Design of high-Q photonic crystal optical cavities through Fourier space methods

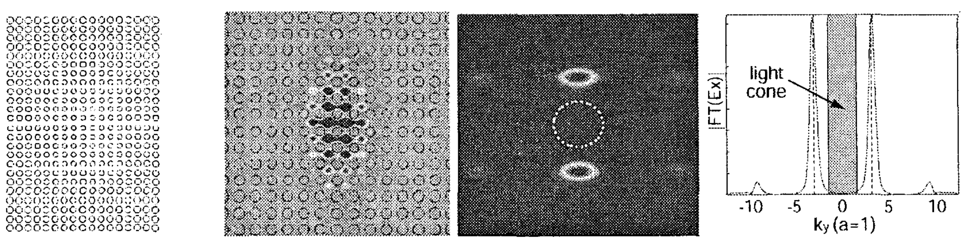
Kartik Srinivasan, Paul E. Barclay, and Oskar Painter
Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.
phone: (626) 395-6269, fax: (626) 795-7258, e-mail: kartik@caltech.edu

Abstract: By describing radiation losses through a Fourier space picture of modal couplings, low loss photonic crystal cavities are designed using a group theory-based analysis and finite-difference time-domain calculations, resulting in predicted quality factors exceeding 10^5.

OCIS codes: (230.5750) Resonators; (140.5960) Semiconductor Lasers

Photonic crystal (PC) defect cavities [1, 2] are promising elements for a number of devices and experiments in the optical sciences, including low threshold semiconductor lasers and resonators for probing coherent electron-photon interactions. These applications take advantage of the cavities' wavelength-scale size, but also require them to have minimal radiation losses, with a quality factor (Q) of 10^4 or 10^5. We consider the design of these cavities in Fourier space, developing a set of simple rules for obtaining high-Q modes, and use a finite-difference time-domain (FDTD) analysis to demonstrate the efficacy of these methods [3]. In addition, efficient fiber-based methods for coupling light into and out of these planar PC cavities are discussed.

Defect modes in two-dimensional PC slab waveguides have in-plane losses that are determined by the size and angular extent of the photonic bandgap in momentum space, while vertical radiation losses result when the mode's in-plane momentum components are insufficient to support waveguiding, and lie within the light cone of the waveguide cladding. To reduce the presence of these small momentum components, we seek modes that are odd about mirror planes normal to the direction of the mode's dominant Fourier components, eliminating the DC ($\mathbf{k}_\perp = \mathbf{0}$) part of the field. Modes of the appropriate symmetry are determined by a group-theory based analysis, which gives approximate forms for donor and acceptor modes localized to defects at various high symmetry points within hexagonal and square lattice PC's.

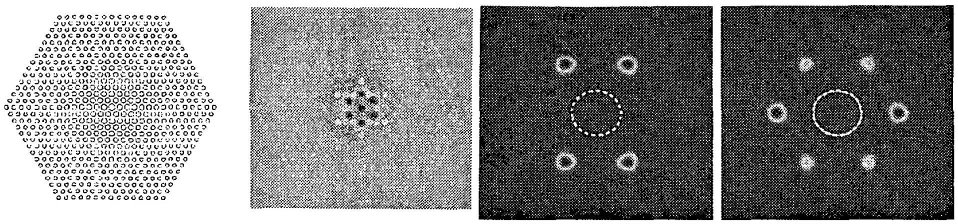


(a) Lattice (b) $|\mathbf{B}|$ (c) $|\widetilde{\mathbf{E}}_x|$ (d) $|\widetilde{\mathbf{E}}_x|$ along k_y axis.

Fig. 1. Graded square lattice and its field characteristics.

FDTD simulations show improved Q factors for defect modes of this prescribed symmetry. Further improvements to both the in-plane and vertical Q's are achieved by considering a Fourier space picture of modal couplings that lead to loss. The analysis is essentially a two-step process, where we start with an approximate form for the defect mode, based on its dominant Fourier components as determined by the group theory analysis. We then consider couplings between this mode and "leaky cavity modes", which consist of vertical radiation modes and PC slab modes that radiate in-plane. The coupling amplitude between these modes is calculated, and indicates that the quantity $\widetilde{\Delta\eta}(\mathbf{k}_\perp)$, the Fourier transformed perturbation to the photonic lattice ($\eta = 1/\epsilon$) due to the defect, couples Fourier components between the basis modes of the system. Thus, by appropriately modifying the lattice to tailor this quantity, we reduce couplings that lead to in-plane and vertical leakage. Doing so results in the square lattice design shown in Figure 1(a). Figure

1(b)-(d) shows the magnetic field amplitude and Fourier transformed dominant electric field component for this mode, indicating the degree to which power has been removed from the cladding light cone. $Q_{\perp} \approx 1.3 * 10^5$ for this design, with $Q_{tot} \approx 9.8 * 10^4$. The design rules described above have also been applied to hexagonal lattice PC's, with FDTD-determined Q values exceeding 10^5. Representative geometries and field patterns for such designs are shown in Figure 2(a)-(d).



(a) Lattice (b) $|\mathbf{B}|$ (c) $|\widetilde{\mathbf{E}}_x|$ (d) $|\widetilde{\mathbf{E}}_y|$

Fig. 2. Graded hexagonal lattice and its field characteristics.

We will present an outline of our momentum space design of high-Q defect cavities in square and hexagonal photonic lattices, concentrating on the methodology behind the symmetry-based analysis for producing approximate forms of the defect modes, and the Fourier space picture of modal coupling used to tailor the cavity geometry. We will also discuss efficient coupling of the cavities with PC waveguide designs, and consider schemes by which cavity-waveguide systems can be passively probed with tapered optical fibers. FDTD simulation results for square and hexagonal lattice designs will be presented, along with our recent progress in the fabrication and characterization of these devices.

References

1. S. Noda, A. Chutinan, and M. Imada, "Trapping and emission of photons by a single defect in a photonic bandgap structure," Nature **407**, 608–610 (2000).
2. S. G. Johnson, S. Fan, A. Mekis, and J. D. Joannopoulos, "Multipole-cancellation mechanism for high-Q cavities in the absence of a complete photonic band gap," Appl. Phys. Lett. **78**, 3388–3390 (2001).
3. K. Srinivasan and O. Painter, "Momentum space design of high-Q photonic crystal optical cavities," Opt. Express **10**, 670–684 (2002).