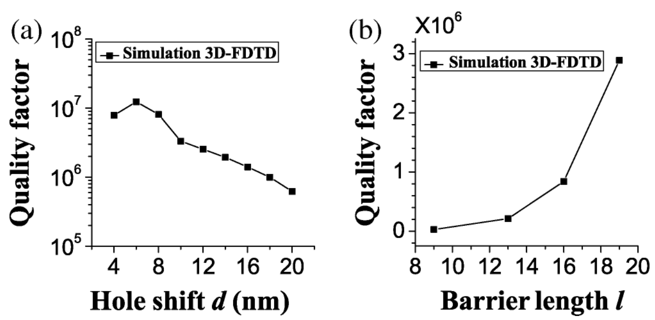

Fig. 2. (a) Calculated quality factor as a function of the barrier length l for a hole shift d of 8 nm. (b) Calculated quality factor as a function of hole shift d for a barrier length l of 29 holes.

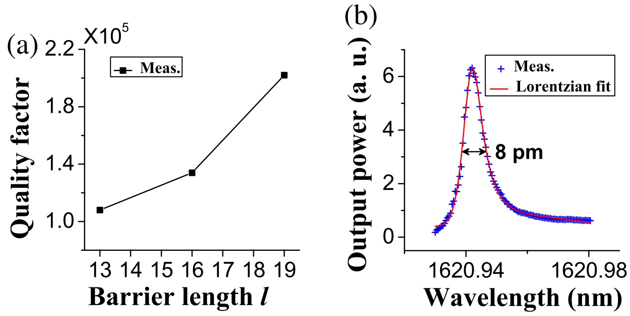

Fig. 3. (Color online) (a) Measured quality factor as a function of the barrier length l. The hole shift d is 8 nm. (b) Measured transmission spectrum of the cavity for a barrier length l of 19 periods.

of this work is only 2 instead of 3 nm in the case of the membrane PhC cavities, the sensibility of the quality factor in regard to the fabrication accuracy is increased. Moreover, because the electromagnetic field has a larger extension in the plane of the PhC in the case of the SOI approach than in the case of the membrane approach, SOI cavities are more sensitive to large-scale disorder.

In summary, we have experimentally demonstrated a high quality factor of 200,000 obtained in a new design of 2D PhC cavity in SOI based on width modulation of the PhC waveguide, with a modal volume of about $2.35(\lambda/n)^3$. This work will be helpful for the design of photonic integrated circuits on SOI and for future nonlinear experiments that require cavities with high quality factors and a small mode volume to enhance light–matter interactions, for example, in Raman scattering experiments and nonlinear detectors [10,11,16].

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