Near field mapping of coupled photonic crystal microcavities

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Abstract We make use of near-field microscopy to image the coupling between two adjacent photonic crystal microcavities A special design of the photonic structures is adopted with selective coupling between different modes having orthogonal spatial extensions Spatial delocalization of coupled-cavity optical modes is found whenever the frequency matching condition is fulfilled On the contrary, in case of large detuning, the modes are localized in each microcavity

1. Introduction
Photonic crystal micro-cavities (PC-MCs) offer the possibility to realize spatially localized optical modes with extremely high quality factor, opening the way to a novel class of efficient nanophotonic devices through the design of the dielectric environment In particular, the light confinement in a PC-MC allows to control the interaction between light and matter [1-2] Whenever the condition of strong coupling is fulfilled, the spontaneous emission from a quantum emitter is transformed in a reversible exchange of energy between the source and the photonic mode [3-6] This has been suggested as a possible basis for producing quantum gates based on the coherent interaction of two quantum dots via a photonic mode [7]

A second route for application in quantum information and communication is to realize a coupling between two spatially separated PC-MC modes [8-10] Similarly to the case of electronic states, the coupling of identical optical modes results in an energy splitting of the resonances and in the formation of delocalized coupled-cavity modes However, it is very difficult to realize real cavities that are identical, and the presence of a double peak in the spectrum can be the signature either of fabrication induced dielectric disorder or of cavity coupling The spatial distribution of the electric field is a very direct test of the coupling: coupled-cavity modes are delocalized over the two cavities, while in the uncoupled situation the field distribution results localized to either one of the two cavities

In this contribution, we study the coupling of PC-MCs by means of scanning near field microscopy (SNOM) The imaging of the optical modes is performed by using the tip induced spectral shift of the optical modes, which is proportional to the electric field intensity at the tip position [11], thus giving a direct and high fidelity mapping of the electromagnetic local density of states (LDOS) [12,13] By imaging the LDOS we demonstrate the spatial delocalization of modes over the two coupled PC-MCs in the case of frequency matching
2. Numerical simulation
In order to investigate the coupling between adjacent PC-MCs we choose a cavity with diamond-like geometry (denominated D2 cavity) The first two modes of the D2 cavity are spatially extended along the two orthogonal diagonals of the D2 rhomb, respectively [12] By exploiting this peculiar behaviour of the D2 cavity we can selectively study, both spectrally and spatially, the coupling regime for the two modes for two different coupled systems Hereafter we will refer to vertically aligned D2 cavities if the major diagonals of the two adjacent D2 cavities lie along the same line We expect that the first two modes of the D2 cavities show different coupling constants

Numerical calculations were performed with both a two dimensional (2D) and a three-dimensional (3D) finite-difference time domain (FDTD) code by using the nominal parameters of the structure, without including the effects of fabrication-induced disorder, with a refractive index of 348 and a grid of 25 nm As excitation sources we employed randomly placed dipoles with different orientations In the left panel of figure1 we report the simulated spectrum (in a simplified 2D geometry) for different coupling configurations from three to zero hole barriers, as shown by the schemes of the samples for each spectrum Obviously the splitting between the coupled modes increases when decreasing the cavity separation, since the spatial overlap of the optical modes increase In addition, the splitting of the fundamental mode of the D2 cavity is much larger than the splitting of the first excited mode of the D2 cavity, as a consequence of the different spatial distribution of the modes of the D2 cavities This is clearly shown in figures 1 (b),(c), which report the LDOS of the P1 and P3 resonances of the coupled system for a 3D calculation and in the case of one hole barrier As a matter of fact, in the horizontal geometry the coupling constant of the first excited mode turns out to be larger that the coupling constant of the fundamental mode Note also that the LDOS of the P1 and P3 resonances directly reflects the spatial distributions of the first two modes of the D2 cavity [12]

![Figure 1](image)

Figure 1 (a) Spectra of the 2D FDTD simulation for different cavities separation as shown by the schemes reported in the figure The dashed lines are guide for the eyes (b) LDOS for the P1 resonances (c) LDOS for the P3 resonances The LDOS are calculated with the 3D FDTD code

3. Experimental details
The investigated PC-MC incorporate InAs quantum dots (QDs) that act as local light source at 1300 nm and are fabricated on a 320 nm suspended GaAs membrane to ensure a confinement in the direction perpendicular to the membrane plane by total internal reflection The structures under consideration consists of a 2D triangular lattice of air holes with filling fraction f=35%, lattice
parameter $a=311$ nm (sample A) and $a=301$ nm (sample B). The cavities are two D2 PC-MCs aligned in the vertical coupling configuration and with a single-hole barrier. The SNOM setup is used in an illumination-collection geometry. We use a chemically etched optical fibre as a pure dielectric uncoated near-field probe. The sample is excited with light from a diode laser (780 nm) coupled into the tip that is raster scanned at a constant height, smaller than 10 nm, on the sample surface. Photoluminescence (PL) from the sample is collected through the same probe and the PL signal is dispersed by a spectrometer. The PL signal is detected by a liquid nitrogen cooled InGaAs array. All the presented measurements have been performed at room temperature.

4. Results and discussion

In figure 2 the experimental results for the sample A are reported. Figure 2(a) reports the PL spectrum with four main peaks (P1-P4). The PL maps indicate that P1 and P2 are delocalized over the entire system (figures 3(b) and 3(c)), and from the spectral shift maps (figures 3(f) and 3(g)), we attribute them to the two coupled-cavity modes originating from the fundamental mode of a single D2 cavity with an overall photonic splitting of 117 meV. This attribution is clearly validated by the comparison of the experimental data (figure 3(f)) with the simulated map of the LDOS for P1, as reported in figure 1(b); the agreement is pretty nice. Similar results are obtained for P2. The other two PL peaks, P3 and P4, show a quite small splitting (8 meV). The experimental near field maps of P3 and P4 are extended over the whole coupled system, demonstrating that these two modes are the symmetric and the antisymmetric coupled-cavity modes originating from the first excited mode of the two single D2 cavities. The small splitting denotes, as expected, a less efficient coupling of the first excited mode of the D2 in the vertical configuration. Therefore, in this particular sample, the matching condition between the two independent D2 cavity modes is very well satisfied and the disorder induced detuning is very small.
Let us now analyze a different realization of the coupled PC-MCs as reported in figure 3 (sample B) The PL spectrum turns out almost identical to the previous case The near field maps of the P1 and P2 modes (not shown here) are delocalized over the entire system and the previous discussion applies also to this case However there is an important difference concerning the near field maps of the P3 and P4 peaks (figures 3(b)-(e)) These are localized on a single cavity, and more precisely the PL signal associated to P4 is concentrated on the bottom cavity, while the PL signal associated to P4 is concentrated on the top cavity The lack of delocalization of the P3 and P4 resonances is a clear demonstration of the presence of uncoupled modes This means that the spectral splitting between P3 and P4 has, in this case to be ascribed to the energy detuning due to structural disorder in the cavity realization

5. Conclusions
In summary, we studied the photonic coupling of two closely spaced PC-MCs The designed coupled PC-MCs have the advantage of having two almost orthogonal modes with very different coupling energy in different alignment configurations By exploiting this feature and by means of near field mapping of the electromagnetic LDOS, we demonstrated that it is possible to discriminate between the mode splitting due either to structural disorder or to mode coupling

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