Design and demonstration of high quality-factor H1-cavity in two-dimensional photonic crystal

Ying-Jhe Fu, Yi-Shan Lee, and Sheng-Di Lin*

Department of Electronics Engineering, National Chiao Tung University, 1001 University Road, Hsinchu 300, Taiwan
**Corresponding author: sdlin@mail.nctu.edu.tw*

Received July 2, 2013; revised September 18, 2013; accepted October 8, 2013;
posted October 21, 2013 (Doc. ID 193249); published November 15, 2013

We introduce a method for designing an H1 photonic crystal cavity to enhance its quality factor (Q factor). The highest theoretical Q factor of 120,000 is obtained. The Fourier transformation of field distribution shows that the enhancement arises from the component reduction of a leaky mode. The Q-factor improvement has also been demonstrated experimentally with the highest value of 11,700. Our design could be useful for studying light–matter interaction in an H1 cavity as the mode volume only increases slightly.

OCIS codes: (230.5750) Resonators; (230.5298) Photonic crystals.
http://dx.doi.org/10.1364/OL.38.004915

Photonic crystal (PhC) cavities have been applied on many areas, including low-threshold nanolasers [1,2], optic filters with waveguides [3,4] and cavity quantum electrodynamics because of their excellent photon confinement within tiny volume. In cavity quantum electrodynamics, a single quantum dot (QD) coupled to PhC cavity has been studied extensively, QD spontaneous emission could be controlled effectively by the Purcell effect [5–9]. With cavities of high quality factor (Q factor) and small-mode volume, the strong coupling [10,11] has also been demonstrated in such systems, which could be an efficient way to eliminate the fine structure splitting (FSS) of QDs for generation of entangled photon pairs [12,13]. Various two-dimensional PhC cavities with high Q factor and small mode volume have been demonstrated, such as the L3 cavity [14] and double heterostructure cavity [15]. However, these cavities have no two degenerate fundamental modes, which are necessary for tuning QD FSS via the strong coupling [12,13]. In this aspect, H1 cavities having two orthogonal dipole modes and relatively small mode volume are promising if the Q factor is high enough for entering the strong coupling regime. An H1 cavity is actually a point-defect PhC cavity formed by removing one hole in a perfect air-hole triangular lattice on a suspending membrane. A perfect H1 cavity has two degenerate and linearly polarized fundamental modes, vertical (V) and horizontal (H) dipole modes, for which the polarization directions are mutually orthogonal [16,17]. In general, an H1 cavity provides relatively small mode volume but low Q factor so improving its Q factor is essential for various applications mentioned above.

To enhance the Q factor of an H1 cavity, a common method is modifying the positions and radii of holes near the defect cavity [11,16–18]. So far, the highest Q factor obtained experimentally is about 25,000 by modifying more holes around the cavity, but the design principle and underlying physics have not been detailed [16]. In this Letter, we propose an alternative method for enhancing the Q factor while the mode volume is nearly unchanged. According to calculation, the Q factor of 120,000 can be obtained with our design, which is the highest Q factor in theory to date. The Q-factor enhancement is explained with the analysis of the Fourier transformation of E-field distribution in cavity, which shows that the designed H1 cavity can effectively suppress its leaky mode component. We have also experimentally demonstrated the improvement of the Q factor and the highest Q factor of 11,700 has been achieved.

Figure 1 shows our design of the H1 cavity based on triangular lattice of air holes, the centered hole is absent leaving a defect as an optical cavity, and the period and radii of air holes are a and r, respectively. Staring with the common design, the six nearest neighbor holes around the cavity are shifted in radial direction and away from the defect a distance denoted as s here. The radii of the six holes are reduced from r to r' [17]. In addition, in our design, one more modification on other air holes is introduced to enhance its Q factor further. We reduce the radii of the fourth, fifth, eighth, and ninth rounds of air holes, as indicated with gray regions I and II in Fig. 1, from r to r''. As we shall present, both in theory and in experiment, the Q factor can be significantly improved by tuning the value of r''.

To simulate the modified H1 cavity, we use the 3D finite-difference time-domain (FDTD) method that is packaged in commercial software (Rsoft, FullWave). The simulated parameters are detailed as follows. The thickness of GaAs PhC membrane, denoted as d, is 130 nm. The lattice constant a is 260 nm and the radius of air hole r is 0.25a. The shifted distance s of the nearest six holes is 0.12a. We use the constant refractive index of 3.36 for GaAs. The values of r' and r'' are varied in our simulation

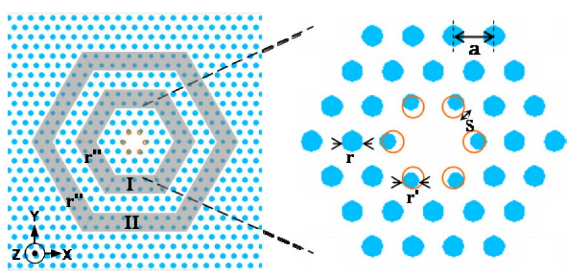

Fig. 1. Schematic modified H1 cavity. The lattice constant is a. The radius of regular air hole is r. The nearest six air holes around defect are shifted and their radii are reduced to r', as illustrated in the enlarged figure on the right. The radii of air holes inside regions I and II are reduced to r''.

to see their effects on the Q factor. The Q value and mode volume are obtained with the method of fast harmonic analysis. We would like to note that the validity of simulation has been verified by calculating the H1 cavity case reported in [16] as they obtained the highest Q factor of about 60,000 previously. By using our simulation tool and their parameters, our theoretical Q factor is considerably consistent with theirs (not shown here).

The calculated Q factors for the modified H1 cavity and the corresponding mode volumes are shown in Fig. 2. In Fig. 2(a), the Q factors of V-dipole cavity mode for r''/r ratios from 0.6 to 1 are plotted. Each curve represents different r' from 0.154a to 0.231a. We can see an evident trend that, with reducing r''/r ratio, the Q factor raises and reaches its maximum around $r''/r = 0.65–0.75$. However, it falls rapidly when the r''/r ratio comes to about 0.6. The strongest dependence is obtained with $r' = 0.192a$. The Q factor for an unmodified H1 cavity ($r''/r = 1$) is about 33,000 and reaches the highest value about 120,000 for the modified one of $r''/r = 0.7$. A fourfold Q-factor enhancement has been achieved. However, for other r', this enhancement becomes less significant. On the other hand, the corresponding mode volumes V are plotted in Fig. 2(b). With decreasing r''/r ratios, the mode volumes V increases monotonically for all r'. Nevertheless, the increased amount is all less than 14% so the parameter Q/V, which governs the coupling strength between cavity and emitter, could be increased. In addition, we would like to note that based on the simulated results, the parameters r', s, and r'' are rather critical to obtain a high Q factor of modified H1 cavity. With appropriate r' and s, a well-tuned r'' could give us an extremely high Q factor. This, of course, would be a challenging task for fabricating the real devices.

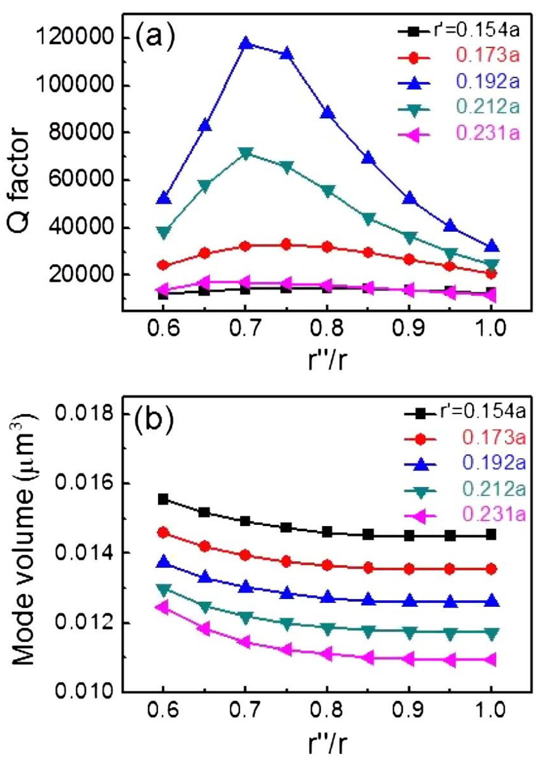

Fig. 2. (a) Simulated Q factors against varied r''/r ratios. Each line represents individual value of r' from 0.154a to 0.231a. (b) Corresponding mode volumes.

To understand how the H1 cavity with modified r''/r ratio reaches a high Q factor, in Fig. 3 we plot the simulated electric field (E_x) distribution and the corresponding spatial Fourier transformation in tangential k-vector space ($k_{\|}$) for the V-dipole mode. The simulated parameters are the same as those used in Fig. 2 except that r' is fixed at 0.192a. Note that the color scales of the Fourier transform profiles are plotted in natural logarithm scale for clarity. In the upper row of Fig. 3, the electric field distributions at a plane of $z = 0$ (the center of the membrane) of the cavities with $r''/r = 0.6$, 0.7, 0.9, and 1.0 have no clear difference between each other. However, in the lower row of Fig. 3, the Fourier transformed profiles show interesting features inside the centered light cone indicated by the white circles. Inside the light-cone circle, the tangential k-component decreases gradually when the r''/r ratios reduces from 1.0 to 0.7 and then increases slightly for that of 0.6. This is consistent with the trend of Q factors in Fig. 2(a). The correlation between the Q factors and the Fourier transform components inside a light cone is expected because the Fourier transform components inside the light cone represent the components of leakage modes for which light would escape out of the membrane cavity [14]. More specifically, the light cone is defined as the region for which tangential k-vector component ($|k_{\|}|$) is smaller than $2\pi/\lambda_0$ (where λ_0 is the wavelength of light in vacuum). When $|k_{\|}|$ of light lies outside light cone ($|k_{\|}| > 2\pi/\lambda_0$), total internal reflection condition is satisfied at the interface between cavity membrane and vacuum, thus light can be confined inside the membrane. Therefore, by reducing the tangential component $|k_{\|}|$ inside the light cone ($|k_{\|}| < 2\pi/\lambda_0$), the Q factor of the cavity can be increased. This explanation has also been stated clearly in [14] for the case of L3 cavity.

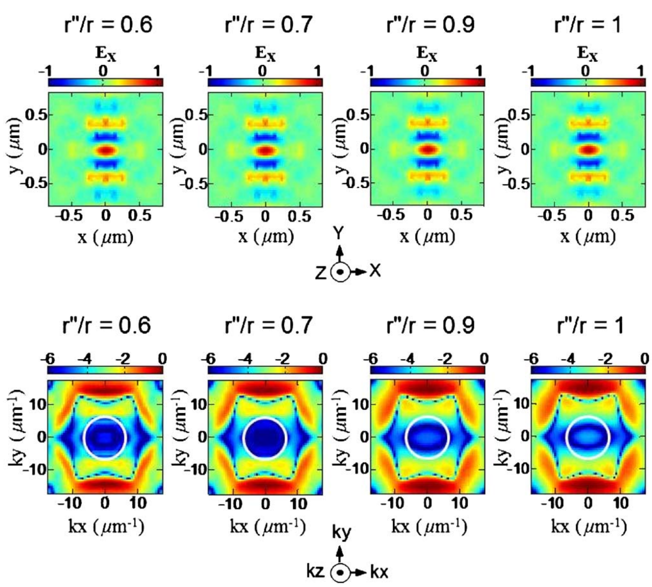

Fig. 3. Simulated electric field distributions (E_x) of V-dipole mode for various r''/r ratios (upper row) and their two-dimensional spatial Fourier transform profiles in tangential k-vector space $k_{\|}$(lower row). Light cones are plotted in white circles.

In our experiment, the modified H1 PhC cavities have been fabricated on a semi-insulating (100) GaAs substrate. The layers were grown by a Varian Gen II molecular beam epitaxy system with solid sources. The sacrificial layer of 1.2 μm thick $Al_{0.9}Ga_{0.1}As$ was grown on the buffered GaAs layer. The InAs QDs centered at 130 nm GaAs were formed with the Stranski–Krastanow mode. To fabricate the PhC cavity, we deposited a SiN_x layer of about 200 nm on the sample as a hard mask by using plasma-enhanced chemical vapor deposition. The PhC cavities were patterned on poly methyl methacrylate (PMMA) resist using e-beam lithography. An inductively coupled plasma/reactive ion etching system was used to transfer the patterns from PMMA to SiN_x layer by using gases O_2/CHF_3, and then from SiN_x to GaAs cavity layer by using gases of $Ar/SiCl_4$. Finally, to confine the light in the z direction by total internal reflection, the suspending membrane was released by removing the sacrificial layer with HF solution. The emission spectra of cavities were measured at 50 K in a microphotoluminescence (μ-PL) setup. A He–Ne laser beam was focused onto the cavity through a microscope objective (N.A. = 0.5). The excited PL signals were collected by the same objective, dispersed through a grating monochromator (0.75 m long), and then detected by a liquid-nitrogen-cooled charged-coupled device, which connected to the exit of the monochromator. The spectral resolution is about 40 μeV.

Figure 4(a) shows the top-viewed scanning electron microscopy (SEM) image of one fabricated H1 cavity. Together with the enlarged images on the right, we can see that the sizes of the six nearest holes and those in the region I and II has been reduced. In Fig. 4(b), the measured spectra taken from one of the fabricated H1 cavities are shown. Two peaks arising from the two fundamental dipole modes (H and V dipoles) are clearly observed. The nondegeneracy arises from unavoidable imperfection during device processing. The difference of peak energies between two dipole modes is about 0.1–2.0 meV among the studied devices. The measured polar plot of the two modes is shown as the inset in Fig. 4(b). It is obvious that two dipole modes are linearly polarized and orthogonal to each other as expected.

The spectra of more than 40 devices were measured and the intentional size parameters of these devices are $a = 260$ nm, $r = 0.25a$, $s = 0.12a$, and $r' = 0.192a$. To see the effect of r''/r ratio on Q factor and to minimize the influence of fabrication nonuniformity, we arrange the devices in group so the every four devices with four different r'' are within an area of 1 mm^2. The measured results are shown in Fig. 5(a). Note that the Q factors in Fig. 5(a) are the average values of two dipole modes. The Q factors of the devices in the same group are plotted with the same symbol. In Fig. 5(a), the devices with r''/r ratio of 1 (reference devices) have the Q factors in the range of 5000–8000 due to the fabrication nonuniformity. Comparing with calculated Q factors shown in Fig. 2(a), the experimental ones are much lower, which we attribute to the imperfection during the sample growth and/or the device fabrication. Nevertheless, among the measured devices, we still can see a common

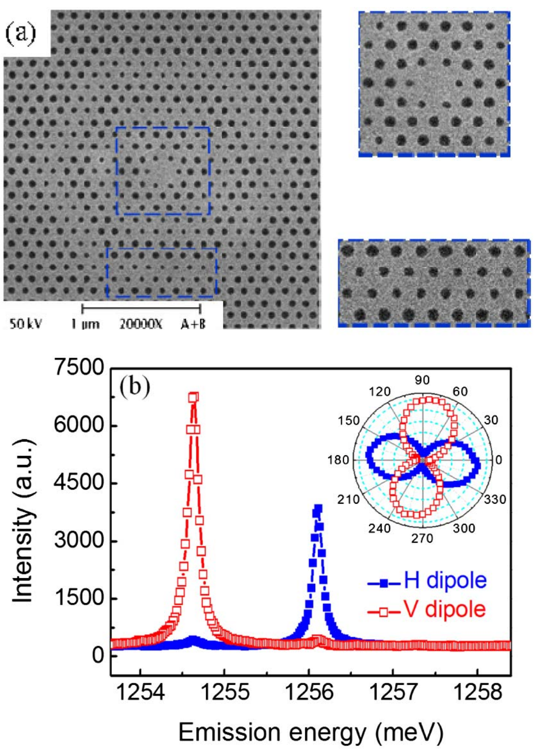

Fig. 4. (a) Top view of SEM image for fabricated H1 cavity. The right figures are the local enlarged images of the six nearest holes and those in region II. (b) Measured spectra showing H- and V-dipole modes of an H1 cavity. The blue and red dots were measured data, and the blue and red curves were fitted data. Inset: the polar plot of cavity modes.

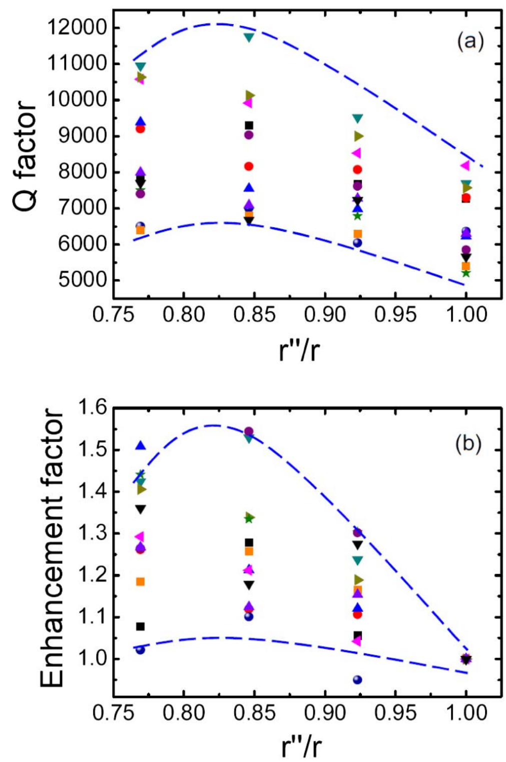

Fig. 5. (a) Measured Q factors and (b) enhancement factors for r''/r ratios of 1, 0.923, 0.846, and 0.769. The grouping devices are plotted with the same symbol. The dashed lines are a guide for the eye.

trend that Q factors gradually increase with decreasing r''/r ratios. When the r''/r ratio comes down to 0.769, the trend becomes unclear. This trend was considerably consistent with the simulated results in Fig. 2(a). We also calculate the enhancement factors defined with Q-factor ratio between devices with modified r'' and unmodified ones. In Fig. 5(b), it is apparent that the enhancement factors of almost all devices with modified r'' are larger than 1. This tells us that our method is quite effective for Q-factor improvement. That is, even with the fabrication nonuniformity from one device to the other, the Q-factor enhancement still exists. The highest enhancement factor is about 1.55 and the highest Q factor is about 11,700.

In conclusion, we have presented a design for enhancing the Q factor of H1 PhC cavity. The recorded Q factor of 120,000 in theory has been achieved with a slight increase of mode volume. In experiment, the Q factors have be improved from 5000–8000 to about 11,700. With our design, one could introduce QDs in the cavity for generating an entangled photon pair by the strong coupling effect.

We thank the financial support from NSC and ATU program of MOE in Taiwan. The equipment help from Center for Nano Science and Technology (CNST) at National Chiao Tung University is highly appreciated.

References

1. O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, and I. Kim, Science **284**, 1819 (1999).
2. M. Loncar, T. Yoshie, A. Scherer, P. Gogna, and Y. Qiu, Appl. Phys. Lett. **81**, 2680 (2002).
3. S. Noda, A. Chutinan, and M. Imada, Nature **407**, 608 (2000).
4. Y. Akahane, M. Mochizuki, T. Asano, Y. Tanaka, and S. Noda, Appl. Phys. Lett. **82**, 1341 (2003).
5. E. M. Purcell, Phys. Rev. **69**, 681 (1946).
6. J. Canet-Ferrer, L. J. Martínez, I. Prieto, B. Alén, G. Muñoz-Matutano, D. Fuster, Y. González, M. L. Dotor, L. González, P. A. Postigo, and J. P. Martínez-Pastor, Opt. Express **20**, 7901 (2012).
7. S. Noda, M. Fujita, and T. Asano, Nat. Photonics **1**, 449 (2007).
8. D. Englund, D. Fattal, E. Waks, G. Solomon, B. Zhang, T. Nakaoka, Y. Arakawa, Y. Yamamoto, and J. Vuckovic, Phys. Rev. Lett. **95**, 013904 (2005).
9. T. D. Happ, I. I. Tartakovskii, V. D. Kulakovskii, J.-P. Reithmaier, M. Kamp, and A. Forchel, Phys. Rev. B **66**, 041303 (2002).
10. T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, and D. G. Deppe, Nature **432**, 200 (2004).
11. Y. Ota, M. Shirane, M. Nomura, N. Kumagai, S. Ishida, S. Iwamoto, S. Yorozu, and Y. Arakawa, Appl. Phys. Lett. **94**, 033102 (2009).
12. R. Johne, N. A. Gippius, G. Pavlovic, D. D. Solnyshkov, I. A. Shelykh, and G. Malpuech, Phys. Rev. Lett. **100**, 240404 (2008).
13. P. K. Pathak and S. Hughes, Phys. Rev. B **79**, 205416 (2009).
14. Y. Akahane, T. Asano, B. S. Song, and S. Noda, Nature **425**, 944 (2003).
15. B. S. Song, S. Noda, T. Asano, and Y. Akahane, Nat. Mater. **4**, 207 (2005).
16. H. Takagi, Y. Ota, N. Kumagai, S. Ishida, S. Iwamoto, and Y. Arakawa, Opt. Express, **20**, 28292 (2012).
17. M. Shirane, S. Kono, J. Ushida, S. Ohkouchi, N. Ikeda, Y. Sugimoto, and A. Tomita, J. Appl. Phys. **101**, 073107 (2007).
18. H.-Y. Ryu, M. Notomi, and Y.-H. Lee, Appl. Phys. Lett. **83**, 4294 (2003).