Scanning near-field optical microscopy of quantum dots in photonic crystal cavities.

Matthias Skacel¹, Marco Francardi², Annamaria Gerardino², Blandine Alloing³, Lianhe Li³ and Andrea Fiore¹

¹ COBRA Research Institute, Technical University Eindhoven, Den Dolech 2, 5600 MB Eindhoven, The Netherlands
² Institute of Photonics and Nanotechnology, CNR, via del Cineto Romano 42, 00156 Roma, Italy
³ Institute of Photonics and Quantum Electronics, EPFL, CH-1015 Lausanne, Switzerland
E-mail: m.s.skacel@tue.nl

Abstract. Nanophotonic devices are of major interest for research and future quantum communication applications. Due to their nanometer feature size the resolution limit of far-field microscopy poses a limitation on the characterization of their optical properties. A method to overcome the resolution limit is the Scanning Near-Field Optical Microscope (SNOM). By approaching a fiber tip into the close vicinity of the sample the optical emission in the near-field regime is collected. This way of collecting the light is not affected by the diffraction limit. We employ a low temperature SNOM to investigate the photoluminescence of InAs QDs emitting at 1300nm wavelength embedded in photonic crystal cavities. At each location of an image scan the tip is stopped and a spectrum is acquired. We then plot maps of the photoluminescence for each wavelength. With this instrument it is now possible to directly observe the coupling of QDs to photonic crystal cavities both spectrally and spatially. We show first results of photoluminescence mapping of InAs QDs in photonic crystal cavities.

Quantum dots (QDs) in photonic crystal cavities are of major interest for future quantum communication and quantum key distribution applications. The spatial alignment of quantum dots to photonic crystal cavities (PhCCs) is still an unresolved issue. As yet, little experimental data is available on how the spatial position of the quantum dot within the cavity affects the coupling of the QD’s excitons to the cavity mode. In order to determine the requirements necessary for proper coupling more information is needed about the dependence on the spatial alignment. To obtain such information an instrument is needed with high spatial resolution. Mostly, solid state cavity QED systems are studied by micro-photoluminescence (µPL). However, µPL relies on the use of lenses, which are limited by the Abbe limit. Thus, for cavity QED systems operating in the telecom wavelength range the achievable optical resolution is in the order of 1µm. The typical QD size is in the range of a few nanometers. Likewise, the mode pattern of a PhCC has spatial features well below 1µm [1, 2]. Comparing this to the resolution of µPL it is evident that the spatial resolution of µPL is far from providing the relevant details of the QD-PhC coupling.

In SNOM a sharp fiber tip collects the non-propagating (spatial) high-frequency components of light, enabling a spatial resolution well below the diffraction limit. We set up a SNOM working at low temperatures (5K) to investigate InAs QDs in PhCCs. It employs a shear-force tuning-fork feedback for distance regulation. The laser for photoluminescence (PL) excitation as well
as the detected PL is coupled through the fiber tip. We use an uncoated fiber tip for optimal throughput and minimal disturbance of the dielectric environment of the photonic crystal [2]. The sample is placed onto a piezo scanner which is mounted, together with tuning fork and tip, onto a dipstick. The dipstick is inserted into a cryostat, in the flow of cold Helium gas. An operating temperature of 7K is chosen with a stability of ±20mK.

The sample under investigation contains low density InAs QDs (approx. 5-10 QDs/μm²), emitting at 1300nm at low temperature, in a 320nm thick membrane on top of a 1.5μm AlGaAs sacrificial layer [3]. PhCCs are fabricated by electron beam lithography, dry etching of the PhC holes and selective wet etching of the sacrificial layer. The addressed cavities are of a modified H1 geometry. In a triangular photonic crystal of air holes with a lattice constant of 350nm a hole is removed to form a cavity. The inner row of holes around the cavity is slightly shifted in position and reduced in size. Figure 3 shows the topography signal of the SNOM of the studied cavity acquired at 7K.

Figure 1 shows the μPL spectrum of such an H1 cavity. It shows three distinct peaks between 1320nm and 1330nm. We attribute the two peaks marked with M1 and M2 to dipole modes of the H1 cavity [4]. We attribute the third one to an excitonic emission of a QD, as will be shown later. Several sharp lines are superimposed onto a broad background between 1280nm and 1320nm, which presumably originate from the emission of several QDs. For comparison, a near-field PL spectrum where the tip is positioned in the center of the same cavity is plotted in figure 2(a). In this case, the undistinguished broad emission observed in μPL breaks up into a small number of sharp lines, indicative of the emission of single QDs. Whereas the sharp lines at 1301nm (denoted as D2) and 1302nm (denoted as D1) are barely apparent in μPL, they are remarkably strong in the near-field spectrum, as it shows much less background emission. This can be explained by the much smaller collection and excitation area of near-field microscopy as compared to far-field collection. In order to confirm the origin of the emission lines we investigated their power dependence. Figure 4 shows the power dependence of the most prominent lines of the near-field spectrum. Whereas, the lines at 1301nm (D2) and 1302nm (D1) show a saturation behaviour, the lines at 1321.7nm (M2) and 1323.4nm (M1) do not saturate with higher pump power, and become dominant at high powers, as shown in figure 2(b). We thus conclude that M1 and M2 are cavity modes while D1 and D2 are related to QD (multi-)excitons. Indeed, while the emission of a QD exciton saturates and decreases for increasing QD population, the cavity resonance can be fed by multiexcitonic transitions involving a large number of carriers in the wetting layer [5].
and is therefore dominant. While the absolute position of the lines is slightly offset in the \( \mu \text{PL} \) and SNOM spectra due to different environmental conditions (e.g. different cryostat, sample temperature, cryo-getting of surface layers [6]), the M1-M2 energy spacing is the same (2 nm). The quality factors are most easily deduced from the high power SNOM spectrum in figure 2 (b) as \( Q(M1) = 1800 \) and \( Q(M2) = 800 \).

Besides spectroscopy, the SNOM can also be used to spatially map the PL by raster-scanning the tip over the surface. At regularly spaced locations during the scan (here at \( 32 \times 32 \) locations) the tip is stopped and a near-field spectrum with an integration time of 1 second is acquired. After the scan has finished the acquired 1024 recorded spectra are rearranged to show the emission maps for each wavelength (one map for each pixel of the CCD of spectrometer). A selection of the most interesting maps is presented in figures 5, 6, 7 and 8. They correspond to the M1, M2, D1 and D2 lines. All maps are taken under cw excitation at 635 nm with a power of \( P = 400 \text{nW} \).

Figures 5 and 6 show the cavity modes M1 and M2. M2 shows a distinct spatial pattern which resembles a dipole mode [4]. On the other hand, M1 has only one lobe. Both modes are displaced to the right side of the cavity center, as compared to the topography (the holes of the PhC are drawn as white circles to guide the eye). We attribute these unexpected features to an asymmetric geometry of the tip [1] and manufacturing imperfections of the PhCC.

The maps of the two sharp lines D1 and D2 are shown in figures 7 and 8, respectively. The round-shaped emission pattern together further confirms that these stem from QDs. Since the spots in figure 7 and 8 both come from approximately the same location in the PhCC we conclude that they are coming from the same QD.

In conclusion we have studied QDs in photonic crystal cavities by scanning near-field optical microscopy. We are able to image the mode profile of photonic crystal cavities with sub-wavelength resolution and can identify individual QDs. Future work will consist of spatially resolved mapping of the PL decay time and of the second-order correlation function, as a function of the QD-mode spectral tuning.

Acknowledgments
We want to thank Silvia Vignolini, Francesca Intonti, Mehmet Dündar, Rob van der Heijden and Fouad Karouta for many helpful suggestions and fruitful discussions.
Figure 5. Cavity mode M1 at 1323nm.

Figure 6. Cavity mode M2 at 1321.7nm.

Figure 7. Map of D1 at 1301.96nm.

Figure 8. Map of D2 at 1301.12nm.

References

[1] Vignolini S, Intonti F, Riboli F, Wiersma D S, Balet L, Li L H, Francardi M, Gerardino A, Fiore A and Gurioli M 2009 Applied Physics Letters 94 163102–3 URL http://link.aip.org/link/?APL/94/163102/1

[2] Intonti F, Vignolini S, Riboli F, Vinattieri A, Wiersma D S, Colocci M, Balet L, Monat C, Zinoni C, Li L H, Houdre R, Francardi M, Gerardino A, Fiore A and Gurioli M 2008 Physical Review B (Condensed Matter and Materials Physics) 78 041401–4 URL http://link.aps.org/abstract/PRB/v78/e041401

[3] Alloing B, Zinoni C, Zwiller V, Li L H, Monat C, Gobet M, Buchs G, Fiore A, Pelucchi E and Kapon E 2005 Applied Physics Letters 86 101908–101908–3 ISSN 10773118

[4] Shirane M, Kono S, Ushida J, Ohkouchi S, Ikeda N, Sugimoto Y and Tomita A 2007 Journal of Applied Physics 101 073107 ISSN 00218979

[5] Chauvin N, Zinoni C, Francardi M, Gerardino A, Balet L, Alloing B, Li L H and Fiore A 2009 Physical Review B 80 241306 URL http://link.aps.org/doi/10.1103/PhysRevB.80.241306

[6] Mosor S, Hendrickson J, Richards B C, Sweet J, Khitrova G, Gibbs H M, Yoshie T, Scherer A, Shtchekin O B and Deppe D G 2005 Applied Physics Letters 87 141105 ISSN 00036951