Observation and Near Field Spectroscopy of Optical Modes in Active Photonic Crystal Microcavity

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Abstract

We report the direct, room-temperature, near-field mapping and spectroscopy of the optical modes of a photonic crystal microcavity containing quantum wells. We use a near-field optical probe to reveal the imprint of the cavity mode structure on the quantum well emission. Furthermore, near-field spectroscopy allows us to demonstrate the strong spatial and spectral dependence of the coupling between the sources and the microcavity. This knowledge will be essential in devising future nanophotonic devices.

We use an optical near-field scanning probe to analyze, at room temperature, the spatial and spectral structuration of the photoluminescence of quantum wells (QWs) by the modes of a PC microcavity. We are able to observe the modes spatial distributions and spectral features that are not accessible with far-field techniques, and which illustrate the strong spatial dependence of the coupling between the sources and the cavity. The PC is prepared by drilling a triangular lattice of air holes in an InP slab using e-beam lithography and reactive ion etching [1]. The InP slab is 250 nm thick, has a refractive index of 3.17 at 1.55 µm and supports only one guided mode around that wavelength. The lattice parameter of the PC is ***a*** and the filling factor is ***f***. The filling factor can be varied to modify the crystal band structure and the spectral position of the cavity modes. Four InAsP quantum wells, separated by InP barrier layers, are embedded at the center of the InP slab. The photoluminescence from the QWs occurs between 1250 nm and 1650 nm. The cavity is formed by introducing an hexagonal defect (omitting 7 holes) into the PC (Fig. 1). This defect willbe refered to as H2 microcavity. The InP slab is wafer-bonded ontoa 1µm thick SiO_2 layer on top of a silicon host substrate.

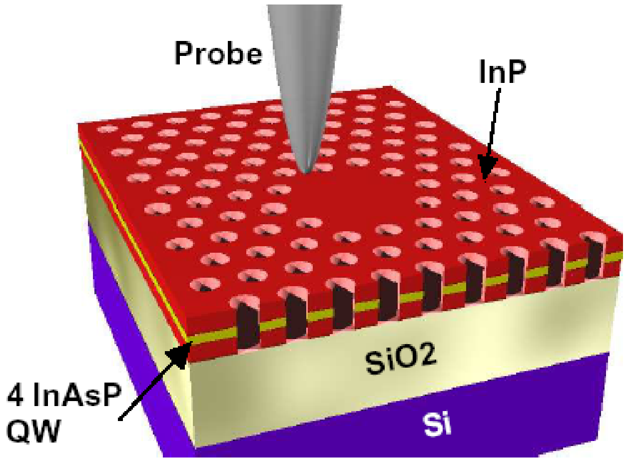

Fig. 1 : Schematic of the H2 cavity and the probe.

H2 microcavities were chosen because they support several resonant modes that are quite well spaced out. Far-field spectroscopy can be used to find the spectral position of the cavity modes of an actual PC structure [1], however, it does not give us any insight in the PL structuration inside the cavity. To observe the effect of the cavity modes on the PL we perform a local study using a near-field optical probe in collection mode (Fig. 1). A laser diode (wavelength 780 nm) is focused to a 15µm diameter spot on the sample through an objective lens. A chemically etched optical fiber tip is used to collect the PL signal in near field [2]. After collection by the probe, the pump light is filtered out by a long-pass filter (cutoff wavelength 1200 nm). A monochromator with a 12~nm resolution in the infrared, and a InGaAs photodetector are used for spectral measurements. X-Y scans of the tip are performed using a piezoelectric scanner. The distance between the probe and the sample is regulated using a non-optical shear-force feedback loop that keeps the probe less than 10 nm away from the sample [2]. In this configuration, the sample topography and the PL near-field map are recorded simultaneously.

The coupling to the PL of the QWs with the optical modes of a H2 cavity is demonstrated in Fig.2 for a crystal structure with lattice parameters ***a***=535~nm and ***f***=0.55. Fig.2a presents the near-field, shear-force topography of the cavity. Figs.2b-f show the near-field optical maps of several modes located at 1370 nm, 1416 nm, 1460 nm,1500 nm, and 1540 nm, respectively. One can see that the field distribution imprinted by the cavity modes on the PL of the QWs can change drastically with the mode structure. Another similar mode with 6 bright spots is observed at 1460 nm except that the lobes are now located at the corners of the cavity. The other two modes that lie within the PL spectrum of the QWs (Fig.2e) and Fig.2f)) exhibit a more complex field distribution. Experiments carried out over several cavities with different lattice parameters show that the first two modes (Fig.2b) and Fig.2c)) always exhibit the same modal structure and seem quite impervious to small fluctuations in the crystal structure. On the other hand, the remaining three modes that lie within the QW PL spectrum are more sensitive to the crystal structure.

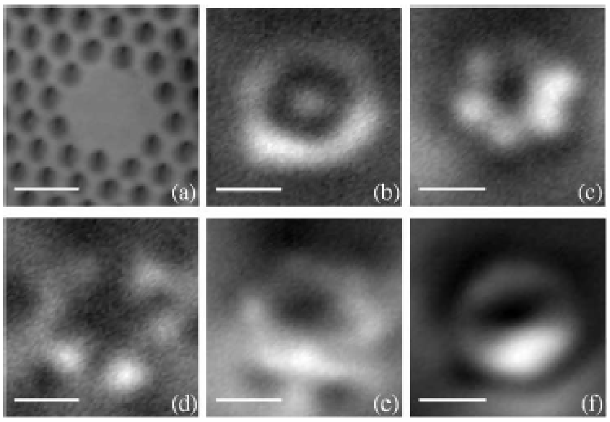

Fig. 2 : Topographical (a) and near-field photoluminescence maps recorded at the spectral locations labelled. (b) 1370 nm, (c) 1416 nm, (d) 1460 nm, (e) 1500 nm, (f) 1540 nm. Bar length is 1µm [5].

The near-field probing of the confined modes yields a direct mapping of the PL structuration by the cavity. It can also be used to gain a deeper insight into the cavity modal structure. Indeed, the development of PC based single-source (such as a quantum dot) devices will require the ability to relate the spatial position of the source in the cavity, to its interaction with the cavity modes, thereby ensuring an optimal electromagnetic coupling. In that spirit, the near-field probe can be used to record the local spectrum of the cavity. Whereas a far-field spectrum collects and merges contributions from all over the cavity, a near-field spectrum unveils the differences in local contributions from different modes. At a given location in the cavity, the spectral contribution of a mode will depend on its spatial features. This is illustrated by the three near-field spectra recorded at three different locations above the previous H2 cavity. The different peaks correspond to the 5 modes presented in Fig.2b)-f). Also shown in the figure are the far-field PL spectrum, recorded with a conventional far-field setup, and the position of the modes as computed by three-dimensional (3D) finite difference in time domain (FDTD). Quite naturally the far-field and near-field spectra agree on the spectral position of the cavity modes however, the near-field spectra contain a more complete description of the modes. This is most interesting in the case of the mode at 1460 nm (Fig.2d)) which is hardly detected in far-field while it appears clearly on the near-field spectrum recorded at the corner of the cavity (curve with triangles in Fig.3). Differences between the three near-field spectra reflect the relative contribution of each modes at different locations inside the cavity. For instance, Fig.3 shows that the center of the cavity (curve with squares) is not the best location to excite modes c) d) or f). Similarly, a source placed near the side of the cavity will couple efficiently with the mode at 1416 nm but not to the mode at 1460nm, whereas a source near a corner of the cavity will have the opposite behavior. This shows that near-field spectroscopy and/or optical mapping can yield valuable information regarding the optimal location to couple efficiently a source to a cavity mode. We emphasize that although computation can give an idea of the mode structure, it cannot always predict accurately the field distribution for an actual cavity.

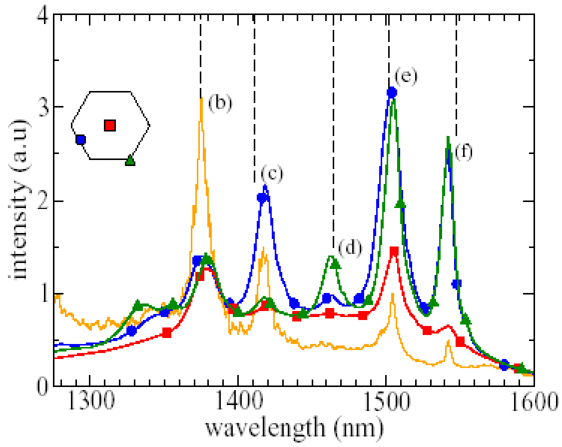

Fig. 3 Photoluminescence spectra. Lines with symbols: near-field spectra recorded at 3 different locations above the cavity (see inset). Solid Line (no symbol): far-field spectrum. Vertical dashed lines: spectral position of the modes calculated by 3D FDTD. The labels b) to f) pertain to the modes of Fig.2.

In summary, we have presented a direct, room-temperature, spatial and spectral near-field analysis of the structuration of quantum-well photoluminescence by the modes of a photonic crystal microcavity. We have observed the structuration of light by H2 PC microcavities. Furthermore, we have shown that the local spectrum can change significantly with the location inside the cavity. This is of crucial importance for the development of photonic components such as single quantum-dot lasers or single photon sources for quantum information applications. Indeed, the technique presented in this letter provides not only a spatial sensitivity beyond conventional far-field techniques, but also a unique opportunity to test computational models, which should help improve the designs of future PC nanophotonic devices.

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