Strong coupling of multimoded photonic crystal cavities of dissimilar size

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A photonic crystal L3 nanocavity, consisting of only three missing neighboring holes, is coupled to a large multimode 60 missing holes cavity, both made in an 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. A single mode from the L3 cavity is shown to couple simultaneously to at least three cavity modes of the large cavity as concluded from level anticrossing data when the small cavity was tuned. The observations are excellently reproduced by a model of coupled Fabry Perot resonators.

Introduction

Photonic crystal (PhC) cavities play an important role in enabling the miniaturization of optical devices since light can be confined in a small mode volume with an ultra-high quality (Q) factor [1]. Many applications make use of the coupling between two or more PhC cavities when brought in a close proximity. Almost exclusively the coupling between identical cavities is considered, which is designated as a homoatomic photonic molecule. Little attention exists for the coupling between dissimilar cavities, designated as a heteroatomic photonic molecule. Coupling is expected generally when the mode of a resonator spectrally matches and spatially overlaps with the mode of the neighboring resonator. The interaction gives rise to mode hybridization which results in supermodes that belong to both cavities and leads to an associated frequency splitting of the original frequencies. Coupling between two cavities of different type has been studied before, in somewhat poorly characterized cavities [2]. The coupling between different modes existent in identical cavities has also been reported recently [3].

In this contribution, we report the coupling between PhC cavities that differ by a factor of 20 in size. The coupling is demonstrated from the level anticrossing behaviour when the small cavity is locally tuned by heating with a focussed laser spot. The coupling of a single mode from the small cavity with multiple closely spaced modes of the large cavity is unambiguously observed.

Experimental Methods

A hexagonal array of holes with a radius-to-lattice spacing ratio of 0.3 defined the photonic crystal, which was fabricated in a 220 nm thick InGaAsP membrane. The lattice spacing is 445 nm. The membrane contains a single layer of self-assembled InAs Quantum Dots (QD's, density 3×10^{10} cm^{-2}/layer) that serves as an internal light source in a microphotoluminescence (micro-PL) configuration. Details regarding the fabrication process can be found in Ref. 4. Fig. 1 shows a Scanning Electron Microscope (SEM) image of a fabricated device with a so called shoulder coupling configuration. It contains a cavity consisting of three omitted holes, known as L3 cavity. Two end holes of the L3 cavity are modified by reducing their radii to 0.22a and shifting them 0.22a outward. For the other cavity a row of 60 holes is omitted and consequently designated as L60 cavity. A single row of omitted holes is often used as a

PhC waveguide known as W1, so the L60 may be considered as a finite length waveguide that accomodates only some of the waveguide modes that reflect at the end mirrors. It thus forms a cavity in an analogous way as a free-space plane parallel Fabry Perot (FP) cavity. The coupling between the cavities is determined by the number of holes separating the cavities and is taken as 2, 3 or 4 in order to vary the coupling strength. It is 3 in Fig. 1.

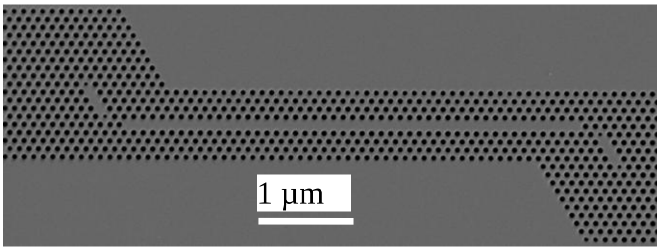

Fig. 1. SEM image top view of the coupled cavities system.

Room temperature PL experiments are performed to characterize the cavities. A power tunable continuous wave diode laser (λ = 660 nm) excites the QDs through a 50x microscope objective (NA=0.5). The excitation spot has a diameter of 3 µm and is focussed at the location of the L3 cavity. The collected signal then is dispersed in a 50 cm focal length monochromator and detected by a liquid nitrogen cooled InGaAs array. The luminescence is collected either at the same location through the same objective, or collected at an independent position by the tip of a Scanning Near Field Optical Microscope (SNOM). By varying the excitation power of the laser, the temperature of the L3 cavity can be varied. Through the temperature dependence of the refractive index the cavity can be tuned in this way [5]. The poor thermal conductivity of the membrane keeps the temperature increase limited to a very local region of about the size of the excitation spot, as was verified from the temperature tuning of the L3 and L60 cavities. The second cavity at the other end of the L60 seen in Fig. 1 can be ignored for the present work as it is tuned out of resonance with the first one.

Results and Discussion

Fig. 2(a) shows the PL spectrum collected from an L3 cavity in a shoulder coupled cavity configuration where the number of barrier holes is three. We will deal with the fundamental L3 mode near 1540 nm in this paper only. Fig. 2(b) shows the L60 spectrum, collected with the SNOM probe located along the L60, with the excitation still at approximately the same location as in Fig. 2(a). The spectrum shows a FP-like pattern until it cuts off near 1550 nm. The cut-off results from the waveguide dispersion cut-off. The waveguide dispersion relation becomes very flat near cut-off ("slow light"), which is the reason for the non-equidistant free spectral range (FSR, separation between adjacent peaks). As for the case with the four holes barrier, the L3 spectrum does not qualitatively change when we photothermally tune its resonance over more than two FSRs of the L60 cavity, so that its frequency will become equal to one of the frequncies of the L60. The absence of level anticrossing phenomena is consistent with weak coupling.

When the number of barrier holes decreases to two, the fundamental L3 resonance splits in three or four peaks, as seen in Fig. 2(c). When the L3 cavity is now photothermally tuned, all peaks shift. In Fig. 2(d), many L3 spectra for different tunings are superimposed. It is observed that some frequencies are avoided corresponding to the deep minima in the superimposed spectra. The avoided frequencies correspond to the unperturbed resonances of the L60 cavity. This is a direct consequence of the level anticrossing phenomenon, when original frequencies are shifted or splitted due to interactons with another resonance. The multiplet of peaks observed in the L3 cavity (Fig. 2(c)) demonstrates that the single L3 resonance interacts simultaneously with 3 or 4 modes of the L60. The uncoupled case (Figs. 2(a)(b)) shows that with the objective exclusively the L3 modes are measured, without measurably mixing in the L60 modes. This proofs that the collection with the objective is very local, so that the mixing in of the L60 modes near the L3 resonance as seen in Fig. 2(c) implies that the modes in Fig. 2(c) correspond to supermodes with intensities distributed over both cavities.

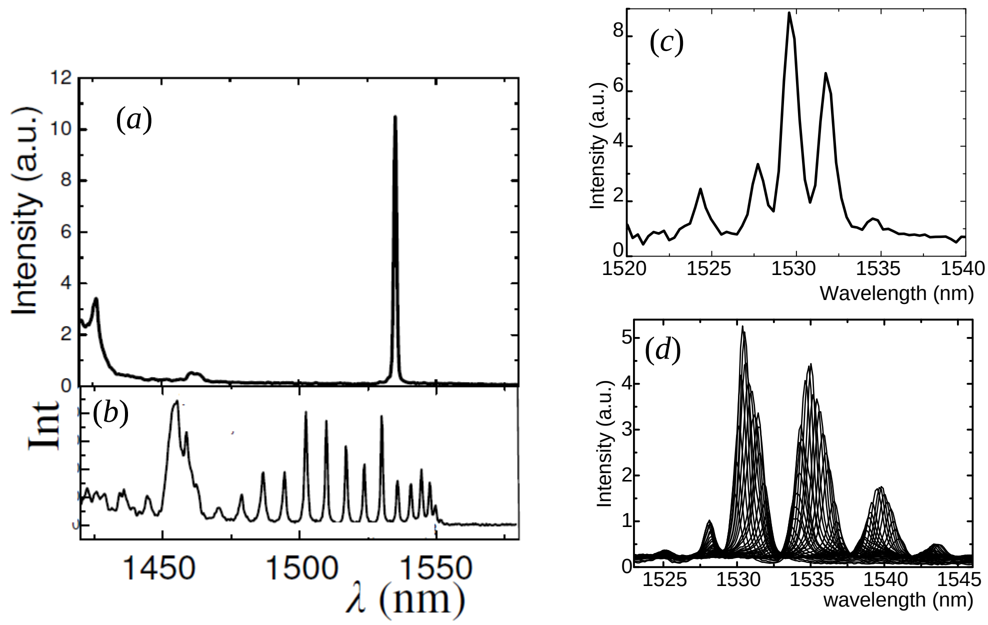

Fig 2. (a) Resonance spectrum of an L3 cavity. (b) Resonance spectrum of an L60 cavity. The cavities in (a) and (b) are only weakly coupled. (c) Resonance spectrum of an L3 cavity when this is strongly coupled to an L60. (d) Superimposed spectra of an L3 cavity, strongly coupled to an L60, when the L3 is photothermally tuned.

In order to further analyze the coupling of the two unequal cavities, we model them as a set of coupled FP resonators having different lengths as shown in Fig. 3. The transmission of the coupled system is calculated by adding the amplitudes of the transmitted and reflected waves at all three mirrors. Each mirror is assumed to have real amplitude reflection and transmission coefficients r_i and t_i ($t_i^2=1-r_i^2$). To calculate the transmission, the transmission of the end mirrors must be finite, but apart from that is arbitrary large. To mimic the experimental situation, the lengths L1 and L2 of the resonators is chosen in the ratio L2/L1=20. The calculations were done by implementing the transfer matrices for the mirrors and free spaces. The coupling is determined by the parameter $1\text{-}r_3$, which varies from 0, no coupling, to 1, complete coupling, which actually corresponds to mirror 3 missing. These limiting cases are displayed as horizontal bars next to the plot in Fig. 3(b) for the case that the short cavity resonance coincides with one of the long cavity resonances. When $1\text{-}r_3 = 0$, we have the unperturbed resonances, with the corresponding field intensities localized in each individual cavity. For the short cavity, this would be a single resonance, corresponding to the L3 resonance as observed in Fig. 2(a). When the coupling is turned on, $1\text{-}r_3 > 0$, the most striking effect for the frequencies is the splitting of the common resonance frequency. However, also all other frequencies of the long cavity shift, as seen from Fig. 3(b). Obviously, the central split mode is a common supermode located in both cavities, but also the nearby distorted long-cavity modes are supermodes with substantial intensity in the short cavity. For frequencies further away from the common central split mode, the modes correspond more and more to the unperturbed long-cavity modes without having appreciable amplitude in the short cavity. The observations in Fig. 2(c) correspond to this model: primarily a split mode is observed, with smaller amplitude modes present, roughly a FSR displaced from the central mode. The maximum coupling in the model, 1-r_3 = 1, corresponds to a single FP again, slightly larger than the original large one, and so with slightly decreased FSR. In Fig. 3(b), it is designated as L63, as it would be realized in the experiment by simply designing a waveguide cavity with 63 holes omitted.

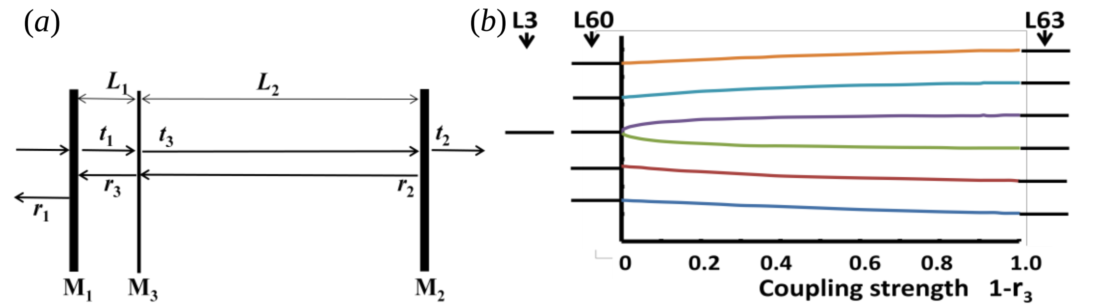

Fig. 3. (a): Fabry Perot model of coupled cavities consisting of two end mirrors and a mirror in between with amplitude reflectivity r_3. (b): Calculated resonances of the coupled cavities of (a) as a function of the coupling parameter 1-r_3 under the condition that without coupling the small cavity resonance coincides with one of the resonances of the large cavity.

Conclusion

Strong coupling between multiple modes of PhC cavities differing a factor of 20 in size has been demonstrated. The observations are well explained by a model of coupled Fabry-Perot resonators.

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