Dispersion-guided and bandgap-guided resonances in semiconductor waveguide-coupled hexagonal photonic-crystal-embedded microcavities

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Abstract: We report dispersion-guided resonances and bandgap-guided resonances in semiconductor waveguide-coupled hexagonal photonic-crystal-embedded microcavities. Our two-dimensional finite-difference time-domain simulations reveal highly efficient coupled high-Q resonances in both types of resonances.

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Waveguiding in photonic crystals (PCs) can be classified into two major types – (1) photonic bandgap (PBG) guiding, and (2) dispersion guiding. Extensive works have long been focused on PBG-based waveguiding and light confinement in defect states. Recently, dispersion-based guiding has also gained substantial interest in phenomena such as self-collimation [1]. In our previous works [2-4], we proposed and analyzed dispersion guiding in planar square PC lattice of submicrometer air-holes in semiconductor square microcavities. We referred to such microstructure devices as *photonic-crystal-embedded microcavities* (PCEMs). Our numerical simulations suggested that semiconductor PCEMs have high-Q resonances that are dispersion guided and can be efficiently side-coupled with submicrometer singlemode waveguides. The dispersion-guided resonances can be efficiently coupled when the dispersion-guided group velocity (energy flow) is nearly parallel with the mode wave vector [4]. In this summary we report semiconductor waveguide-coupled hexagonal PCEMs that comprise triangular lattice of submicrometer air-holes embedded in hexagonal microcavities [5]. Our two-dimensional finite-difference time-domain (FDTD) simulations suggest that efficiently coupled high-Q resonances in hexagonal PCEMs can be either dispersion-guided or PBG-guided.

Figure 1 (a) shows the schematic of a waveguide-coupled hexagonal PCEM. The key design parameters are labeled and detailed in the figure caption. The waveguide width $w = 0.4 \mu\text{m}$ is chosen in order to only couple with modes in the PC first band. Figure 1(b) shows the FDTD-simulated TE-polarized ($\mathbf{E}$ -field in-plane) transmission spectrum of the waveguide-coupled hexagonal PCEM with 7 rows of air-holes in the ΓM direction.

Fig. 1. (a) Schematic of a waveguide-coupled hexagonal PCEM comprised of a triangular lattice of air-holes ($a = 0.465 \mu\text{m}$; $r = 0.3 a$) embedded in a silicon (refractive index $n = 3.5$) hexagonal microcavity. Yellow arrows in the PCEM depict a dispersion-guided three-bounce ray orbit near the ΓK direction. The red-dotted line shows the wavefronts. $L = 2.94 \mu\text{m}$; $m = 0.105 \mu\text{m}$; $w = 0.4 \mu\text{m}$; $g = 0.2 \mu\text{m}$. (b) FDTD-simulated TE-transmission spectrum of the waveguide-coupled hexagonal PCEM. Dashed line indicates the first band-edge frequency at the K-point. (c) Steady-state intensity patterns of modes A.

Fig. 2. (a) Fourier transforms (FTs) of mode A field patterns superimposed with the first band equi-frequency contours. The contour line is spaced in $a/\lambda = 0.05$ interval. Blue dotted lines represent the first Brillouin zone boundary. (b) Zoom-in view of dashed-line region in (a). Blue arrows represent velocity v_g directions.

The PCEM transmission spectrum reveals four pronounced resonance modes in the PC first band frequency range. Mode A frequency is just below the band-edge frequency, with the highest $Q \approx 2,300$ and a high coupling efficiency of ≈ 26 dB. Fig. 1 (c) depicts the simulated steady-state intensity patterns of mode A, with the maxima of intensity located in the air-holes. Mode A has an intensity enhancement of about 36 times at the maxima, evolving as a near standing-wave.

In order to demonstrate that mode A is dispersion guided, we analyze the mode-field pattern by means of spatial Fourier transform (FT) and interpret the FT using the first band equi-frequency contours (EFCs). Fig. 2 (a) shows that mode A have dominant Fourier components located in the vicinity of the K point, and thus the mode wave vectors point near the ΓK direction. Moreover, the overlaid EFCs suggest that mode A has group velocities v_g (EFC gradients) dominant near the ΓK direction (Fig. 2(b)). The nearly matched wave vector direction and the v_g direction thus enable preferential mode coupling with orbits propagating in the ΓK direction - three-bounce orbits in the hexagonal PCEM (see the yellow arrows in Fig. 1(a)).

Waveguide-coupled hexagonal PCEMs also support PBG-guided resonances. Here we demonstrate the PBG-guided resonances by removing the air-hole layer next to the PCEM sidewalls, resulting in a hexagonal ring defect structure as shown in Fig. 3(a). Lightwave propagating in the hexagonal ring defect structure can be partially confined by PBG from the PCEM bulk and by total internal reflection at the flat cavity sidewalls. It is

Fig. 3. (a) Schematic of a waveguide-coupled hexagonal PCEM with a ring defect. $a = 0.465 \mu\text{m}$; $r = 0.35 a$; $L = 2.71 \mu\text{m}$; $m = 0.8 a$; $w = 0.275 \mu\text{m}$; $g = 0.2 \mu\text{m}$. Yellow arrows in the PCEM depict whispering-gallery-like resonance ray orbits. (b) Projected band structure along the ΓK direction of a waveguide-coupled truncated PC structure. Inset shows the unit-cell used in the calculation. The structural parameters i.e. r/a , w , g and m , are as same as that depicted in (a). The light gray area represents the modes in the PC first band. Red-dotted curve and the blue-dotted curve represent the defect mode and the waveguide mode, respectively. The dark gray area represents the radiation modes above the light line.

expected that lightwave coupled to the ring defect propagates in both forward and backward direction due to the Bragg scattering by the PCEM bulk (see the yellow arrows in Fig. 3(a)). We optimized the design by using $r/a = 0.35$ and $m = 0.8 a$. The waveguide width is chosen at $w = 0.275 \mu\text{m}$.

In order to demonstrate the PBG-guiding, we first employed the plane-wave expansion method to calculate the projected band structure along the ΓK direction of a waveguide-coupled truncated triangular PC lattice, as shown in Fig. 3(b). Inset depicts a schematic of the unit-cell. A narrow gap near $a/\lambda = 0.23$ is originated from the coupling between the defect mode (red curve) and the waveguide mode (blue curve).

Figure 4 (a) shows the FDTD-simulated TE-polarized transmission spectrum. Two resonances E_1 and E_2 are coupled with a high coupling efficiency of about 27 dB with Q of ≈ 500 . Figures 4 (b) and 4 (c) show the whispering-gallery (WG)-like intensity patterns of modes E_1 and E_2 , evolving as the standing-waves with an integer number of a wavelength in one round trip. Hence, the wavefront-matching condition upon traveling each cavity round trip is satisfied in this case in order to build up the resonances. Note that both modes attain about 20 times internal intensity enhancement.

Fig. 4. (a) FDTD-simulated TE-transmission spectra of the hexagonal PCEM with a ring defect. The steady-state intensity patterns of the surface mode (b) E_1 , (c) E_2 .

In summary, we analyzed dispersion-guided resonances and PBG-guided resonances in waveguide-coupled semiconductor hexagonal PCEMs. In the dispersion-guided regime, resonance lightwave group velocities are guided near the ΓK direction, enabling preferentially coupling with three-bounce ray orbits guided near along the ΓK direction. In the PBG-guided regime, resonance lightwave are bandgap guided along the hexagonal rim region as a ring defect. We demonstrated highly efficient coupled high- Q resonances with each type of resonances. At present, we are fabricating the waveguide-coupled hexagonal PCEM devices on thin-film silicon-on-insulator substrates for experimental verification.

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