Optical fiber-based measurement of ultra-small mode volume and a high quality factor in a photonic crystal microcavity

Kartik Srinivasan, Paul E. Barclay, Matthew Borselli, 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: Using an optical fiber taper that simultaneously probes the spectral and spatial properties of resonant cavity modes, two-dimensional Si photonic crystal microcavities with a quality factor Q 40,000 and modal volume V_{eff} $0.9(\lambda/n)^3$ are experimentally demonstrated.

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One important application of an optical microcavity is in cavity quantum electrodynamics (cQED)[1] where strongly coupled atom-photon systems have been proposed for use in quantum computing[2]. Here, we report a semiconductor-based photonic crystal (PC) microcavity[3] that simultaneously exhibits a quality factor (Q) 40,000 and an in-plane localization consistent with a modal volume V_{eff} $0.9(\lambda/n)^3$, values that could enable chip-based strong coupling[4] to both atomic (cesium) and InAs quantum dot systems. These PC microcavities are studied using a novel optical fiber-based measurement that characterizes their spatial and spectral properties.

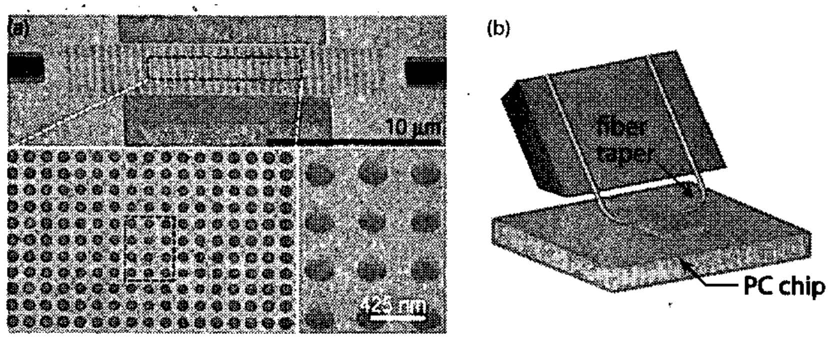

Fig. 1. (a) Scanning electron microscope micrographs of a fully fabricated PC microcavity. (a) Cross-sectional, top, and angled views of the cavity. Total cavity dimensions are $\sim 13\mu m$ x $16\mu m$. (b) Schematic illustrating the fiber taper probe measurement setup.

Microcavities are fabricated in silicon-on-insulator wafers (Figure 1(a)) and consist of a graded square lattice of air holes in a high-index slab waveguide[5]. They are probed by a single-mode optical fiber that has been tapered to a diameter of 1 μm, producing an evanescent field in the surrounding air that can be used as a near-field excitation source (as previously reported for microsphere whispering-gallery-mode excitation[6]). The taper is mounted above and parallel to an array of PC microcavities (Fig. 1(b)), and when brought close (1 μm) to the cavity, is used to *both* source and out-couple the cavity modes. The wavelength-dependent transmission through the taper when it is positioned 500 nm over a cavity is given in Fig. 2(a), and shows a number of resonances. By studying spectral shifts in their positions between devices with a varying average hole radius, we identify the mode of interest (labeled A_2^0), the fundamental resonance within the in-plane bandgap.

A wavelength scan of the taper transmission for the A_2^0 mode in a device with a=425 nm is given in Fig. 2(b) (inset), and a linewidth γ 0.047 nm is measured. This linewidth is a *maximum* estimate for the cold-cavity linewidth γ_0, due to loading effects of the taper. Reducing these loading effects by increasing the taper-cavity separation (Fig. 2(b)) gives an asymptotic value of γ_0=0.041 nm, corresponding to a cold-cavity Q 39,500. Three-dimensional finite-difference time-domain simulations for this cavity predict Q 56,000 and a/λ_c 0.266 (consistent with the measurements), and predict $V_{\mathrm{eff}} = 0.88(\lambda_c/n)^3$.

The same taper used to source the cavity modes is used as a near-field probe to map their in-plane spatial localization, by measuring the strength of coupling as a function of lateral taper displacement (microsphere studies[7] have used a related method where a second probe, different from the excitation source, was used to map the spatial profiles). For the taper aligned along the long ($\hat{y}$) and short ($\hat{x}$) axes of the cavity, the depth of the resonant dip for the desired

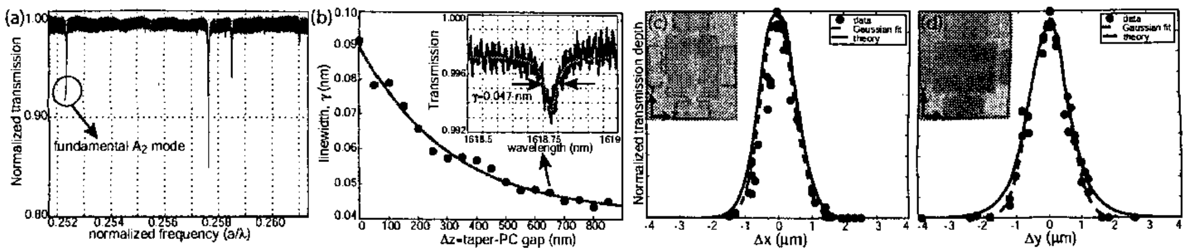

Fig. 2. (a) Normalized taper transmission for a cavity with lattice spacing a=409 nm, highlighting the mode of interest. (b) Measured linewidth (blue dots) vs. taper-PC gap for the mode of interest in a sample with a=425 nm. The red curve is a fit to the experimental data. (Inset) Normalized taper transmission for this device when the taper-PC gap is 650 nm (c) Measured normalized taper transmission (dots) as a function of taper displacement along the (c) $\hat{x}$ and (d) $\hat{y}$ axes of the cavity. The dashed lines are Gaussian fits to the data and the solid lines are numerically calculated coupling curves based on the FDTD-generated cavity field and analytically determined fiber taper field. The insets in (c)-(d) are optical micrographs of the taper aligned along the y and x axes of the cavity, respectively. The cavity is the central reddish-brown rectangular region.

cavity mode versus taper displacement is shown in Fig. 2(c)-(d), respectively. Calculations based upon a simple picture of the taper-PC cavity coupling are performed (solid lines in Fig. 2(c)-(d)), and are consistent with the experimental data. From these measurements, it is confirmed that the mode of interest is indeed both high-Q and small V_{eff}.

In addition to applications in strongly-coupled systems in cQED, these semiconductor-based microcavities have potential for enhanced light-emitters (an extremely high maximum Purcell factor of 3500 is predicted from the measured Q and V_{eff}), single-photon sources, and microcavity-enhanced devices in nonlinear optics and sensing.

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