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Nonlinear optical tuning of photonic crystal microcavities by near-field probe

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We report on a nonlinear way to control and tune the dielectric environment of photonic crystal microcavities exploiting the local heating induced by near-field laser excitation at different excitation powers. The temperature gradient due to the optical absorption results in an index of refraction gradient which modifies the dielectric surroundings of the cavity and shifts the optical modes. Reversible tuning can be obtained either by changing the excitation power density or by exciting in different points of the photonic crystal microcavity. © 2008 American Institute of Physics. [DOI: 10.1063/1.2960259]

Optical microcavities, in particular photonic crystal microcavities (PC-MCs), are of profound interest in several fields of nanophotonics.1–3 A crucial issue in the progress of the field is the possibility to control and tune the optical modes. Different approaches have been so far, used to tune the PC-MCs resonance.1–3 Successive oxidation and wet etching cycles have been used for enlarging the radius of holes in the PC and decreasing the membrane thickness; this method allowed a large mode shift up 37 nm, but in an irreversible way.4 Gas condensation onto a PC slab MC maintained at low temperature has been used to modify the dielectric mismatch of the PC-MCs and to shift the cavity mode wavelength by as much as 5 nm. The method works, however, only at low temperature.5 Local changes of the refractive index of the air holes via infiltration of liquids at the single hole level6 have been already demonstrated, but only on pore sizes slightly below one micron. Recently, scanning microscope tip induced shifts of the PCs cavities modes have been studied as well.9–12 In this case, the dielectric tip acts as an external nano-object that locally modifies the dielectric environment and tunes the optical mode in a reversible and dynamical way.

In this paper we report on a nonlinear method to control and tune the dielectric environment of PC-MCs by exploiting the local heating induced by near-field laser excitation at different excitation powers. The temperature gradient due to the optical absorption results in an index of refraction gradient which modifies the dielectric surroundings of the cavity and shifts the optical modes. Reversible tuning can be obtained either by changing the excitation power density or by exciting in different points of the MC. We therefore demonstrate a nonlinear enhancement of the reversible tip induced tuning of the optical modes.

The investigated PC-MC incorporates QDs acting as local light sources and is fabricated on a GaAs suspended membrane. Three layers of high-density InAs QDs emitting at 1300 nm are grown by molecular beam epitaxy at the center of the 320-nm membrane. The details on the fabrication can be found in Ref. 13. The structure under consideration consists of a two-dimensional triangular lattice of air holes with lattice parameter a=301 nm and filling fraction f=35%, where the cavity is formed by four missing holes organized in a diamond-like geometry. A scanning electron microscope image is reported in Fig. 1(a). A commercial scanning near-field optical microscope (SNOM) is used in an illumination/collection geometry with a combined spatial and spectral resolution of 250 and 0.1 nm, respectively. In this geometry, the sample is excited with light from a diode laser (780 nm) coupled into a chemically etched, uncoated near-field fibre probe,14 that is raster scanned at a constant height on the sample surface. PL spectra from the sample were collected at each tip position through the same probe. Numerical simulations are performed with the finite-difference time-domain (FDTD) method, using a freely available software package (MEEP).15

Figure 1(b) shows a typical PL spectrum of the structure under investigation characterized by two main peaks, M1 and M2, centered around 1266.8 and 1241.3 nm, respec-

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**FIG. 1.** (Color online) (a) Scanning electron microscope image of the investigated sample. (b) Typical PL spectrum collected by the near-field probe. The inset (l) shows the spatial intensity distribution associated to the mode M1; the white circles superimposed on the image denote the topographic positions of the pores.

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of the mode M1. The spectra reported with a straight line are collected at the vertical edge of the cavity region, while the dotted ones are collected outside the cavity. The inset corresponds to the same peak. For sake of simplicity and concision, we are using uncoated SNOM tips, we can completely neglect the effects due to the heating of the probe itself, observed in the case of a metal coated tip, where the tip-to-sample heat transfer is, however, small. In our case, the mode shifts on the red side and, therefore, we attribute the power dependent shift to thermal heating as expected for cw excitation.

Our understanding of the physics behind the observed data is as follows. The laser pumping with a nanometric SNOM tip induces an inhomogeneous heating of the cavity, as schematically illustrated in the inset (I) of Fig. 2(b). Since we are using uncoated SNOM tips, we can completely neglect the effects due to the heating of the probe itself, observed in the case of a metal coated tip, where the tip-to-sample heat transfer is, however, small. In our case, the heating mechanism is due to the optical absorption in the sample and it creates a change of the index of refraction of the sample and therefore a modification of the dielectric environment of the PC-MCs. The thermal gradient is enhanced due to the reduced heat diffusion out of the PC membrane. In order to map the thermal gradient created in this configuration, we report in Fig. 3(a) the spatial decay of the spectral shift of the cavity mode as the excitation density power is increased. For low excitation power (blue dots), the decay constant associated to the mode spectral shift is comparable with the one associated to the PL intensity (black squares). By assuming an exponential decay of the mode we obtain, in this case, a decay constant of roughly $150 \pm 50$ nm. In this case, the heating effect could be neglected and the map of the spectral shift reproduces the map of the electric field intensity associated to the mode. For higher excitation powers, the profile of the mode shift broadens due to the thermal gradient and we observe a reduction of the spectral shift of 1.3 nm by moving the SNOM tip by 500 nm. This result indicates that with this method we are able to obtain information about the spatial distribution of the temperature averaged over the cavity mode volume.

In order to interpret in a quantitative manner the experimental results, we can consider, at least in the case of spatially non resonant excitation and given to the small volume of the PC-MC mode, an effective average temperature and neglect the thermal gradient. The thermal tuning of the optical mode has been then quantified by performing low excitation measurements at different temperatures by heating the PC-MC with a resistor. By linearly fitting the dependence of the mode spectral position on the temperature, we obtain a thermal tuning of 0.12 nm/K. This means that the 2.1 nm spectral shift reproduced in Fig. 2(b) can be attributed to a heating of the sample of about 150 nm. The inset (I) provides a schematic representation of the heating mechanism.
maximum shift experimentally observed under nonresonant excitation would correspond to a global heating of the PC-MCs of the order of 18 K. From FDTD simulations, a red-shift of 2.1 nm can be retrieved by a global increase of the index of refraction of MCs of the order of 18 K. From FDTD simulations, a red-shift of the index of refraction corresponding to the maximum of LDOS of the PC-MCs the photogenerated gradient of index of refraction strongly modifies the shape of the dielectric defect, resulting in a slightly different PC-MC. In the FDTD calculation, we simulate this effect by using an additional cylinder of larger index of refraction \( \Delta n \) placed in different positions of the PC-MC. Within this crude model, it is possible to obtain a different spectral shift of the mode for different combinations of the dielectric cylinder diameter \( d \) and \( \Delta n \). Figure 3(b) reports the simulated spectra obtained by placing a dielectric cylinder with \( d = 300 \text{ nm} \) in the center of the cavity and increasing at steps of 0.01 the values of its refractive index from 3.5 (that is the same value of refractive index of the cavity), to 3.55. The inset (I) of Fig. 3(b) shows the behavior of the peak position as the refractive index is increased in the case where the dielectric cylinder is placed in the center or at the vertical edge of the cavity from a value of refractive index of 3.55 to 3.75. The peak position moves to larger wavelengths with the increase of the refractive index and the slope depends on the overlap between the spatial electric field distribution associated to mode and the position of the cylinder. The theoretical results reproduce the measured spatially resonant shift if we assume an increase of \( \Delta n = 0.03 \) in the refractive index of the dielectric cylinder, corresponding to a local heating of roughly 100 K. Note that the optical shift of the mode is roughly proportional to the hot spot diameter (at least for \( d \) smaller that the mode volume); for \( d = 400 \text{ nm} \) the local heating decreases to 75 K.

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