Dispersion-guided resonances in two-dimensional photonic-crystal-embedded microcavities

Kevin K. Tsia and Andrew W. Poon

Department of Electrical and Electronic Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

Abstract: We analyze dispersion-based guiding of resonances in two-dimensional (2-D) photonic-crystal-embedded microcavities (PCEMs) that comprise a finite-size square lattice of submicrometer air holes embedded in a high-index contrast square microcavity. Our 2-D finite-difference time-domain simulations of waveguide side-coupled PCEMs suggest high-Q quasi-periodic multimodes within the PC first band. The Q can increase by orders of magnitude as the mode frequency approaches the band-edge frequency or as the lattice dimension increases. By mapping the Fourier transform of the mode-field distributions onto the PC dispersion surface, we show that the modes \( k \)-vectors and group velocities are pointing near the \( \Gamma M \) direction.

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References and links

1. Introduction

High-index contrast two-dimensional (2-D) photonic crystals (PCs) [1] and planar optical microcavities [2] are two major classes of emerging nanophotonics technologies that have attracted substantial interest for on-chip photonic information processing. In the 2-D PCs front, extensive works have been focused on photonic bandgap (PBG) based confinement and waveguiding, including point-defect microcavity lasing [3] and line-defect waveguiding around sharp bends [4]. Recently, a host of PC dispersion-based waveguiding phenomena - self-collimation [5], superprism effect [6], and negative refraction [7], have also gained increasing attention. Dispersion-based PC components utilizing high-index contrast square lattice of submicrometer air holes have been experimentally demonstrated on silicon-on-insulator (SOI) substrates [8, 9]. Numerical simulations also suggest that lightwave can be dispersion-guided within the PC first band near the square lattice ΓM direction [10]. Compared with PBG-based waveguiding, dispersion-based waveguiding have the advantages of relatively broadband and of a relatively wide lattice area for waveguiding.

In the planar optical microcavities front, high-Q whispering-gallery modes in high-index contrast waveguide-coupled circular microdisk and microring resonators are the most investigated. However, conventional waveguide side-coupled circular microcavities suffer from a short interaction length between the curved microcavity sidewall and the straight waveguide sidewall, and thus impose tight constraint on the submicrometer air-gap separation between the waveguide and the microcavity. Recently, square microcavities that have the advantage of flat cavity sidewalls for the ease of lateral coupling have been proposed as an alternative planar microcavity design [11-14]. Lightwave in square microcavities can be partially confined by total internal reflection (TIR) at the microcavity flat sidewalls. High-Q resonances with four-bounce ray orbits can be excited only when the cavity wave front-matches with the input-coupled wave upon traveling each round-trip. However, such four-bounce modes are dispersed over a range of discrete k-vectors, resulting in multimodes [12, 13] that are undesirable for many applications including channel add-drop for wavelength-division multiplexing (WDM) communications.
Earlier it occurs to us that combining the 2-D PC dispersion and the planar microcavity high-Q resonances may give rise to important components and techniques for controlling lightwave on photonics chips. Specifically, the multimode issues in square microcavities can possibly be mitigated by means of dispersion-based guiding of modes along a reduced set of wavefront-matched ray orbits. To this end, we proposed [15, 16] to embed a finite-size square PC lattice of submicrometer air holes in a high-index contrast square microcavity. We referred to this new class of structures as photonic-crystal-embedded microcavities (PCEMs) [15, 16]. We postulated that the PC dispersion could guide or collimate lightwave within a frequency band near the square lattice $\Gamma M$ direction, and thus enable preferential coupling with square microcavity ray orbits that are in the vicinity of the $\Gamma M$ direction. By using 2-D finite-difference time-domain (FDTD) method, we showed numerically that waveguide side-coupled PCEMs have quasi-periodic high-Q modes with a maximum coupling efficiency of about 90% and nearly two-orders-of-magnitude field intensity enhancement in the air holes [16]. Our FDTD simulations suggested that waveguide-coupled PCEMs have significantly fewer modes than waveguide-coupled square microcavities without the PC [16]. Moreover, PCEM mode field have been shown to be partially confined in either the dielectric regions [15] or the air-hole regions [16].

Here we report an analysis of dispersion-based guiding of resonances in waveguide-coupled PCEMs using 2-D FDTD method. We study the quasi-periodic multimode transmission spectra as a function of finite-size square PC lattice dimension. We analyze the modes by means of their steady-state electric field distributions. By mapping the Fourier transform of the mode-field distributions in k-space onto the PC dispersion surface, we show that the coupled modes have $k$-vectors near the $\Gamma M$ axis and have group velocities pointing towards the $\Gamma M$ direction.

Section 2 reviews concepts pertinent to finite-size effects on PCs and presents an analytical one-dimensional PCEM model based on T-matrix calculations. Section 3 outlines the principle of dispersion-based guiding of resonances in 2-D PCEMs. Section 4 presents an analysis of the multimode transmission spectra with different lattice dimensions. Section 5 discusses the PCEM mode-field distributions and the Fourier transform analysis of the mode-field distributions with superimposed PC dispersion surface. Section 6 concludes this work.

2. Dispersion-guided resonances in 1-D PCEMs

Fig. 1. (a) Schematic of a 1-D PCEM: a finite-size multilayered periodic structure of high and low-index media bounded by Fresnel reflections at normal incidence at the two end faces. (b) Schematic of a 2-D PCEM: a finite-size square PC lattice of air holes bounded by total internal reflections at 45° incidence at the square microcavity sidewalls. Circulating rays represent dispersion-guided energy flow in (a) a Fabry-Pérot orbit, and (b) a four-bounce orbit.

The concept of PCEMs can be realized in one-dimensional (1-D) or higher dimensions. Figure 1(a) shows the schematic of a 1-D PCEM, in the form of a finite-size multilayered periodic structure of high and low-index media bounded by Fresnel reflections at normal incidence at the two end faces. The 1-D PC can be considered as embedded in a conventional Fabry-Pérot resonator. Circulating rays represent dispersion-guided energy flow in a Fabry-Pérot orbit. Figure 1(b) shows the schematic of the proposed 2-D PCEM, in the form of a
finite-size square PC lattice of air holes bounded by TIRs at 45° incidence at the square microcavity sidewalls. Circulating rays represent dispersion-guided energy flow in a four-bounce orbit.

Fig. 2. (a) - (d) Calculated reflectance spectra of the 1-D PCEMs for lattice dimension \( N = 4, 8, 12 \text{ and } 20 \). Dashed line denotes the first band-edge frequency. Inset shows the schematic of a 1-D PCEM designated by \( \text{air/(HL)}^N\text{H/air} \). \( n_H = 3.5, n_L = 1; h_H = 0.4 a, h_L = 0.6 a, \) and \( a = h_H + h_L = 0.465 \mu m \). (e) Q-factors (triangles) of 1-D PCEM \( (N = 20) \) modes and group velocity \( \upsilon_g \) (squares) obtained from the PC first band as a function of the normalized frequency. Dashed line denotes the band-edge frequency. Inset shows the Q-factor of the highest frequency mode as a function of \( N \).

Finite-size effects on 1-D PC structures are well known [17-21]. For instance, quasi-periodic oscillations (resonances) in the transmittance of a finite-size 1-D PC [19], as well as of a semi-infinite square lattice of submicrometer air holes in a high-index medium with endface reflections along the direction of incidence [21] have been reported.

Here we first review and model a 1-D PCEM using the T-matrix method [23] in order to lay down fundamental concepts pertinent to PCEMs and to put our 2-D PCEM discussion into context. The modeled 1-D PCEM comprise \( N \) periods of alternately high and low-index layers (denoted as \( H \) and \( L \)) with lattice periodicity \( a \). The structure is designed to be symmetric and designated by \( \text{air/(HL)}^N\text{H/air} \). The modeled parameters are detailed in the figure caption and follow those of the 2-D PCEM (Section 3).

Figures 2(a) – 2(d) show the T-matrix calculated 1-D PCEM reflectance spectra for \( N = 4, 8, 12 \text{ and } 20 \). We assume an incoming plane wave from free-space with normal incidence on the \( H \)-layer. We obtain quasi-periodic Fabry-Pérot resonances below the first band-edge frequency of the 1-D PC \( (a/\lambda = 0.165, \text{red dashed line}) \). The PC band was numerically calculated using a commercial PC band solver [24]. The resonances strongly depend on the PC dispersion. Figure 2(e) shows the observed orders of magnitude rise of \( Q \) (triangles) for \( N = 20 \) and the calculated drop of the group velocity \( \upsilon_g \) (squares) as the mode frequency approaches the band-edge frequency (dashed line). We obtained the \( \upsilon_g \) from the infinite-size PC dispersion curve. It is well known that the “slowed light” near the band edge frequency can have a relatively long lifetime in the PCEM, and thus can attain a relatively high-Q value. As \( N \) increases the resonance wavelengths blueshift nonlinearly and the blueshift saturates at large \( N \), with the highest frequency mode approaching the band-edge frequency. Inset shows
the near exponential rise of the Q-factors of the highest frequency mode as \( N \) increases. It is intuitive that the finite-size PC band (at off-resonance frequencies) and the band-edge frequency approach those of the infinite-size PC as \( N \) increases.

3. 2-D PCEM Structures

3.1 Principle of dispersion-guided resonances in 2-D PCEMs

![Diagram of 2-D PCEM structure](image)

Fig. 3. Schematic of a waveguide side-coupled PCEM comprised of a \( 7 \times 7 \) square lattice of air holes bounded by a silicon square microcavity \( (n = 3.5) \). Ray orbits (orange solid) represent energy flow along the PC dispersion-guided directions. Energy flow in other directions (red dashed) is prohibited by PC dispersion. An evanescently side-coupled waveguide of width \( w = 0.375 \) \( \mu m \) is oriented in the \( \Gamma X \) direction and has an air gap separation \( g = 0.2 \mu m \) from the PCEM sidewall. Zoom-in view shows the symmetry directions in red arrows and a unit cell in dashed orange line. Period \( a = 0.465 \mu m \) and radius \( r = 0.3 \) \( a \). Sidewall length \( L = (Na + d) \), where \( d = 0.4 \) \( a \) is the margin width.

Here we analyze the proposed 2-D PCEM composed of a high-index contrast silicon (refractive index \( n = 3.5 \)) square microcavity with an embedded \( N \times N \) square PC lattice of submicrometer air holes \([15, 16]\). Figure 3 shows the schematic of a waveguide side-coupled PCEM. Ray orbits (orange solid) represent energy flow along the PC dispersion-guided directions. Resonances can be excited only when the dispersion-guided lightwave components are wavefront-matched with the input-coupled lightwave upon each round trip. Energy flow in other directions (red dashed) is prohibited by PC dispersion. The modeled parameters are detailed in the figure caption. We adopted the lattice constant \( a = 0.465 \mu m \) and the air-hole radius \( r = 0.3 \) \( a \). The air-hole diameter and the edge-to-edge spacing between adjacent air-holes correspond to the dimension \( h_L \) and \( h_H \) of the 1-D PCEM model. We chose waveguide width \( w = 0.375 \mu m \) in order to couple with the first PC band.

In order to examine the concept of dispersion-based guiding of resonances in 2-D PCEMs, we approximate the microcavity-bounded PC dispersion surface with the infinitely extended 2-D PC dispersion surface. Figure 4(a) shows the TE-polarized (\( \mathbf{E} \)-field in plane) equi-frequency contours (EFCs) of the first-band dispersion surface of an infinitely extended square PC lattice of air-holes corresponding to the embedded PC lattice shown in Fig. 3. The PC band was calculated by using a commercial PC band solver \([24]\).

Figure 4(b) shows the zoom-in view of the first Brillouin zone. Within a range of \( \mathbf{k} \)-vectors and normalized frequencies (between about 0.16 and about 0.22) near the M point, the EFCs are nearly flat and perpendicular to the \( \Gamma M \) direction. The EFCs gradients (denoted as
blue arrows) indicate that lightwave with \( \mathbf{k} \)-vectors and normalized frequencies within such flat EFCs region have the group velocity \( \mathbf{v}_g \) predominantly pointing towards the \( \Gamma M \) direction, a phenomenon referred to as self-collimation [7]. Because of the wavefront-matching condition for resonances, only modes that have \( \mathbf{k} \)-vectors pointing near the dispersion-guided group velocity directions can be preferentially coupled. We see that the condition of matching the mode \( \mathbf{k} \)-vector direction and the group velocity direction is necessary but not sufficient condition for preferential mode coupling in a waveguide-coupled PCEM. The coupling efficiency also depends on design parameters, namely waveguide width \( w \), the air-gap separation \( g \), and the square cavity sidewall length \( L \). Based on the finite-size effects on 1-D PC [17-21], the square microcavity modes can give rise to discrete steps at resonance frequencies in the microcavity-bounded 2-D PC dispersion surface. Nonetheless, it is still reasonable as an initial analysis to employ the infinite-size PC dispersion surface to gain insights to dispersion-based guiding in 2-D PCEMs, particularly when the lattice dimension is sufficiently large.

3.2 Transmission characteristics

We employed a commercial 2-D FDTD simulation tool [25]. The details of the simulations follow Refs. [15, 16]. We adopted a 15-nm spatial step size (31 computation points per period \( a \)) and a 0.02 fs temporal step. We excited a Gaussian pulse with \( e^{-2} \)-width of 12-fs centered at normalized frequency \( a/\lambda = 0.258 \) (free-space wavelength \( \lambda = 1.8 \mu m \) and bandwidth = 3.6 \( \mu m \)). We assumed a slab waveguide fundamental mode profile at the waveguide input. The spectral resolution was about 0.02 nm – about 0.04 nm limited by computation time. We applied perfectly matched layer (PML) absorbing boundaries (with reflectivity of \( 10^{-8} \)) with a thickness of 0.5 \( \mu m \) in both the x and y-directions surrounding the computation domain. The mode-field distributions were obtained by launching a continuous-wave (CW) at resonance frequencies. Here we focus on analyzing the TE-polarized (E-field in plane) modes.
Fig. 5. (a)-(i) FDTD calculated TE-polarized transmission spectra of the waveguide-coupled 2-D PCEMs with the lattice size $N$ span from 3 to 11. The red dashed line shows the first band-edge frequency $a/\lambda = 0.219$ at the M point. The two highest frequency modes $A_N$ and $B_N$ are labeled.

Figures 5(a) – 5(i) show the FDTD calculated TE-polarized transmission spectra of the waveguide-coupled PCEMs with lattice dimension $N = 3$ to $N = 11$. We observe quasi-periodic high-Q multimodes. All coupled modes are below the band-edge frequency $a/\lambda = 0.219$ (dashed line) at the M-point, and are within the relatively flat EFCs region (between about 0.16 and about 0.22) of the corresponding infinite-size PC first band. The multimode resonance wavelengths blueshift non-linearly and saturate at large $N$. Mode $A_N$ frequency approaches the band-edge frequency. Like 1-D PCEMs, it is intuitive that the finite-size PC band (at off-resonance frequencies) and the band-edge frequency approach those of the infinite-size PC as $N$ increases.
Fig. 6. Q of the resonance modes for $N = 7$ (green square) and $N = 11$ (triangle) as a function of normalized frequency. Group velocity $v_g/c$ along the $\Gamma M$ direction (red square) of the infinite-size PC is also shown. The band-edge frequency ($a/\lambda = 0.219$) at the M-point is denoted as orange dashed line. Inset shows the Q-factor of mode $A_N$ and $B_N$ as a function of $N$.

For each $N$, the Q-factors for the dominant modes increase as the frequencies approach the band-edge frequency. Figure 6 shows the Q-factors of the 2-D PCEM modes for $N = 7$ (green square) and for $N = 11$ (triangle). In both cases the Q-factors increase by orders of magnitude as the resonance frequencies approach the first band-edge frequency at the M-point (dashed line). Such increase in Q can be expected from the drop in the group velocity along the $\Gamma M$ direction (red square), obtained from the infinite-size PC dispersion relation. This suggests that the coupled modes strongly depend on the dispersion relation along the $\Gamma M$ direction. For $N = 11$, there are two relatively high-Q modes ($a/\lambda \approx 0.195$ and $a/\lambda \approx 0.205$) that deviate from the overall trend. These modes probably are not guided exactly along the $\Gamma M$ direction. Inset shows the nearly exponential increase in the Q-factors of modes $A_N$ and $B_N$ as $N$ increases.

4. Mode-field patterns of waveguide-coupled PCEMs

Here we study the steady-state mode-field distributions of 2-D PCEMs. We focused on the two highest frequency modes ($A_N$ and $B_N$) below the band-edge frequency and chose modes $A_7$ and $B_7$ as examples.

Figure 7(a) shows the FDTD calculated mode $A_7$ steady-state electric-field distribution. The field extrema are partially confined within the air-holes. The distribution evolves as a standing wave. Following the analysis of square microcavity modes [12-14], we may label this PCEM mode using a pair of integer mode numbers $(m_x, m_y) = (7, 7)$, where $m_x$ and $m_y$ are integer numbers of field extrema inside the PCEM along the $x$ and $y$ directions. This PCEM mode-field distribution resembles the $(m_x, m_y) = (7, 7)$ mode-field distribution of a bulk square microcavity [13]. The PCEM mode $k$-vector angle (relative to the normal of the waveguide-coupled cavity sidewall) can then be given as $\theta = \tan^{-1} (m_y/m_x) = 45^\circ$, which strongly suggests that mode $A_7$ (or $A_N$ in general) has a $k$-vector along the $\Gamma M$ axis.
Fig. 7 (2515 KB) Electric-field evolution of mode A₇ at $a/\lambda = 0.215$. The Gaussian profile evolves as a standing wave, with the field extrema partially confined at the submicrometer air-hole array. (b) 3-D surface plot of the mode A₇ field intensity. (c) (2586 KB) Electric-field evolution of mode B₇ at $a/\lambda = 0.203$. The two-lobe mode-field pattern circulates in an unexpected anticlockwise direction. (d) 3-D surface plot of the mode B₇ field intensity.

Figure 7 (b) shows the mode A₇ normalized intensity profile at the maximum in a three-dimensional (3-D) surface plot. The profile has an overall Gaussian distribution, with the maximum near the PCEM center hole and the minimum near the cavity sidewalls. We observed a maximum intensity enhancement of about 60 times inside the 279-nm diameter air hole. Intensity enhancement exceeding two orders of magnitude can be obtained for $N = 11$. The orders of magnitude internal field intensity enhancement is largely due to the square microcavity feedback. Only a weak normalized intensity of about 0.15 is obtained at air holes by using the same finite-size PC air-hole array but without the microcavity feedback. This can readily be modeled by replacing three of the microcavity sidewalls with PML absorbing boundaries. We see the PCEM air-hole lattice as an array of low-index nanocavities where light field can be partially confined and enhanced in intensity potentially by orders of magnitude.

Figure 7 (c) shows the FDTD calculated mode B₇ steady-state electric-field distribution. The two-lobe field pattern has field extrema partially confined within the air holes. Surprisingly, the two-lobe field distribution circulates in an anticlockwise direction. The nodal line (along the square microcavity diagonal) has practically zero field intensity and also rotates anticlockwise. Such two-lobe field pattern and circulation have not been observed in waveguide-coupled square microcavities [11-14], and may be intrinsic to waveguide-coupled...
high-index contrast 2-D PCEMs. The mechanism of this unexpected coherent resonance phenomenon should deserve further investigation. Figure 7(d) shows the mode B7 normalized intensity profile at the maximum in a 3-D surface plot. Mode B7 only has about an order-of-magnitude maximum internal-field intensity enhancement in the air-holes.

A major shortcoming of the 2-D FDTD simulation is that issues concerning the vertical dimension, such as the out-of-plane radiation losses, cannot be accounted for. However, it is well-known that modes near the band-edge are typically well below the light cone, as long as the refractive index contrast between the 2-D PC slab and the upper cladding is sufficiently large. In our work, the silicon PC slab is assumed to be air-clad, and thus having a high refractive index contrast (i.e. 3.5:1). Ideally, the mode field is well confined in the PC slab with negligible out-of-plane radiation loss. Similar phenomena can be observed in Ref. [26, 27]. In practice, PCEMs will no doubt suffer from out-of-plane radiation losses, due to scattering from hole-sidewall roughness as well as from non-uniformity of the hole-sidewall.

5. Fourier transform (FT) analysis of mode-field patterns

More quantitatively, we analyze the coupled modes in k-space by means of Fourier transform (FT) of the mode-field distributions. The result can be displayed as FT amplitudes in the first Brillouin zone (BZ). By superimposing the PCEM FT amplitude distributions in k-space onto the EFCs of the corresponding infinite-size PC first band, we show that the coupled modes k-vectors fall on the flat EFCs that are orthogonal to the \( \Gamma M \) direction. We only analyze modes A7 and B7 as examples.

Figure 8(a) shows the FT of mode A7 field distribution (Fig. 7(a)). The FT distribution is overlaid on the EFCs of the PC first band. The Fourier amplitude distributions are concentrated near the four M-points of the first BZ (i.e. \( |k_x| = \pi/a \), \( |k_y| = \pi/a \)). This shows that mode A7 has k-vectors near the \( \Gamma M \) axis. Figure 8(b) shows the zoom-in view of the mode A7 FT peak near the M-point. According to the gradient of the EFCs, mode A7 only has a very low group velocity of about 0.004 \( c \) (\( c \) is the speed of light in free-space) in the \( \Gamma M \) direction. This strongly suggests that mode A7 is dispersion-guided along the \( \Gamma M \) direction. For a larger \( N \), mode A7 FT amplitude distributions are more concentrated near the M-points, suggesting a lower group velocity and thus a higher Q.

![Fig. 8. (a) Fourier transform (FT) pattern of mode A7. The FT pattern is superposed on the EFCs of the PC first band. The Fourier amplitude distributions are concentrated in the vicinity of the M-points. The first BZ is indicated by the dashed lines. The color scale measures the FT amplitude. (b) Zoom-in view of mode A7 FT distribution near the M point. Blue arrows represent the magnitude and direction of the group velocity near the M-point. The EFC normalized frequency is labeled in 0.1 steps.](image-url)
Fig. 9  (a) Fourier transform (FT) of mode B7 field pattern. The FT pattern is superposed on the EFCs of the PC first band. The first BZ is indicated by the dashed lines. The color scale measures the FT amplitude. (b) Zoom-in view of the mode B7 FT distribution near the M point. The Fourier amplitude distributions are concentrated on the flat EFCs near the M-point and near the ΓM axis. Blue arrows represent the magnitude and direction of the group velocity near the M-point. The EFC normalized frequency is labeled in 0.1 steps. The side-lobe can be attributed to the two-lobe modulation in real space.

Figure 9(a) shows the FT of mode B7 field distribution (Fig. 7(b)). The FT distribution is again overlaid on the EFCs of the PC first band. The Fourier components are near the M-points and nearly along the ΓM axis in the 2nd and 4th quadrants of the first BZ. This shows that mode B7 has k-vectors near the ΓM axis. The field distribution in real-space has a diagonally spaced two-lobe modulation in the 2nd and 4th quadrants of the square PCEM (taking the origin at the PCEM center).

Figure 9(b) shows the zoom-in view of the mode B7 FT pattern near the M-point. The dominant Fourier components are in the form of an elliptical pattern along a flat EFC (orthogonal to the ΓM direction) at \( a/λ \approx 0.21 \), which is reasonably consistent with mode B7 frequency (\( a/λ \approx 0.203 \)). According to the gradients of the EFCs in the vicinity of the FT peak counts, the group velocity is about 0.02 \( c \) and points at an angle of about 52° relative to the ΓX direction (or about 7° from the ΓM direction). This suggests that mode B7 is dispersion-guided in the vicinity of the ΓM direction, yet with a possible larger angle mismatch between the mode k-vectors and the group velocities. Contrast with mode A7 (or AN in general), the relatively higher group velocity results in a relatively low Q for mode B7 (or BN in general).

We attribute the side lobes of the main Fourier components to the diagonally oriented two-lobe modulation in real-space. The side lobes are spaced about 0.23π/\( a \) from the main lobes, as shown in Fig. 9(b). The spacing between the two-lobe modulated field peaks in real-space is about 4.24 \( a \) (\( a/0.23 \)), which is in good agreement with the k-space side-lobe separations from the main components.

6. Conclusion and future work

In conclusion, we numerically examined the concept of dispersion-based guiding of resonances in waveguide-coupled planar photonic-crystal embedded-microcavities (PCEMs) by means of 2-D FDTD method. This work focused only on the 2-D PCEMs that comprised a finite-size square PC lattice of submicrometer air holes embedded in a high-index contrast
square microcavity. Like the analysis of finite-size 1-D PCs, our simulations of the 2-D PCEMs showed quasi-periodic high-Q multimodes within the PC first band. The Q can rise by orders of magnitude as the mode frequency approaches the band-edge frequency, consistent with a similar drop in the group velocity obtained from the PC dispersion curve along the $\Gamma M$ direction. The Q can also rise by orders of magnitude as the finite-size PC lattice increases in dimension, consistent with the intuition that the finite-size PC dispersion generally approaches the infinite-size PC dispersion. Our transmission spectra analysis strongly suggests that the coupled modes in 2-D PCEMs are guided by PC dispersion.

In order to further confirm the dispersion guiding mechanism for PCEM resonances, we simulated the steady-state mode-field distributions and analyzed the spatial distributions in Fourier space (k-space) in light of the superposed equi-frequency contours (EFCs) of the PC first band dispersion surface. Our study reveals that the coupled modes k-vectors are near the $\Gamma M$ axis, and are in the vicinity of flat EFCs with gradients (or group velocities) pointing towards the $\Gamma M$ direction. This strongly suggests that PCEM modes can be preferentially coupled only when the dispersion-guided group velocity and the mode k-vector are nearly matched in direction. In the present case, this means wavefront-matched ray orbits near the $\Gamma M$ direction can be preferentially coupled by means of PC dispersion. Currently, we are optimizing the planar waveguide-coupled PCEM designs and fabricating the device structures on silicon-on-insulator (SOI) substrates for experimental verification. Other 2-D PCEM configurations, such as hexagonal PC lattice of air-holes embedded in a high-index contrast hexagonal microcavity [28], is also under study. We envision waveguide-coupled 2-D PCEMs can potentially open up a host of applications utilizing the high-Q resonances and the enhanced field in the air-hole array nanocavities, including ultra-compact photonic filters, biochemical sensors and microfluidic devices.

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