Ultrahigh-*Q* Nanocavity with 1D Photonic Gap

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Abstract: Recently, various wavelength-sized cavities with theoretical *Q* values of ~10^8 have been reported, however, they all employ 2D or 3D photonic band gaps to realize strong light confinement. Here we numerically demonstrate that ultrahigh-*Q* (2.0×10^8) and wavelength-sized ($V_{\mathrm{eff}}\sim1.4(\lambda/n)^3$) cavities can be achieved by employing only 1D periodicity.

OCIS codes: (230.5750) Resonators; (250.5300) Photonic integrated circuits; (230.5298) Photonic crystals.

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1. Introduction

Small and high-*Q* (quality factor of cavities) optical cavities are required for various applications in the fields in optics [1], including cavity quantum-electrodynamics [2], single-photon emitters [3], spontaneous emission control and low-threshold lasers [4,5,6], low-power switches [7,8,9,11], adiabatic wavelength conversion [10,11], because they generally enhance intrinsically small light-matter interactions. Since light is essentially difficult to localize, it is hard to realize wavelength-sized optical cavities with strong light confinement. Recently, however, rapid progress has been made on this issue by employing the strong light confinement of photonic bandgaps (PBGs) in well-designed multi-dimensional photonic crystals [12-19]. Optical cavities with Q higher than 10^6 and a mode volume comparable to $(\lambda/n)^3$ have been realized experimentally in two-dimensional (2D) photonic crystals. This means that we can store photons for longer than one nanosecond in a wavelength-sized volume. In contrast, such an ultrahigh-*Q* with a wavelength-sized volume has not been achieved in other types of microcavities, such as micro-post cavities with dielectric stack mirrors [3] (microcavities with 1D PBGs), 1D photonic crystal slab structures [20,21], and whispering-gallery mode (WGM) ring cavities (cavities that rely on total-internal reflection (TIR) without a PBG) [22]. This can be understood by looking at the difference between the light confinement mechanisms in TIR and PBGs. TIR only holds for a certain restricted range of wavevectors, and thus it becomes ineffective when the cavity size becomes small because localization in the real space leads to delocalization in the *k* space, which eventually breaks the TIR condition. In principle, PBG confinement works regardless of the wavevector range (which is the definition of a PBG), and thus it is essentially more advantageous for confining light in a small volume than TIR.

The recent achievement of an ultrahigh-*Q* in photonic crystal cavities has confirmed these speculations. In reality, however, the situation is somewhat subtle, because the above-mentioned ultrahigh-*Q* 2D PBG cavities utilize the PBG in two dimensions and TIR in one dimension (the direction perpendicular to the 2D plane). That is, a combination of 2D PBG and 1D TIR is employed. Of course, theoretically 3D PBG systems should be better than 2D PBG systems, but the precise fabrication of 3D PBG systems is still extremely difficult, and this has prevented the realization of small cavities with ultrahigh-*Q* in 3D PBG systems. Since combining a 2D PBG with 1D TIR would be much more advantageous than combining a 1D PBG with 2D TIR (such as, micro-post cavities) or 3D TIR (WGM cavities), it is naturally believed that 2D or 3D PBGs are essential if we were to realize ultrahigh-*Q* and small cavities.

Contrary to this widely held view, here we demonstrate that such ultrahigh-*Q* and wavelength-size volume does not essentially require 2D or 3D PBGs, and we show ultrahigh-*Q* (Q>10^8) with V=1.4$(\lambda/n)^3$ in optical cavities with only 1D PBGs (and 2D TIR). As far as we

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know, this is the first report of wavelength-size cavities with $Q>10^6$ without multi-dimensional PBGs.

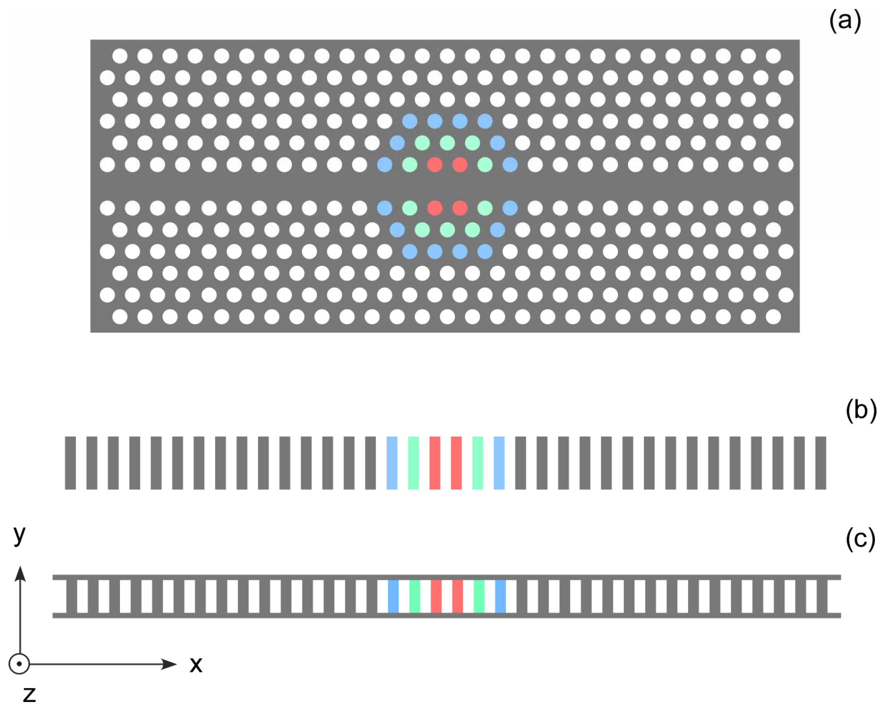

Fig. 1. Size-modulated cavities based on mode-gap waveguides. (a) Width-modulated line-defect cavity in a 2D triangular-lattice air-hole photonic crystal slab. The red, green, and blue holes are shifted away from the line defect center by 9, 6, and 3 nm, respectively. (b) Proposed size-modulated 1D stack cavity. The colored parts just represent some form of size modulation. The exact modulation scheme is described later. (c) Proposed size-modulated 1D ladder cavity.

2. Reexamination of width-modulated cavity in 2D photonic crystal

First, we reexamine ultrahigh-Q cavities in 2D photonic crystals. Figure 1(a) shows an example of the ultrahigh-Q design of optical cavities in 2D PBG structures, which we reported previously [14]. The structure is based on a single missing-hole line defect waveguide (so-called W1 waveguide) in a triangular-lattice air-hole photonic crystal. This W1 waveguide has a sharp mode gap at the low frequency edge of the propagating mode with even parity in the PBG [23], as shown in Fig. 2(a). To realize light confinement, the effective width of the waveguide is locally modulated (locally widened in this case). In our design, we slightly shift the position of the red, green, and blue holes away from the waveguide by 9, 6, and 3 nm, respectively. This widening modulation locally lowers the mode gap edge, which creates cavity modes in the modulated region. This is the basic mechanism of the light confinement in this type of line-defect mode-gap cavity. In fact, Fig. 1(a) is one example of the family of mode-gap confined line-defect cavities in photonic crystals [12,16,24,25], in which the position of the mode gap is locally modulated in various ways. The most noteworthy aspect of this type of cavity is its extremely high Q with a small cavity volume [12]. We have reported that the cavity in Fig. 1(a) has theoretical Q of 1.5×10^8 with $V_{\mathrm{eff}}=1.5(\lambda/n)^3$ [19]. Although silica WGM cavities [22] have much higher theoretical Q, their cavity mode volume is much larger. If we consider cavities whose volume is comparable to the wavelength, no cavities other than photonic crystal cavities have yet demonstrated such ultrahigh-Q.

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The reason for this type of cavity having such high-Q can be intuitively understood as follows. The original W1 line defect without a modulation theoretically has true guided modes in the PBG, which means that there is no out-of-plane radiation loss. This is apparent from the dispersion relation of W1 shown in Fig. 2(a). The guided mode (indicated by an arrow) is located outside the light cone of the air cladding (shaded region, labeled as "radiation modes"). If we terminate this waveguide to form a cavity, this termination normally causes a large perturbation in the originally loss-free mode profile, which results in significant radiation loss for the cavity modes. With the mode-gap cavity design, the waveguide is not terminated, but slightly modified to create a local modulation of the gap position. Furthermore, the use of *gradual* width modulation produces light confinement with minimum mode profile perturbation [26]. Since the key issue with respect to realizing high-Q in 2D PBG cavities is the mode distribution in the k space, we again describe the situation in the k space. In the k space, the original W1 waveguide mode is concentrated entirely outside the light cone of the air cladding, which is the signature of any guided mode. Any local modulation of the guided modes generally delocalizes the mode distribution in the k space, but if the modulation is sufficiently gradual, the delocalization can be minimized. Since the position of the mode gap edge is very sensitive to the structural parameters of photonic crystals, we can introduce gentle but sufficiently strong confinement with minimal structural modification, which is required if we are to achieve high-Q in the 2D PBG cavities.

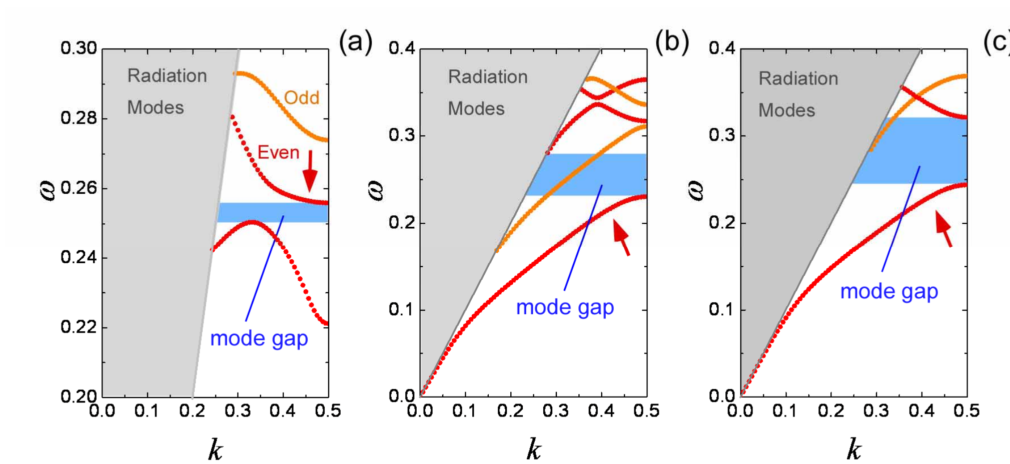

Fig. 2. Dispersion relation of TE modes in various mode-gap waveguides. The gray shaded region corresponds to the light cone of the air cladding where radiation modes exist. (a) W1 line defect in a triangular-lattice air-hole photonic crystal slab. The hole radius is 0.55a. a is the lattice constant. (b) 1D stack array waveguide. W_x=0.5a, W_y=3a. The definition of W_x, W_y, and D_y is given in Fig. 3(c) 1D ladder waveguide. W_x=0.5a, W_y=1.5a, and D_y=0.125a. The dispersion is calculated by 2D plane-wave expansion method with the effective index of 2.8.

3. Size-modulated 1D stack cavity

When we consider the above explanation, it is not obvious whether or not the high-Q mechanism of mode-gap waveguide cavities essentially requires 2D PBG, since a mode gap can appear even in a 1D PBG. Of course, it must be generally advantageous to have a 2D PBG rather than a 1D PBG because we have to suppress radiation loss only on one axis for 2D, but on two axes for 1D. In addition, there is a greater degree of freedom for 2D than for 1D in the momentum space design. However, we can expect that a similar high-Q mechanism would work at least to some extent even in a 1D system. The design simplicity of a 1D system will be beneficial. Recently, we found that width-modulated 2D PBG mode-gap cavities (Fig. 1(a)) can maintain ultrahigh-Q even with a lateral barrier width as thin as a few lattice constants [27], which indicates that a complete 2D PBG is not needed to obtain ultrahigh-Q.

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With this in mind, we examine the possibility of achieving ultrahigh-Q in wavelength-sized cavities with true 1D periodicity. An example structure is shown in Fig. 1(b), which is based on a simple periodic array of dielectric blocks (hereafter we assume that the dielectric is silicon, which has a refractive index, n, of 3.46) in air. This array may have true guided modes in the x direction, and it apparently has a true 1D PBG on the x axis. Thus, we can effectively employ the same design strategy as that used for Fig. 1(a). We can expect that light confinement will be achieved by some local structural modulation. Since this is simply a model 1D PBG cavity, for the moment, we are unconcerned about how we fabricate it. We will consider realistic cavity structures later.

First, we have to examine the dispersion relation of waveguide modes. Figure 2(b) shows the dispersion relation of TE modes (the magnetic field lies along the z axis) in the structure in Fig. 1(b). The structural parameters are given in the figure caption. The mode indicated by an arrow is located outside the light cone of the air cladding, and thus it is a loss-free mode. The second-order mode (colored orange) immediately above the fundamental mode has an odd parity (in terms of the x-z plane reflection) which does not couple with even-parity modes. Hence if the structure is mirror symmetric across the x-z plane, there is a even-parity mode gap above the higher edge of the fundamental even mode (shaded blue). Thus, if the effective width of this waveguide is locally narrowed (while maintaining the mirror symmetry), an even-parity optical cavity would be formed in the narrowed region. It should be noted that we have to reduce the size for this particular mode, although we increased it in the previous case because the dispersion is reversed.

To modulate the mode gap, we introduce the modulation of the stack thickness, as shown in Fig. 3(a). Note that the periodicity of the 1D array is constant. To create a cavity mode, we have to introduce a gradual reduction in the stack thickness. Of the various possible modulation functions, here we employ that proposed for a mode-gap cavity based on a 2D photonic-crystal line defect with a parabolic dispersion [28] because the dispersion curve of the present 1D waveguide is also parabolic (Fig. 2(b)).

We have numerically calculated the cavity modes and cavity Q of these model structures with the 3D finite-difference time-domain (FDTD) method. The method is basically the same as that in our previous report for 2D PBG cavities before [14]. We estimate cavity Q by calculating electromagnetic energy decay as a function of time. For the most of the calculations, we assumed mirror symmetry, but we have checked that the same result is obtained without assuming symmetrical boundary condition. We use the conventional definition for the cavity mode volume (V_{eff}), which is the ratio of the total electric field energy to the maximum of the electric field energy density.

Subsequently, we found that this local modulation of the stack thickness produces very strong light confinement. Figure 3(b) shows the z component of the magnetic field (H_z) distribution of the size-modulated 1D stack, which reveals that a distinctive resonant mode is formed in this structure. The modulation parameters are detailed in the figure caption. The calculated Q of this mode is approximately 6.3×10^7, which is much higher than values reported for 1D PBG cavities [20,21] and comparable to those for ultrahigh-Q 2D PBG cavities [13,19]. The calculated mode volume is $2.1(\lambda/n)^3$, which is slightly larger than that for 2D PBG cavities but still comparable to the wavelength size in the high-index material. This result clearly shows that ultrahigh-Q wavelength-sized cavities are indeed possible to realize without 2D or 3D PBGs.

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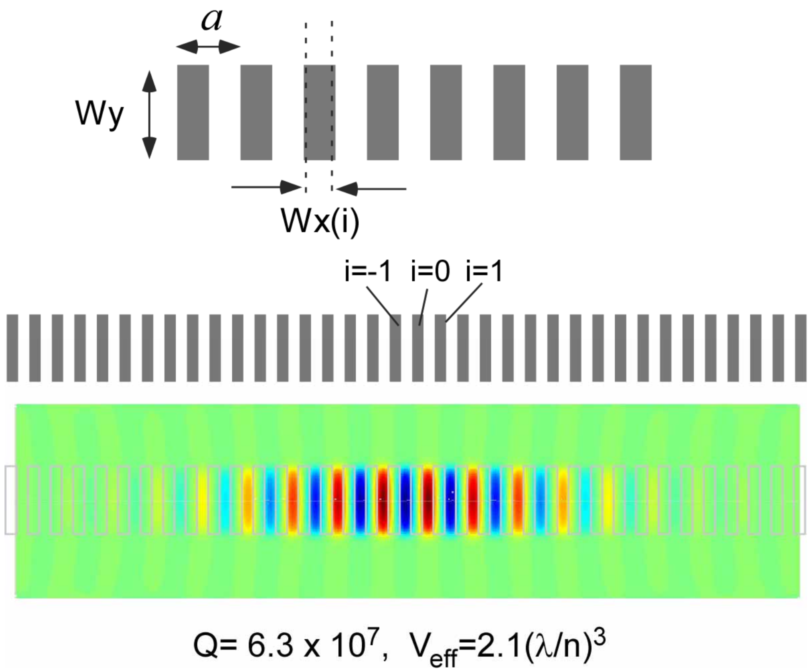

Fig. 3. Schematic of a 1D stack cavity and calculated magnetic field (H_z) distribution profile. The thickness in the z direction is $0.5a$, W_y is $3a$. $W_x(i) = W_{x0}(1+(i/30)^2)$ for $|i| < i_{mod}$, otherwise $W_x = 0.5345a$. $W_{x0} = 0.45a$ and $i_{mod} = 14$ in the present case

4. Size-modulated 1D ladder cavity

As noted in the previous section, a 1D stack cavity with air cladding is difficult to fabricate in reality. Thus, in this section, we investigate more realistic 1D cavities with air claddings which can be made with the conventional air-bridge fabrication process. The new model cavity, which has a ladder-like structure, is shown in Fig. 1(c). The dispersion relation of the TE modes in the structure is shown in Fig. 2(c). The dispersion characteristics of this structure is similar to that of the 1D stack waveguide (Fig. 2(b)). The even-parity mode of interest is indicated by an arrow, above which there is a large even-parity mode gap. Therefore, we can expect that size modulation similar to that described above will lead to ultrahigh-Q with a small mode volume.

After trying a range of size parameters, we found a very high-Q cavity mode with this ladder design, whose H_z distribution is shown in Fig. 4. The calculated mode volume V_{eff} is $1.4(\lambda/n)^3$, and the cavity Q is as high as 2.0×10^8. These Q and V_{eff} are comparable to or even better than those obtained for width-modulated 2D photonic crystal cavities. This directly demonstrates that a 2D PBG is not essential to realize ultrahigh-Q and a small mode volume, at least in terms of mode-gap waveguide cavities.

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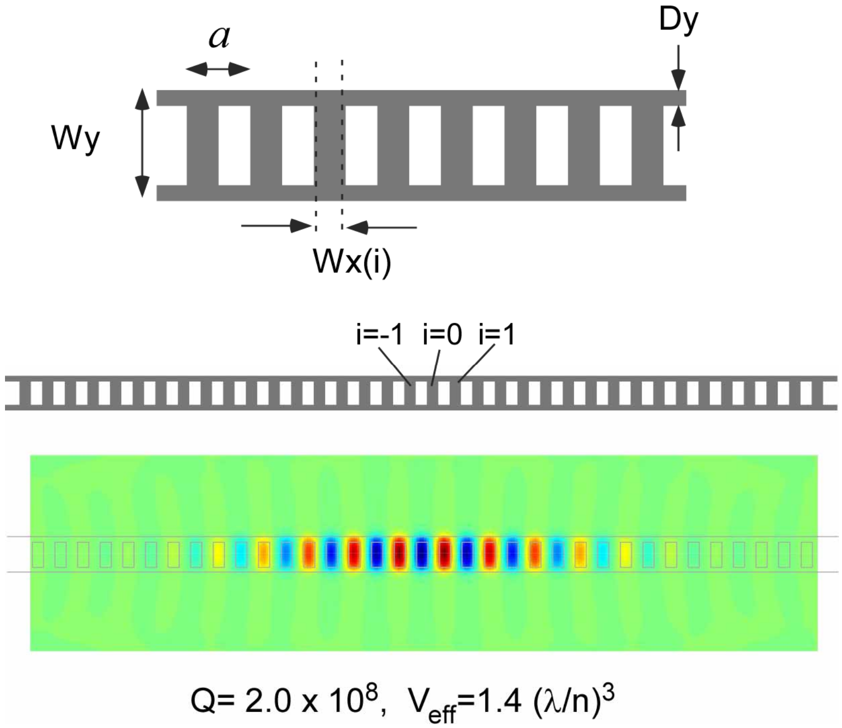

Fig. 4. Schematic of a 1D ladder cavity and calculated magnetic field (H_z) distribution profile. W_y=1.5a, and D_y=0.125a. The thickness in the z direction is 0.5a. $W_x(i) = W_{x0}(1+(i/30)^2)$ for $0 \leq |i| \leq i_{mod}$, otherwise W_x =0.548a. W_{x0}=0.45a and i_{mod}=14 in the present case.

Although we have not fully investigated a large space for size and modulation parameters for this design, we examined some size parameter dependence, as shown in Fig. 5. The mode volume monotonically decreases as the cavity width (W_y) decreases (Fig. 5(a)). Q slightly increases from W_y =4a to W_y = a, but abruptly decreases at W_y =0.75 a, which might be because the mode gap becomes too small. As shown in Fig. 5(b), Q also depends on the modulation depth (the modulation depth is defined as $|W_x(i_{mod})- W_{x0}|/W_{x0}$, and reaches its maximum value at around 20%. The mode volume slightly decreases as the modulation depth increases. These characteristics are largely reasonable and similar to those for width-modulated line-defect cavities. Note that V_{eff} is $1.3(\lambda/n)^3$ and Q>10^8 when the cavity width is 1.0a.

Roughly speaking, the cavity characteristics of 1D ladder cavities are similar to those of width-modulated line-defect cavities, in terms of Q and V. However, considering possible applications, 1D ladder cavities are distinctive in comparison to ultrahigh-Q cavities based on 2D photonic crystals. Apparently, the structure is much simpler, which will be advantageous in terms of fabrication error tolerance. Although the cavity mode volume is almost the same, the geometrical area of the cavity is much smaller. In fact, in the case of the 2D photonic crystal cavities, significantly large area of a surrounding barrier region is required to realize strong confinement. This advantage will be useful as regards packing several cavities into a tiny area. In addition, the small area means that this type of cavity can be extremely light in terms of their mass. We have already reported that ultrahigh Q nanocavities based on 2D photonic crystal slabs can realize super-efficient optical micro-machines [29], because the optomechanical interaction is dramatically enhanced. Ultralight and ultrahigh-Q 1D ladder cavities should prove effective in further enhancing the optomechanical interaction. We believe these 1D cavities will exhibit many other distinctive features.

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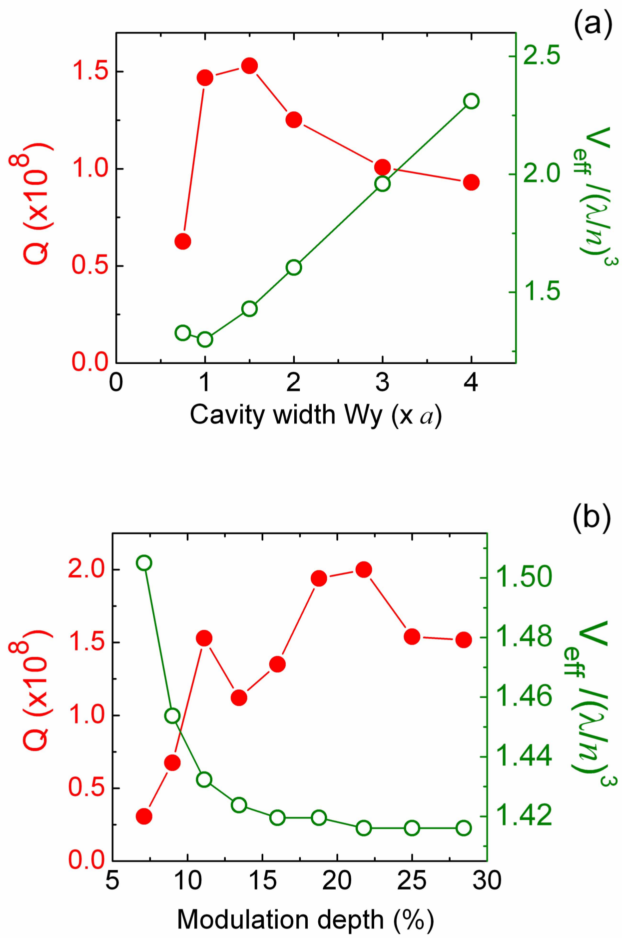

Fig. 5. Parameter dependence of Q and V for 1D ladder cavities. (a) Dependence on cavity width W_y. W_{x0}=0.45a. The modulation depth is 25%. (b) Dependence on modulation depth, $|W_x(i_{mod})$- $W_{x0}|/W_{x0}$. W_y=1.5a and W_{x0}=0.45a. Other parameters are assumed to be the same as those in Fig. 4.

5. Conclusion

We have demonstrated that ultrahigh-Q wavelength-sized optical cavities can be realized with size-modulated 1D photonic crystals. The achieved performance in terms of theoretical Q and V_{eff} is comparable to that for state-of-the-art ultrahigh-Q nanocavity designed in 2D photonic crystals. Thus, we believe that the simple 1D PBG cavities we have described have the potential to replace these 2D PBG cavities in many situations, and their uniqueness and simplicity of geometrical configuration will open up new possibilities for ultrahigh-Q nanocavities. Experimental verification is now under way in our laboratories.

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