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Multimodal strong coupling of photonic crystal cavities of dissimilar size

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A photonic crystal three missing holes nanocavity, having only a few modes, is coupled to a 60 missing holes long multimode cavity, both fabricated in the same InGaAsP membrane. The coupling was studied in detail by the photothermal tuning of the small cavity over about three free spectral ranges of the large cavity. Strong coupling effects, involving at least three large cavity modes simultaneously, were observed from level anticrossing data. The observations are excellently reproduced by a model of coupled Fabry Perot resonators. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3688301]

Interacting optical resonators have been intensively studied both because of their fundamental interest and because of their applications. In recent years, much work has appeared on coupled photonic crystal (PhC) cavities since they present the smallest possible dielectric optical resonators that can be made, imposed by the diffraction limit. They are expected to find application as building blocks of lasers or delay lines in future integrated photonic circuits or in on-chip quantum optical devices. The majority of these works deals with the coupling between identical cavities in two-dimensional arrays, line arrays, or in photonic molecules consisting of only two cavities. Coupling between non-identical cavities was already studied in very early work, albeit in poorly defined cavities. More recently, the coupling between different modes existing in identical cavities was reported. Also, an extended local defect has been described in terms of a coupled set of three or five small resonators. In the present paper we report the coupling between PhC cavities that differ by a factor of 20 in size. Unambiguous evidence for the coupling of a single mode from the small cavity with multiple closely spaced modes of the large cavity is obtained from level anticrossing behaviour when the small cavity frequency was tuned.

The cavities were made in a 220 nm thick InGaAsP membrane hexagonal photonic crystal with a layer of InAs Quantum Dots (QDs) in the center to generate photoluminescence (PL) near a wavelength of 1.5 μm (see Fig. 1(a)). The small cavity, designated as L3, consists of three missing air holes, with the end holes modified in size and/or position. The large cavity (“L60”) consists of 60 missing air holes. The two cavities are separated by 2, 3, or 4 (rows of) holes, in the shoulder coupling configuration, where both cavities are oriented under 60°. There are L3 cavities at each end of the L60, but for the present work one can be ignored since it is tuned out of resonance. Both cavities can be thought of as being derived from an infinitely long waveguide consisting of a one missing row of air holes, known as W1 waveguide. The dispersion relations of the two lowest W1 waveguide modes (“even” and “odd”) are shown in Fig. 1(b).

The cavity spectra, both for the case of isolated and coupled cavities, were obtained from micro PL. A 660 nm excitation source is focused at the L3 cavity by a microscope objective with numerical aperture 0.5. The PL light is

![Image](http://example.com/image.png)

FIG. 1. (Color online) (a) Scanning electron microscope image of the coupled cavities device. The light-shaded areas designate the excitation spot (circle) and a position for the SNOM probe (triangle). Insets show an expanded view of L3 with 2-hole barrier and sketches of 3- and 4-hole barriers. (b) Part of the band diagram of the photonic crystal with a one row of missing holes waveguide, showing the dispersion relation of the even and odd parity mode of the W1 waveguide. Lattice constant a = 425 nm; hole radius r = 0.3a; membrane thickness t = 220 nm. (c) Photoluminescence (PL) spectrum of a typical (isolated) L3 cavity (a = 445 nm; r/a ≈ 0.3). The end-holes have a reduced radius r’ ≈ 0.22a, their positions are not shifted; the inset shows the intensity distribution of mode M1 at midplane (Ref. 22). (d) PL spectrum of a typical (isolated) L60 cavity (a = 425 nm; r/a ≈ 0.3). The structure near 1550 nm corresponds to the bulk PhC dielectric band edge. The cavities for (c) and (d) were separately fabricated on a different part of the same chip as the coupled cavities. For (c) the excitation and collection were both done with the microscope objective, focused on the L3 cavity center. For (d), the excitation laser spot was focused by the objective near the end of the L60 cavity, while the collection was done with the SNOM probe, positioned along the L60 cavity, close (∼ few microns) to the excitation spot.

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collected either from the same location through the same objective or at a second independent location by the tip of a scanning nearfield optical microscope (SNOM). The PL from L3 is always collected through the same objective as used for the excitation. A typical L3 cavity spectrum is shown in Fig. 1(c).\textsuperscript{22} Here we will be concerned with the lowest order mode M1. The spectrum of the L60 cavity was obtained from the SNOM probe, positioned along the W1 waveguide, but close to the excitation spot. Its multimode spectrum in Fig. 1(d) consists of Fabry Perot modes of the closed section of the W1 waveguide. The modes are non-equidistant due to the strong dispersion of the W1 mode and not resolved in Fig. 1(d) near cut off, corresponding to the waveguide flat dispersion edge. The structure at shorter wavelength, which is also present in the L3 spectrum (\textasciitilde“M4”), corresponds to a transverse resonance of the W1 waveguide. Actually we will work only in the wavelength region between the M1 and M2 resonance of the L3, so that we deal with a neat L60 Fabry Perot spectrum, which derives completely from the even mode W1 dispersion. The L60 cavity volume is largely unpumped except at its end. Due to the presence of the QDs it is absorbing, which is, at least partially, responsible for the relatively broad resonance lines.

Fig. 2(a) shows the spectrum collected from the L3 cavity location, in a spectral range around mode M1 of the isolated cavity, separated from the L60 by 4 barrier holes (see inset Fig. 1(a), for different excitation laser powers. No influence of the L60 can be seen, and actually the complete spectrum is very similar to that of an isolated cavity (Fig. 1(c)). The absence of the L60 spectra shows that in this configuration, we are not sensitive to the L60 cavity, although this might also be pumped by the large pumping spot (estimated \textasciitilde3 \textmu m in diameter). With increasing laser power, the peak is redshifted over a range which typically may correspond to more than two free spectral ranges (FSR) of the L60 cavity (FSR \textasciitilde 3 nm). The tuning is due to the temperature increase of the semiconductor from the laser absorption and the temperature dependence of the refractive index. The heating is very local and decays within microns from the hot spot. It was verified that the tuning of the L60 peaks under this condition was at least an order of magnitude less than the tuning of the M1. The selective local heating was confirmed by a numerical calculation of the temperature profile using the geometry and thermal conductivities corresponding to the experiment. This selective photothermal tuning effect has been exploited before.\textsuperscript{4,10} The laser power was adjusted to obtain the required tuning in each experiment, as determined by the peak shifts. The maximum power delivered to the sample was estimated to be in the order of 10–100 \textmu W. The power was not calibrated and may vary between experiments. The arbitrary units given for different data should not be intercompared. The signal is not proportional to the power since the PL intensity depends on power and because the QD efficiency decreases with temperature.

When the L3–L60 separation is reduced to a 3-hole barrier, the changes are still not large. However, when the L3 is very finely tuned, a small, but clear peak splitting is observed in a narrow wavelength interval, as seen in Fig. 2(b). As will become clear from the following, this splitting is due to level anticrossing when the tuning power is such that the L3 resonance would become degenerate with one of the L60 cavity resonances.

As shown in Fig. 2(c), the spectrum as observed at the L3 cavity site strikingly changes when it is separated from the L60 by only a 2-hole barrier (see inset Fig. 1(a)). A multiplet of three to four peaks is now observed, attributed to strong coupling with the L60 resonances. Conversely, the L60 resonances are also perturbed in the vicinity of the L3 resonance wavelength, as seen in the L60 spectrum of Fig. 2(d) (actually from another device than Fig. 2(c)). The spectrum was taken at the edge opposite to the position of the excitation spot, which partially explains why the spectrum near the long-wavelength cut-off is more smeared out than in Fig. 1(d). Note that the L60 resonance positions are hardly affected by the tuning. Due to the closely spaced resonances, as well as due to the complication that the L60 has one “hot end” with associated modified dispersion relation, we will not use the L60 spectra for further analysis. It should be emphasized again that the L60 spectrum is not visible in Fig. 2(c), other than by mixing up with the L3 resonance. It confirms that we very locally probe the resonant mode intensity at the location of the L3. Consequently, the resonances in Fig. 2(c) correspond to supermodes with appreciable intensities in both the short and long cavities.

To prove that the splitting in Fig. 2(c) is due to strong coupling, we have superimposed the L3 spectra from another device for different detunings in Fig. 3(a). The prominent presence of deep minima in the superimposed spectra is a consequence of the avoided crossings of the L3 resonances with the L60 resonances. Another, more familiar way of showing the same effect is by plotting all peak positions of the L3 resonances as a function of the tuning parameter,
was modeled as a set of coupled plane-parallel Fabry-Perot cavities, with vanishing intensity at the mirrors to be real. To correspond to the experiments, the length of the small cavity was assumed to be constant, while the length of the large cavity was taken as nearly 200 μm. A partially transparent mirror was inserted in between, simulating a large cavity by a 2-hole barrier when it is photothermally tuned (lattice spacing 445 nm; hole radius 0.28 μm).

The resulting frequencies of the coupled system are displayed in Fig. 4(b). The unperturbed frequencies of the long cavity resonances of (a), as a function of excitation laser power. The thin solid lines are guides for the eye, but roughly correspond to the fixed L60 resonances and tuned L3 resonances for uncoupled cavities.

To support the interpretation of the data, the PhC device was modeled as a set of coupled plane-parallel Fabry-Perot resonators, shown in Fig. 4(a). The two end mirrors $M_1$ and $M_2$ are assumed to have arbitrary large reflectivity. A partially transparent mirror $M_3$, inserted in between, simulates a coupled cavity system consisting of the $M_1$-$M_3$ and $M_3$-$M_2$ Fabry-Perot cavities. The resonances of this coupled system were determined by calculating the transmission spectrum of the system with the transfer matrices method.\(^\text{23}\) The spectra were calculated as a function of the coupling strength between the cavities, which is determined by the amplitude reflectivity $r_3$ of mirror $M_3$. Mirror $M_3$ was assumed to be lossless, implemented by taking $r_3^2 + t_3^2 = 1$, where $t_3$ is the amplitude transmissivity of $M_3$. Both $t_3$ and $r_3$ were assumed to be real. To correspond to the experiments, the length $L_2$ of the $M_1$-$M_3$ cavity was taken as nearly $20 \times L_1$, where $L_1$ is the length of the $M_1$-$M_3$ cavity. The refractive index of the large cavity was assumed to be constant, $n_{ave}$, while the refractive index $n_1$ of the small cavity was varied around $n_{ave}$ to tune it over a few Free Spectral Ranges of the long cavity. The resulting frequencies of the coupled system are displayed in Fig. 4(b). The unperturbed frequencies of the long cavity are given by the horizontal lines, the unperturbed frequency of the short cavity by the sloped straight line. The value of $r_3$ was adjusted to qualitatively resemble the experimental traces of Fig. 3(b), yielding a value of $r_3$ $\approx$ 0.8, or a power reflectivity of $\approx$0.6.

The multiplet of peaks as displayed in Fig. 2(c), together with the pronounced level anticrossing behaviour displayed in Fig. 3(b), along with the confirmation of the interpretation of Fig. 4(b), convincingly proves the strong coupling between the cavities. The coupling strength is usually expressed as the frequency splitting at the anticrossing condition (vertical arrows in Fig. 4(b)). From Fig. 3(b), it follows that it is comparable to the mode separation of the large cavity. It is easily found from the Fabry-Perot model that this is the maximum splitting that can be obtained. From Fig. 3(b), it can be seen that the single level of the small cavity couples strongly to two levels of the large cavity simultaneously, meaning three peaks are seen simultaneously. The fourth simultaneously visible peak, meaning coupling to three modes, is just absent in Fig. 3, but was regularly observed in other data (e.g., Fig. 2(c)). The present observations are distinctly different from previous coupled cavity experiments that only involve one resonance per cavity, usually from photonic molecules build from identical cavities. Our experimental results should also be distinguished from the multiplet resonances that result from the coupling of a large number of identical cavities.\(^\text{3,9,24}\)

In conclusion, we have experimentally demonstrated the simultaneous strong coupling of a single mode from a small PhC cavity with at least three modes of a large PhC cavity. The coupling was inferred from level anticrossing data by photothermal tuning of the small cavity over several resonance frequency intervals of the large cavity. Apart from any direct applications, the device is a convenient model system for studying the hybridization of states of coupled dissimilar objects.

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FIG. 3. (Color online) (a) Superimposed spectra of an L3 cavity, as coupled to the L60 cavity by a 2-hole barrier when it is photothermally tuned (lattice parameter $a = 445$ nm; hole radius $r = 0.3a$; reduced hole radius $r' \approx 0.22a$). (b) Resonant peak positions of the L3 cavity resonances of (a), as a function of excitation laser power. The thin solid lines are guides for the eye, but roughly correspond to the fixed L60 resonances and tuned L3 resonances for uncoupled cavities.

FIG. 4. (Color online) (a) Schematic of the coupled Fabry-Perot cavities. (b) Calculated positions of the transmission peaks of the coupled system of (a) as a function of the normalized refractive index $n_1$ of the small cavity. Normalized units $\lambda/2n_{ave}L_1$, where $n_{ave}$ is the average refractive index, assumed constant in the large cavity with length $L_2 = 20L_1$, $r_1$, $t_1$ are the amplitude reflectivities and transmissivities of the mirrors $M_1$, $M_2$, $M_3$. $n_{ave}$ is the average refractive index of the small cavity. Normalized units $\lambda/2n_{ave}L_1$, where $n_{ave}$ is the average refractive index, assumed constant in the large cavity with length $L_2 = 20L_1$, $r_1$, $t_1$ are the amplitude reflectivities and transmissivities of the mirrors $M_1$, $M_2$, $M_3$.