Finite-difference time-domain investigation of band-edge resonant modes in finite-size two-dimensional photonic crystal slab

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We investigate characteristics of optical modes near band edges of finite-size two-dimensional photonic crystals and photonic crystal slab structures by using finite-difference time-domain calculations. Mode patterns, spectra, and quality factors are calculated near several photonic band edges of triangular lattice air-hole structures. As the size of a photonic crystal pattern increases, the spectral peak approaches the photonic band edge and the quality factor increases. It is interesting to find that, in spite of out-of-plane radiation loss, band-edge quality factors of the photonic crystal slab larger than those of the two-dimensional photonic crystal with equivalent effective refractive index. This fact originates from the slower group velocity near band edges of photonic crystal slab structures compared with two-dimensional photonic crystals. High quality factors > 2000 are achieved from the second Γ point of the photonic crystal air-bridge slab with only 15 layers of air holes.

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I. INTRODUCTION

During the last decade, there has been considerable interest in photonic band gap materials or photonic crystals due to their ability to control the properties of light emission and propagation.1–14 Most studies on photonic crystals have been devoted to the utilization of point or line defects for application to low-threshold lasers or low-loss waveguides. However, photonic crystals without any defects can also function as good photonic devices by exploiting photonic band-edge states.5–27 For example, lasing action,8–14 enhancement of nonlinear interaction,15–17 and spontaneous emission control18–20 have been reported by use of photonic band edges of one- or two-dimensional photonic crystals. These optical phenomena result from the enhancement of the optical density of states or decrease of group velocity near photonic band edges. The small group velocity is also experimentally demonstrated recently.21,22

The two-dimensional (2D) photonic band-edge laser can be regarded as a 2D analogue of the (1D) distributed feedback (DFB) laser. Experimentally, successful band edge laser operation has been demonstrated from semiconductor or organic materials.8–14 For example, Noda et al. demonstrated electrically-pumped single polarization mode 2D band-edge lasers that have potential for high-power surface-emitting lasers.13 Most band edge lasers are based on the low-index-contrast heterostructure, so device size is usually larger than 100 µm and practically regarded to be infinity. Very recently, Ryu et al. reported lasing actions from the band edges of InGaAsP air-bridge slab photonic crystals.14 Due to the strong refractive index contrast, low-threshold lasing action from a small structure size (∼ 10 µm) was achieved. This high-index-contrast band edge laser structure is expected to exhibit small optical losses. However, thorough theoretical investigation is required to understand the mode characteristics of this laser.

Finite-size 2D photonic crystal band-edge laser structure has also been analyzed theoretically.23–26 In contrast to the DFB laser, 2D photonic band edge lasers have various feedback mechanisms due to their extended degree of freedom.12,26 Therefore, the conventional coupled-mode theory cannot describe the 2D band-edge lasers and ingenious numerical analyses should be employed. Recently, Nojima investigated optical modes near band edges by using the resonance scattering method and found that threshold gain is inversely proportional to photon lifetime,26 implying that the long photon lifetime is advantageous for achieving low-threshold band-edge lasing action. Resonant states with relatively long photon lifetimes are formed near band edges of a finite-size photonic crystal. In most theoretical works, however, only 2D structures were investigated, and high-index-contrast photonic crystal slabs that require 3D analyses have not been treated.

In this paper, we study characteristics of optical modes near band edges of finite-size 2D photonic crystals and photonic crystal slabs by using the finite-difference time-domain (FDTD) method. The FDTD method is a powerful tool to calculate optical mode properties of complex photonic structures. This method has been successfully applied to the calculation of various properties of photonic crystal defect modes. However, it has not been applied to the investigation of the band-edge optical modes in finite-size photonic crystals. The FDTD analyses of band-edge resonant modes in the photonic crystal slab will help to understand the characteristics of the air-bridge slab band edge lasers.14

In this work, we mainly focus on the photon lifetime of the band edge resonance. The photon lifetime is usually represented as a dimensionless quantity, quality (Q) factor. The Q factor is defined as the product of the photon lifetime and the angular frequency. In band edge resonant modes of finite-size photonic crystal structures, the Q factor will increase as the group velocity decreases. This is because photons have a
much longer time to interact with the structure if the group velocity is very slow. The high-$Q$ factor at low group velocity can also be understood by the following argument. The band-edge Bloch wave vector $k$ in a finite photonic crystal is not determined exactly and there exists some region of $k$-space uncertainty. In a band diagram, the range of $k$ in a given band corresponds to some frequency range. The width of this frequency range represents the $Q$ factor. If the group velocity decreases, the band will be flatter. Then, the width of the frequency range decreases and the $Q$ factor increases. In other words, the $Q$ factor is the measure of flatness of a band edge, and can be regarded as an important parameter that characterize band-edge resonant modes. In this sense, we believe the FDTD method that can accurately evaluate $Q$ factors will be advantageously used for the investigation of band edge resonance of finite-size photonic crystals.

Using the FDTD method, we present high-$Q$ resonant properties of the band edge states in both 2D photonic crystals and photonic crystal slabs with high index contrast. First, we calculate mode spectra, field distribution, and $Q$ factors near several photonic band edges in 2D triangular air-hole photonic crystals. Then, the 3D FDTD method is applied to the calculation of real photonic crystal slab structures of air-bridge types or low-index cladding types. In photonic crystal slab structures, out-of-plane radiation loss exists in addition to the in-plane propagation loss of a finite structure. In spite of such additional loss, it will be shown that the photonic crystal slab has a higher band-edge $Q$ factor than the 2D photonic crystal with similar structure parameters, and the underlying principle for this observation will be exploited.

II. COMPUTATIONAL METHOD

In this section, we introduce the method of calculations and describe the problem. The triangular lattice circular air-hole structure is considered in our study. Figure 1 shows the horizontal view of a calculation domain and reciprocal space representation of a triangular lattice. The FDTD method calculates radiation fields in open space by use of the appropriate boundary condition. We employ the perfectly matched layer boundary condition in the FDTD calculation.28 The dependence of resonant mode properties near band edges on structure size is mainly investigated in this work. Here, we introduce a size parameter $N$ that means the number of air-hole layers in the $G$-$M$ direction. For example, $N$ is 7 in the calculation domain of Fig. 1. This domain contains 37 air holes. For all calculations, the air-hole radius is kept to be 0.35$a$, where $a$ is lattice constant. The refractive index of dielectric material for a 2D photonic crystal and a photonic crystal slab is assumed to be 2.8 and 3.4, respectively. The refractive index of 2.8 in the 2D calculation roughly corresponds to the effective refractive index when the 2D air-bridge photonic crystal slab structure with moderate thickness is approximated.

The 2D band structure for transverse electric (TE) polarization is calculated by the plane-wave expansion method and shown in Fig. 2 when the air-hole radius is 0.35$a$ and the refractive index of dielectric material is 2.8. We consider three band-edge points: the K point of the first band (K1), the M point of the second band (M2), and the $\Gamma$ point of the second band (\$\Gamma'$2). The normalized frequency (ratio of lattice constant to light wavelength in vacuum) of each band-edge point is 0.27, 0.374, and 0.494, respectively. These points have zero group velocity in the infinite-size structure. In fact, the group velocity of the M point of the first band

![PML](image1.png)

FIG. 1. (a) Horizontal view of the FDTD calculation domain surrounded by PML boundaries. Here, the number of air-hole layers, $N$ is 7. (b) Reciprocal space ($k$ space) of a triangular lattice. The hexagon area represents the first Brillouin zone and dots denote reciprocal lattice points.

![Band structure](image2.png)

FIG. 2. Band structure of a 2-D air-hole triangular lattice photonic crystal. The air-hole radius is 0.35 times lattice constant, and the refractive index of material is 2.8. Three band-edge points (K1, M2, $\Gamma'$2) that will be investigated are indicated on the band structure.
(M1) can also be zero, and a resonant mode will be formed at this point. However, we do not treat the M1 point in this study since it is not a true band-edge point in contrast to K1, M2, and Γ2 points.

In the FDTD calculation, the electromagnetic field is initiated by exciting a point dipole with TE polarization at some dielectric region near the central air hole. The point dipole source has a Gaussian pulse shape centered near the band-edge frequency. The resonant spectrum is obtained by Fourier transform of the time-evolved field. The resonant field distribution and the Q factor of a specific mode can be obtained by exciting the very resonant mode. The Q factor might be determined by the linewidth of the resonant spectrum. However, it should be evaluated more precisely from the decay slope of logarithm energy-time relation. We use the latter method for the calculation of Q factors. For the accurate determination of Q factors, it is important to excite only one resonant mode. So, it is not easy to calculate the Q factors of the densely spaced modes in higher normalized frequency region of the band structure. Therefore, we restrict our interest to the three low-lying band edges mentioned above. The lattice spacing a is discretized to 20 mesh points for 2D FDTD calculations and 15 mesh points for 3D FDTD calculations. We checked, in the 3D FDTD calculation, that the relative difference of Q factors between the 15-mesh case and the 20-mesh case is less than 10%.

III. 2D PHOTONIC CRYSTAL

In this section, we show that the FDTD method can calculate well the general features of band edge resonant modes such as resonant spectra, resonant mode distribution, and Q factors by applying the method to 2D photonic crystals. First, we calculate resonant spectra near band edges for several N values. In Fig. 3, electric field intensity as a function of the normalized frequency is shown for the M2 point and the Γ2 point. The main spectral peak in Figs. 3(a) and 3(b) corresponds to the band edge resonance of M2 and Γ2, respectively. The small peak at the high frequency side of the M2 peak and the low frequency side of the Γ2 peak respectively comes from the K point of the second band and the M point of the third band, as one can see from the band structure in Fig. 2. The spectral shape varies a little with initial conditions of a dipole source such as the peak and the width of a pulse. However, the peak position and the width of the spectra are nearly constant irrespective of the initial conditions.

The width of the main resonance spectrum becomes narrower as N increases, which means that the Q factor increases with the structure size. With increasing structure size, the distribution ranges of the Bloch wave vector k, and consequently the normalized frequency, become narrower. That is, the band edge position is defined more and more accurately as the N value increases, which results in the spectral narrowing and large Q factors. Since the spectral width is narrower in a flatter band, band-edge resonant states with low group velocities show large Q factors. The ratio of the full width at half maximum to the normalized frequency in the resonant peak gives the Q factor. This Q factor is consistent with the Q factor obtained by the decay rate of electro-

FIG. 3. Spectra near band edges for three N values. Thin vertical lines indicate the normalized frequency of each band edge in the infinite-size structure. (a) M2 band edge. (b) Γ2 band edge.

magnetic energy that will be shown in Fig. 6. For the same N value, the spectral width of the Γ2 peak is narrower than that of the M2 peak. This implies that the Q factor of the Γ2 point is larger than that of the M2 point, and the group velocity is slower near the Γ2 point.

In addition to the spectral narrowing, the shift of normalized frequencies with N is also observed in Fig. 3. Three vertical lines in Fig. 3 correspond to the band-edge frequency of the infinite-size structure. The peak of the spectrum approaches the band-edge position as N increases. However, the direction of the spectral shift is different for each case. The normalized frequency of the M2 peak decreases with N, whereas that of the Γ2 peak increases with N. These results are related to the shape of the band. In Fig. 2, the M2 band edge is located at the local minimum of the second band. Therefore, in a finite-size structure, the spectrum should mainly be distributed above the M2 band edge and approach that band-edge point as the structure size increases. The opposite interpretation can be adopted to explain the behavior of the Γ2 peak since the Γ2 band edge is positioned at the local maximum of the band.

Field distributions of the resonant band-edge state are calculated. Figure 4 shows a z-component of the magnetic field pattern (\(H_z\)) at the Γ2 peak when N is 11. The real space amplitude pattern (\(H_z(\mathbf{r})\)) and the k-space intensity pattern (\(|H_z(k)|^2\)) are drawn in Figs. 4(a) and 4(b), respectively. The
$H_z$ in real space has a sixfold symmetry and is similar to the eigenmode pattern of the $\Gamma^2$ point that is referred to as a hexapole mode.\textsuperscript{27} The field pattern changes a little with initial conditions of a dipole source. However, the basic hexapolelike field distribution is still maintained regardless of the excitation condition.

The $k$-space field distribution is obtained by the Fourier transform of the real space pattern. The $k$-space representation helps to understand the properties of resonant modes.\textsuperscript{29–31} In order to exclude influence of fields outside a photonic crystal pattern, fields outside the photonic crystal area are set to be zero before the Fourier transformation.\textsuperscript{31} In Fig. 4(b), hexagon lines represent the first Brillouin zone and reciprocal lattice points $\Gamma$ and $\Gamma'$ are denoted. Actually, there are six equivalent $\Gamma'$ as can be seen from Fig. 1(b). High intensity spots at six $\Gamma'$ points reveal that the field pattern in Fig. 4(a) indeed originates from the $\Gamma^2$ band-edge point. In addition, six high-intensity $\Gamma'$ points imply that the $\Gamma^2$ band edge corresponds to coupling of waves propagating in six different directions, which is consistent with the interpretation of Ref. 27. Weak intensity spots other than the $\Gamma'$ points seems to come from boundary effects. We also calculated field distribution of the K1 and M2 band-edge resonances, and confirmed that each resonance corresponds to six K points and M points of the Brillouin zone by the $k$-space transformation.

Next, $Q$ factors are calculated as a function of $N$ for the K1, M2, and $\Gamma^2$ points and plotted in Fig. 5. As expected, $Q$ factors generally increase with $N$. However, the increasing behavior is not so regular, possibly because of other factors such as boundary effects. For the same $N$ value, the $Q$ factor of the $\Gamma^2$ point is much larger than that of other points. The $Q$ factor of the $\Gamma^2$ point is larger than 500 for 11 air-hole layers and 1000 for 15 air-hole layers. The $Q$ factor of the M2 point is a little larger than that of the K1 point, and their $Q$ factors are still less than 500 when $N$ is increased up to 17. The high $Q$ factor at the $\Gamma^2$ point results from the fact that this band edge is much flatter than other ones. The flatness of higher band edges has also been reported in other works.\textsuperscript{23,24}

In a 1D photonic crystal structure, there are no such flat bands and flatness is the same for all band edges. The high $Q$ factor of the $\Gamma^2$ point can explain the experimental results that many 2D band-edge lasers operate at this point.\textsuperscript{11–14}

IV. PHOTONIC CRYSTAL SLAB

In Sec. III, some basic characteristics of band-edge resonant modes have been investigated from finite-size 2D photonic crystal structures. In this section, we apply 3D FDTD calculations to band-edge resonant states in photonic crystal slab structures. Air-bridge type photonic crystal slabs are mainly studied. The 2D photonic crystal lattice structure is the same as in the previous case. The Air-hole radius is 0.35$a$, and the refractive index of the slab material is 3.4. General features of the band-edge resonance in the photonic crystal slab are basically the same as those in the 2D photonic crystal such as spectral properties, field distributions, and $Q$ factors. In this section, we present results of $Q$ factor calculations for several situations.

$Q$ factors are calculated for the K1 and $\Gamma^2$ band-edge points. The slab thickness for the K1 and $\Gamma^2$ band-edge calculations is set to be, 0.6$a$, and 0.3$a$, respectively. These values of the slab thickness correspond to the actual slab thickness of ~250 nm when the light wavelength is 1.55 mm, and the slab operates as a single mode waveguide at the band-edge frequency. In addition, the spectral peak of each band-edge resonance exists at the normalized frequency of 0.27 and 0.51, respectively. These frequency positions are similar to the 2D calculation result when an effective refractive index of 2.8 is used.

Calculated $Q$ factors are plotted as a function of $N$ in Fig. 6. The $Q$ factor increases with $N$ and the $\Gamma^2$ point has larger $Q$ factors than the K1 point as in Sec. III. However, the actual $Q$ factor values of a photonic crystal slab case are larger than that of a 2D photonic crystal case. Compared with the 2D results in Fig. 5, the $Q$ factors of the slab band edge are about two times larger. The $Q$ factor of the $\Gamma^2$ point is ~1000 when $N=11$ and >2000 when $N=15$. This $Q$ factor of the $\Gamma^2$ band-edge resonant state is larger than or comparable to the $Q$ factor of some resonant modes of a point-defect photonic crystal slab with a similar number of air-hole layers. For example, the dipole mode of a triangular lattice single defect is only a few hundred,\textsuperscript{32} and the mono
FIG. 6. Total quality factors as a function of the number of air-hole layers (N) for the K1 and the Γ2 band edge of a photonic crystal slab.

FIG. 7. Horizontal quality factors (solid line) and vertical quality factors (dotted line) of the Γ2 band edge resonant mode are plotted as a function of the number of air-hole layers (N).

pole mode of a modified single defect is \(~\approx 2000\). However, note that the band-edge modes have much larger mode volumes than the defect modes. Therefore, if the mode volume is not a matter of concern, we expect that the band-edge resonant state of a photonic crystal slab can also be a good candidate for a high-Q resonant mode.

In the resonant mode of a photonic crystal slab, the Q factor can be decomposed into horizontal and vertical Q factor components. By this decomposition, it is possible to evaluate the portion of light that is guided or radiated. The boundary for separating vertical radiation from laterally evaluated modes is positioned at approximately a half-wavelength from the slab surface. The K1 point exists below the light line of a band structure, so generated light is guided along the photonic crystal slab plane. At this band-edge point, the vertical Q factor is found to be more than 20 times larger than the horizontal one for all values of N, which means the out-of-plane radiation is very small and the total Q factor is nearly the same as the horizontal Q factor as expected. A small but non-negligible amount of radiation is attributed to scattering caused at the interface between the photonic crystal pattern and uniform dielectric region.

The Γ2 point lies on the leaky mode above the light line of a band structure, so there could exist a large out-of-plane radiation loss. The vertical and horizontal Q factors of the Γ2 point are plotted as a function of N in Fig. 7. Horizontal Q factors are larger than the vertical Q factors for all N values, and the difference of each Q factor becomes larger as N increases. When N is 15, the horizontal Q factor is \(>8000\), which is over three times as large as the vertical Q factor. So, in a sufficiently large structure, the total Q factor would be determined mainly by the vertical Q factor. The fact that the vertical Q factor is much smaller than the horizontal one well explains the experimental result that the air-bridge slab band-edge lasers operating at this point are vertical emitters.

In an infinite-size photonic crystal slab structure, it has been pointed out that certain band-edge points at the exact Γ point have infinite photon lifetimes since the resonant modes of those band edges do not couple to free space due to symmetry mismatch. So, it is expected that the vertical Q factor will increase and approach infinity as the structure size becomes large. In photonic crystal defect modes, however, the vertical Q factor is regarded as the ultimate Q factor when the number of photonic crystal elements increases. That is, the vertical Q factor of the defect modes is nearly constant irrespective of the structure size. In contrast to this, there is no limitation of vertical Q factors in the band-edge resonant mode, and very high Q factors should be achieved if the structure size is sufficiently large. In this sense, the band-edge resonant mode could be more advantageous for achieving a very high Q factor than the defect resonant mode, so long as the structure size or mode volume is not an important issue.

It is interesting to note that the Q factors of slab-structure band edges are larger than those of 2D structure band edges for the same N value. It would be naively think that, band-edge Q factors of the 2D structure with equivalent refractive indexes might be larger than those of the photonic crystal slab because there exists an out-of-plane radiation loss in the photonic crystal slab case. However, the Q factor in the slab case is always larger for all investigated band-edge modes. In order to find underlying reasons for this computational observation, we calculate the band structure near band edges in detail. Figures 8(a) and 8(b) show the band near the K1 and M2 points, respectively. Band structures are calculated by the plane-wave expansion method. Bands for the photonic crystal slab and the 2D photonic crystal are displayed together. In the band structure calculation of 2D photonic crystals, the effective refractive index is chosen so that the band-edge frequency may correspond to that of the photonic crystal slab. The 2D effective refractive indexes are 2.7586 for the K1 point and 2.5884 for the M2 point, respectively. Calculation of a band structure near the Γ2 point that exists above the light line has not been tried because it is not possible to calculate it by the plane-wave method.

For both the K1 and M2 points, band edges of the slab structure are flatter than those of the 2D photonic crystal. As mentioned previously, a flatter band edge means higher Q factors and a lower group velocity. So this band-edge flatness can explain the difference of band-edge Q factors between 2D photonic crystals and photonic crystal slabs. Actually, the sign of the curvature for each band-edge point is different.
The K1 band edge has a convex shape and the M2 edge has a concave shape. This means that the band edge of the photonic crystal slab is always flatter than that of the 2D photonic crystal regardless of the shape of a band. Therefore, the band edge of the G2 point is also expected to be flatter in the photonic crystal slab case, which contributed higher Q factors. Due to the flatter band edges or higher Q factors, the photonic crystal band-edge modes based on strong-index-contrast slab structures will be advantageously used in real application.

In Fig. 8, the slope near the band edge is also shown in the inset of each band structure. The slope of the band structure, \( dv/dk \), gives the group velocity. The group velocities from the K point into the \( \Gamma \)-K direction and from the M point to the \( \Gamma \)-M direction are plotted in the insets of Figs. 8(a) and 8(b), respectively. Very low group velocity near each band edge is confirmed, and the group velocity of the photonic crystal slab case is smaller than that of the 2D photonic crystal. Near the K1 band edge, the group velocity of the photonic crystal slab is about two times smaller than that of the 2D photonic crystal. Note that the Q factor near the K1 point is also about two times larger in the photonic crystal slab. However, additional work should be performed to clearly understand the relation of the group velocity and the Q factor near band edges because the group velocity changes with the direction in the 2D k space.

One possible explanation for the flatter band edge in the photonic crystal slab can be found by considering the effect of slab waveguiding. In the photonic crystal slab, there exists dispersion due to the strong waveguiding of the air-bridge slab in addition to the dispersion of a 2D photonic crystal. So, it can be inferred that this slab-waveguiding-induced dispersion enhances the degree of dispersion and thus results in a flatter band edge. At the K1 point, for example, the dispersion of a slab waveguide lowers the effective refractive index of a structure as the magnitude of \( k \) decreases from the band edge, which will increase the resonant frequency of the 2D photonic crystal dispersion at \( k \) points deviated from the K1 point. In the photonic crystal slab, the effect of slab guided modes and that of 2D photonic crystal Bloch modes are combined to result in a guided Bloch mode that shows flatter band edges. These two effects are not easily separable, so there should be limitation to apply the 2D calculation with simple effective refractive index to the photonic crystal slab structure. In order for the 2D effective index calculation to coincide well with the 3D photonic crystal slab calculation, different effective refractive indexes should be used for each \( k \) point and each band.

Finally, we calculate the variation of Q factors when a dielectric material is employed as the cladding material of a photonic crystal slab. This is important for real applications to photonic devices since the air-bridge-type photonic crystal slab has practical restrictions due to its poor thermal conduction and mechanical instability. If a dielectric material with a low refractive index and high thermal conductivity is used as the cladding material, thermal and mechanical properties of a photonic crystal slab would be greatly improved without degrading optical properties seriously. The total Q factor of the

![Figure 8: Band structure near the band edge of a 2D photonic crystal (solid circle) and a photonic crystal slab (open circle) calculated by the plane-wave method. (a) K point of the first band (K1). The inset shows the group velocity near the K1 point along the \( \Gamma \)-K direction. (b) M point of the second band (M2). The inset shows group velocity near the M2 point along the \( \Gamma \)-M direction.](image)

![Figure 9: Total quality factors as a function of refractive index of cladding materials for the G2 band-edge resonant mode when \( N = 11 \). The same material is used for both top and bottom cladding in the symmetric photonic crystal slab, and cladding material is placed on only one side of the slab core and the other side is air in the asymmetric case.](image)
Γ2 point is plotted as a function of the refractive index of cladding material in Fig. 9. The number of air-hole layers \( N \) is 11 in this calculation. Both symmetric and asymmetric slab structures are considered. In the symmetric photonic crystal slab, the same dielectric material is used for both top and bottom claddings. In the asymmetric slab, the dielectric material is placed on only one side of the slab core material, and the other side is air. The \( Q \) factor decreases with increasing refractive index since out-of-plane diffractive coupling increases with the refractive index. However, the decrease rate of \( Q \) factors is not so large. The rate of the decrease is slower in the asymmetric photonic crystal slab. When the refractive index of the cladding material is 1.5, the \( Q \) factor decreases by 20% in the symmetric slab and only 10% in the asymmetric slab structure. Therefore, we expect real application of band edge resonant modes such as band edge lasers is quite promising.

V. CONCLUSION

We have numerically investigated resonant mode properties near band edges of finite-size triangular 2D photonic crystals and photonic crystal air-bridge slab structures. The FDTD method is successfully applied to the calculation of mode distributions, spectra, and \( Q \) factors of several band-edge resonant states. The \( Q \) factor represents the degree of flatness of the band edge. A large \( Q \) factor (long photon lifetime) means a low group velocity and a high photon density of states.

High \( Q \) factors >2000 are achieved from the \( Γ \) point of the second band in the air-bridge photonic crystal slab with 15 air-hole layers. In addition, \( Q \) factors are not significantly decreased when the low refractive index material is introduced as the cladding of the photonic crystal slab, which promises practical application of band edge resonant modes to real miniaturized photonic devices. It has been found that \( Q \) factors of the band-edge resonant modes in the photonic crystal slab are about two times larger than those in the 2D photonic crystal with equivalent effective refractive index. This result indicates that the group velocity near band edges is slower in the photonic crystal slab case, as confirmed by the band structure calculation. Slab waveguiding effects as well as photonic crystal effects contribute high \( Q \) factors of band-edge resonant modes in the photonic crystal slab structures.

In this work, we show that the FDTD method is well suited for the investigation of band-edge resonant modes in finite-size photonic crystals, and expect that it will be a very useful tool for studying optical processes in photonic band edges such as band-edge lasing, spontaneous emission control, and nonlinear interaction.

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