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Near-field mapping of quantum dot emission from single-photonic crystal cavity modes

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Abstract

We directly investigate, by means of near-field spectroscopy, the spatial distribution of the optical cavity modes of 2D photonic crystal microcavities. Numerical simulations confirm that the photoluminescence maps of quantum dots embedded in the photonic structure qualitatively match the spatial modulation of the electric field intensity.

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Keywords: Quantum dots; Near-field spectroscopy; Photonic crystals; Microcavities

Introduction

Great interest has been recently dedicated to solid-state cavity quantum electrodynamic systems, where a semiconductor quantum dot (QD) is monolithically embedded in a photonic microcavity, leading to a single-photon source, Purcell effect and possibly strong coupling between excitons and photons [1–3]. A major problem in this very promising field is the difficulty of predetermining the exact resonance energy of the microcavity mode and the spatial location of the emitter. On one side, the deterministic nucleation of the QDs in the spatial position corresponding to the maximum amplitude of the optical mode is very complicated due to the self-aggregation nature of Stransky Krastanov dots [2]. On the other side, the exact spectral position of the resonance defect mode within the two-dimensional (2D) photonic crystal (PC) cannot be predicted with the desired accuracy due to lack of precise control of all fabrication parameters.

In this contribution, we investigate, by means of near-field spectroscopy, the spatial distribution of the optical modes in microcavities fabricated on a 2D PC Slab. The lateral confinement is achieved by the photonic structure, while the suspended membrane assures the confinement in the vertical direction. We use a GaAs-based heterostructure: three layers of self-aggregated InAs QDs emitting at 1300 nm are grown in the middle of a 320 nm thick GaAs membrane [4]. The cavity under investigation consists of triangular lattice PC mirrors (filling fraction $f = 35\%$, lattice parameter $a = 311$ nm) with modified L3 geometry: three missing holes in a line where both lateral displacement of the first hole adjacent to the cavity, d_L, and their radius, r, were changed (Fig. 1(b)). A commercial SNOM (Twinsnom, OMICRON) is used in an illumination/collection geometry with a combined spatial and spectral resolution of 250 and 1 nm, respectively. The experimental lateral spatial resolution is directly extracted from the photoluminescence images and is defined as the full width

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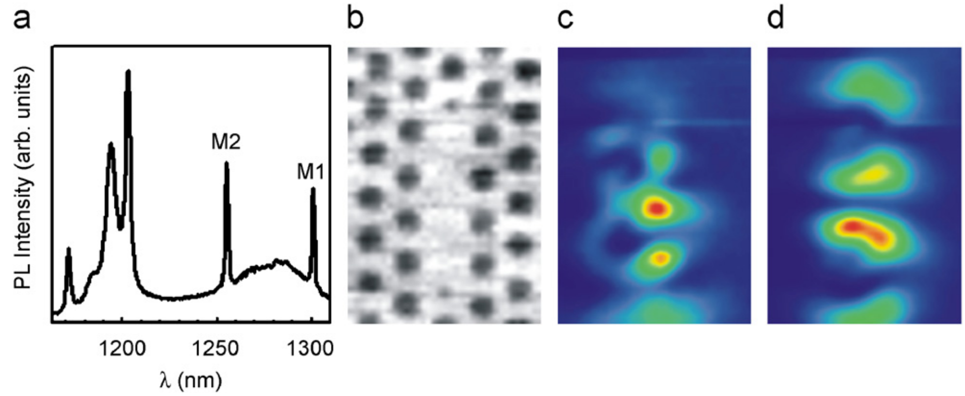

Fig. 1. (a) Experimental PL spectrum. (b) Topography acquired during the near-field scan. Spatial distribution of the modes at (c) 1300.5 nm, mode M1, (d) and at 1254.5 nm, mode M2. The images cover an area of 1.4 μm × 2.0 μm.

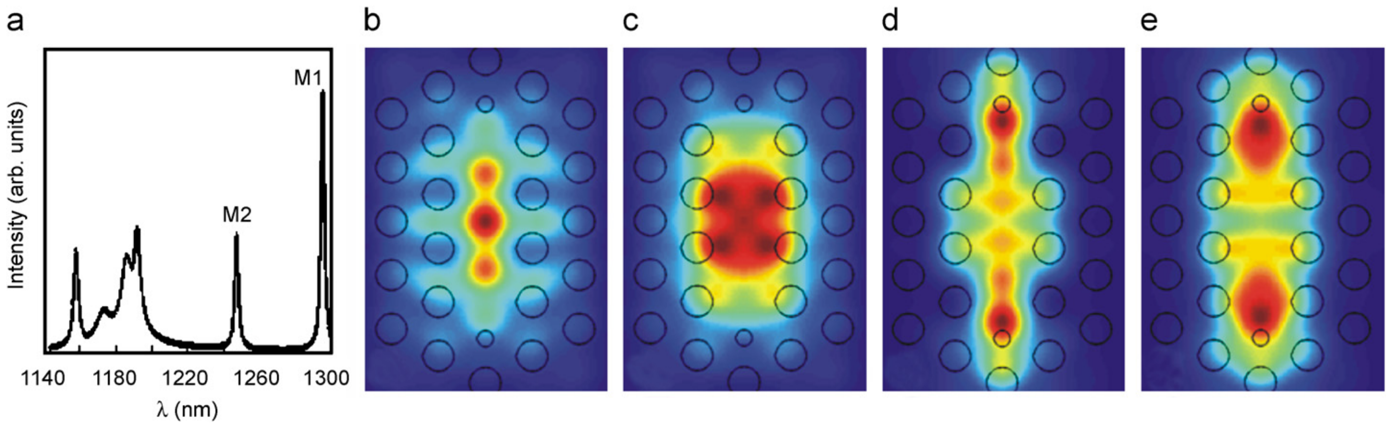

Fig. 2. (a) Computed PL spectrum. Computed spatial distribution of E_x^2 (b) and E^2 (c) related to the mode M1. Computed spatial distribution of E_x^2 (d) and E^2 (e) related to mode M2. The images cover an area of 1.4 μm × 2.0 μm and are convoluted with a Gaussian filter with an FWHM of 200 nm.

at half-maximum (FWHM) of the profile of the smallest feature that can be resolved. Spatially resolved images were recorded by scanning the probe tip over the sample. The sample is excited with light from a diode laser (780 nm). Photoluminescence (PL) spectra were recorded at each tip position with a monochromator in conjunction with a cooled InGaAs array. Aperture probes were made by chemically etching single-mode optical fibers.

The excitation density employed in the experiment determines the population of both the ground and first excited states of the embedded QDs. Therefore, we observed PL signal in the wavelength range between 1160 and 1310 nm.The black curve of Fig. 1(a) shows a typical PL spectrum of the structure under investigation collected through the near-field probe. The presence of several sharp peaks indicates, as expected, that the PC microcavity strongly modifies the local density of optical states. In the following the two modes at longer wavelength will be indicated as M1 and M2. The quality factor of the fundamental resonant mode (M1) is found to be as high as 1000. Figs. 1(c) and (d) show the spatial distribution of the PL intensity at the wavelength positions of the cavity modes M1 and M2, respectively. All the modes show a spatially localized signal that stems only from the vertical region with missed holes that corresponds to the cavity. Mode M1 (Fig. 1(c)), is characterized by three main lobes, where the most intense is located in the center of the cavity and the other two are symmetrically positioned above and below. The spatial distribution of the PL signal related to mode M2 (Fig. 1(d)) follows a different behavior. This resonance is characterized by four lobes placed symmetrically with respect to the center of the cavity. Therefore, differently from mode M1, the mode M2 is characterized by a minimum of intensity in the central position. These PL intensity maps are usually assumed to reproduce, at first approximation, the spatial distribution of the electric field intensity [5,6]. The spectral spontaneous emission enhancement and the near-field have been simulated with a 3D finite element Maxwell solver [7,8]. Fig. 2(a) shows the simulated spectra obtained by a spatial average of the spectral spontaneous emission enhancement and subsequent filtering to simulate the effect of the limited resolution of the spectral analysis [7]. The simulated curve reproduces the experimental spectrum with high accuracy: all the resonances are well distinguishable and also the relative spectral distance between the peaks is in perfect agreement with the near-field data. Figs. 2(b)–(e) show the electric field intensity of the computed eigenmodes M1 and

M2 10 nm above the slab waveguide surface. This distance has been chosen to match the position of the SNOM tip. The electric field intensity has been convoluted with a Gaussian filter with an FWHM of 200 nm in order to take into account the finite spatial resolution of the experiment. A FWHM of 200 nm represents the aperture that better reproduces the details of the experimental data. For aperture sizes that are small compared to the wavelength, the interference effects can be neglected. The convolution is therefore applied on the intensity according to custom [5,6]. Both E_x^2 and E^2 associated with M1 (Figs. 2(b)–(c)) have a maximum of intensity at the center of the cavity, and conversely, both E_x^2 and E^2 associated with M2 (Fig. 2(d)–(e)) have in that position a minimum of intensity. Nevertheless, the calculated field distribution that better matches the optical near-field image related to M1 is clearly E_x^2 (Fig. 2(b)), indicating that the experimental setup seems more sensitive to one electric field component. This behavior can be retraced to the presence of disorder in the refractive index profile of the sample, and/or to an asymmetric near-field probe that can promote a polarization orientation. For mode M2, the comparison is less ambiguous. Both E_x^2 and E^2 reproduce the two lobes around the central position of the cavity and the other two more distant lobes located at the border of the cavity.

In conclusion, even if the PL signal collected through the tip can be influenced by different aspects, such as shape asymmetries of the tip, the eventuality that the tip collects also far-field components, and the possible spatial and spectral inhomogeneity of the QDs, near-field spectroscopy represents a valid tool to qualitatively investigate the spatial distribution of PC eigenmodes.

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