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Sub-wavelength probing and modification of photonic crystal nano-cavities

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Abstract

In this work we present a sizeable and reversible spectral tuning of the resonances of a two-dimensional photonic crystal nano-cavity by exploiting the introduction of a sub-wavelength size glass tip. The comparison between experimental near-field data and results of numerical calculations shows that the spectral shift induced by the tip is proportional to the local electric field intensity of the cavity mode. This observation proves that the electromagnetic local density of states in a microcavity can be directly measured by mapping the tip-induced spectral shift with a scanning near-field optical microscope. Moreover, a non-linear control on the cavity resonance is obtained 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.

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1. Introduction

Near-field optical microscopy has already proven to be a powerful tool for studying the optical response of photonic structures and in particular two-dimensional photonic crystal nano-cavities [1–4]. Near-field microscopy not only permits to get information about the optical properties of these structures but also allows to locally modify their optical behaviour [5–9]. The opportunity to control the spectral response of such nano-cavities after the growing process is a crucial issue in the progress of the field. The possibility to control and tune the optical modes, in fact, has a big impact both for the technological point of view, in order to realise devices that operate at a specific frequency [10], and also for fundamental physics, like the case of solid state cavity quantum electrodynamics experiments where the modes of nano-cavities have to be tuned into resonance with emission of sources [11]. Many different methods

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are proposed to that end [12–15], but only few of them are completely reversible [12,13]. Moreover, since the strength of the tip-induced tuning is proportional to the electric field stored in the structure, by simply mapping the induced spectral shift it is possible to obtain a high resolution ($\lambda/16$) map of the electric field intensity associated to the mode of the structures. This additional information is particularly suitable in the case of using uncoated near-field probe, where the standard resolution is of the order of $\lambda/5$.

2. Tip-induced tuning

The investigated samples are two-dimensional photonic crystal nano-cavities on membrane. In particular, the hetero-structure consists of three layers of high-density InAs quantum dots (QDs) emitting at 1300 nm grown by molecular beam epitaxy at the center of the 320-nm-thick GaAs membrane. The membrane is grown on top of a 1500-nm-thick $Al_{0.7}Ga_{0.3}As$ sacrificial layer. The fabrication process consists of patterning a 150-nm-thick SiO_2 mask by 100 kV e-beam lithography and CHF_3 plasma etching and then transfer on the GaAs layer by $SiCl_4/O_2/Ar$ reactive ion etching. The membrane is then released by a selective etching of the $\mathrm{Al}_{0.7}\mathrm{Ga}_{0.3}\mathrm{As}$ sacrificial layer in a HF solution. More details on the fabrication can be found in Ref. [16]. The photonic structures under consideration consist of a 2D triangular lattice of air holes with lattice parameter, $a = 301$ nm and filling fraction, $f = 35\%$. In particular we study two different cavities: one that is formed by four missing holes organized in a diamond like (D2-cavity) geometry and another that consists of three missing hole organized as a triangle (T2-cavity). To investigate the properties of such photonic active structures is convenient to use the SNOM in illumination/collection geometry. In this configuration the light of a diode laser (780 nm) is coupled into a mono-mode optical fibre that it is directly connected with the near-field probe. This probe scans at a constant height with respect to the sample surface and excites the active material (excitation density of 4 MW/cm^2). The resulting photo-luminescent (PL) signal from the sample is collected at each tip position through the same probe and then dispersed by a spectrometer and detected by a cooled InGaAs array with a spectral resolution of 0.01 nm. In the following all the experimental results are obtained using a chemically etched uncoated near-field fibre probes (home-built).

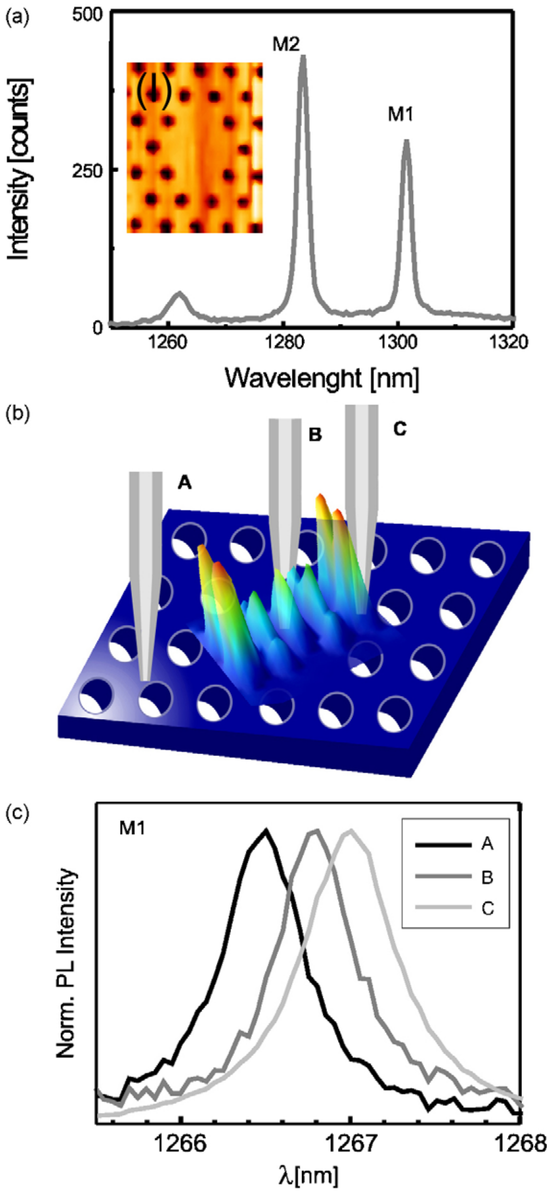

Fig. 1. (a) Experimental near-field spectrum of the D2-cavity (averaged on a region of 2 μm × 2 μm). (I) Sample topography acquired concurrently with the optical data, image dimension of 1.5 μm × 2 μm. (b) Schematic representation of the tip-induced spectral shift, the electric field intensity of the mode $M1$ of the D2-cavity is reported in colour scale in correspondence with the cavity region. The three position A–C indicates also the position of the tip in which the spectra reported in panel (c) are collected. (c) Normalized near-field spectra of the mode $M1$ collected at three different tip positions as indicated in panel (b).

In the inset (I) of Fig. 1(a) the shear-force topography image of the D2-cavity is presented. The opportunity of simultaneously having the information about both the topography of the sample and the optical signal from the sources permits to localize the signal in determinate positions around the cavity and to access the spatial distribution of the optical modes. In Fig. 1(a) a typical