Quantum Dot Photonic Crystal Nanocavities: Transition from Weak to Strong Coupling and Nonlinear Emissions

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Abstract: Photonic crystal slab nanocavities containing one layer of quantum dots have exhibited: strong coupling to a single quantum dot; tuning by condensation of xenon gas; linewidth broadening due to ensemble dot absorption; gain and lasing.

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Over a year ago, vacuum Rabi splitting was achieved between an InAs single quantum dot and a photonic crystal slab nanocavity [1]. Since then we have observed such anticrossings in many different nanocavities, and nonlinear emission experiments have been performed with nonresonant excitation and begun with resonant excitation.

We report tuning such a nanocavity by as much as 5 nm by the condensation of Xe gas onto the slab and into the photonic crystal holes [2]. Compared with temperature scanning, it has an eight times larger scan range and avoids phonon broadening. This new method is a great improvement in the search for the two accidental coincidences (dot spatially in a field antinode with a spectral transition frequency degenerate with the cavity mode) essential for cavity QED and strong coupling experiments. Fig. 1 displays two anticrossings with two different quantum dots in the same nanocavity.

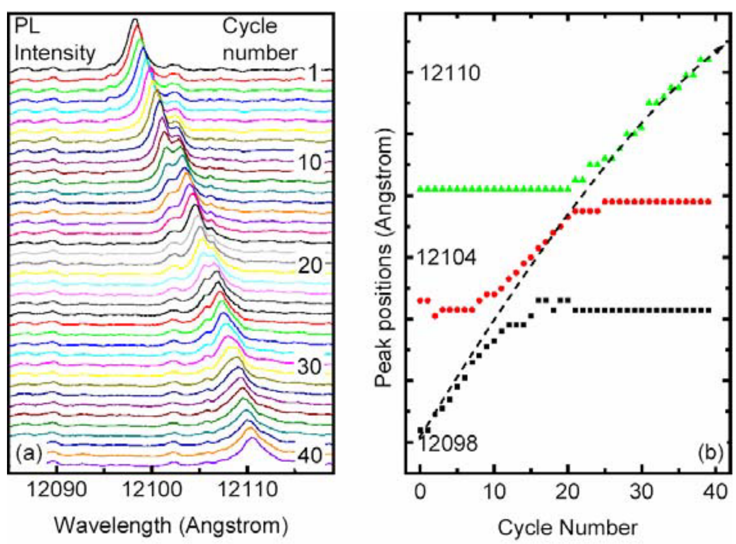

Fig. 1. Strong coupling anti-crossings using Xe condensation to scan. (a) PL spectra at 25 K with low-power (1.2 µW; 10 s exposure time) cw excitation at 770 nm as a function of detuning controlled by condensing Xe in increments of 0.46 torr each cycle. (b) Peak positions in the spectra versus cycle number. Two anti-crossings (the signature of vacuum Rabi splitting strong coupling) occur between the nanocavity mode and two distinct single quantum dots. The dashed line shows the positions of the cavity peak for high-power (125 mW; 0.2 s exposure time) excitation.

Emission linewidths of quantum dot (QD) photonic-crystal-slab nanocavities are measured as a function of temperature and fabrication parameters with low- and high-power, cw and pulsed, nonresonant excitation [3]. The cavity linewidth is dominated by the absorption of the ensemble of QDs having a density of $\cong 400/\mu m^2$; above the absorption edge the cavity linewidth broadens considerably compared with the empty cavity linewidth as shown in Fig. 2(b&c). Such a high QD density was necessary to have any hope of finding the two accidental coincidences. The greater scan range provided by xenon condensation should permit the dot density to be lowered by a factor of four or five in future experiments, thereby reducing the ensemble absorption and cavity linewidth.

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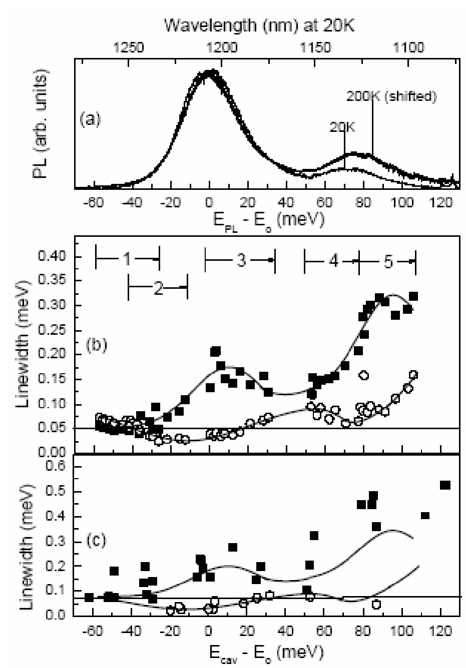

Fig. 2 Quantum dot emission spectra and cavity linewidths. (a) Ensemble QD emission spectra at 20 and 200 K versus energy relative to the ensemble QD ground state transition peak E_o. (b) Nanocavity FWHM linewidth for several temperatures between 20 and 200 K versus the detuning of the nanocavity mode peak from the ensemble QD ground state transition peak. The solid squares are for low-power (2-10 μW) cw excitation, and the open circles are for high-power (720 μW) cw. Five nanocavities were selected that cover the energies of the QD ground and first excited state transitions, with the detuning increasing with temperature. All five were from the same fabrication run and have the same ratios (hole radius)/(hole separation) and (spacer end hole shift)/(hole separation). The low-power linewidths follow the expected ensemble QD absorption spectrum. The high-power linewidth drops below the empty-cavity straight line, indicating the presence of gain. (c) Nanocavity FWHM linewidth for low temperatures around 20 K versus detuning. The nanocavities were selected from two different fabrication runs and have a wider range of lattice constants, radii, shifts, and dosing values than those in (b). Solid squares: 2-20 μW cw; open circles: 1 mW diode-laser peak power. The solid curves are the same ones in (b) with a slight shift upward to take account of the higher average empty-cavity linewidth. The behavior of the linewidth is clearly similar to that in (b).

Gain (Fig. 2(b&c)) and lasing are seen for high-power pumping; it is estimated that only a small number of quantum dots contribute to the lasing. The QD's in our sample are identical to those in the first quantum dot photonic crystal laser and have the same density in each layer [4]. They concluded that only 80 dots contributed to lasing. Since their sample had five layers of dots and ours has only one, we conclude that no more than 16 quantum dots contribute to the lasing here.

Although strong coupling and vacuum Rabi splitting have been used interchangeably in this summary, it has not yet been shown that any of the QDs used in the three single QD vacuum Rabi splitting experiments is small enough for the QD-nanocavity coupled system to exhibit true strong coupling signatures such as evidence for higher rungs of the Jaynes-Cummings ladder [5]. Another way to express the problem is to note that the Jaynes-Cummings ladder is true only for a two-level system, so the question remains: can a real QD adequately approximate such a two-level system?

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References:

[1] T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, and D. G. Deppe, "Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity," Nature **432**, 200–203 (2004).

[2] S. Mosor, J. Hendrickson, B. C. Richards, J. Sweet, G. Khitrova, H. M. Gibbs, T. Yoshie, A. Scherer, O. B. Shchekin, and D. G. Deppe, "Scanning a photonic crystal slab nanocavity by condensation of xenon," Appl. Phys. Lett. **87**, 141105 (2005).

[3] J. Hendrickson, B. C. Richards, J. Sweet, S. Mosor, C. Christenson, D. Lam, G. Khitrova, H. M. Gibbs, T. Yoshie, A. Scherer, O. B. Shchekin, and D. G. Deppe., "Quantum dot photonic-crystal-slab nanocavities: quality factors and lasing," Phys. Rev. B **72**, 193303 (2005).

[4] T. Yoshie, O. B. Shchekin, H. Chen, D. G. Deppe, and A. Scherer, "Quantum dot photonic crystal lasers," Electron. Lett. **38**, 967–968 (2002).

[5] G. Khitrova, H. M. Gibbs, M. Kira, S. W. Koch, and A. Scherer, "Vacuum Rabi splitting in semiconductors," review submitted to Nature Physics.