Planar Photonic Crystal Nanocavities as Functional Microparticles

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Planar photonic crystal nanocavities, made in a thin semiconductor membrane and suspended by breakable tethers, are released after fabrication. The cavity spectrum can be read out remotely by detecting the photoluminescence of embedded Quantum Dots. Both transfer printing and deterministic positioning of the cavities on foreign substrates by individual micromanipulation is demonstrated. The microscopic environment of the particles, including their bonding to the substrate, determines the cavities' resonance spectrum, which can be exploited in applications. As the first application, we demonstrate a novel fiber-optic sensor with a PhC cavity chiplet attached to the tip of a single-mode optical fiber.

Introduction

Membrane type photonic crystal optical cavities are well known as ultrasmall functional components in photonic integrated circuits. Micro- and nanoparticles have found widespread use as autonomous entities for sensing and fluid tracing. The use of microparticles can be enhanced if they have a higher level of intelligence. In the present work we investigate micron-sized thin membranes patterned with a photonic crystal (PhC) structure to serve as independent particles after release from the host-chip. One possible application is in biosensing where there exists an increasing demand for multiplexed assays. This is traditionally realized with position-encoded microarrays. This approach suffers from the slow reaction kinetics, the problems of localization of the probe molecules on the platform and the inflexibility of probe combinations used in an assay. The alternative are the suspension arrays where several micrometer-sized solid particles with chemically functionalized surfaces are used to capture the target molecules [1]. The PhC particles presented in this work have Quantum Dots as internal light sources that enable remote communication. The cavity spectrum, as read out in a photoluminescence (PL) experiment, is used both for particle identification [2] and for label free refractive index sensing.

In the present contribution, we present transfer printing and individual micromanipulation methods to release particles from their substrates. The condition of the particle is monitored from its PL-spectrum. A single cavity is mounted at the core of a standard single mode optical fiber to serve as a fiber-optic refractive index sensor.

Experimental Methods

During electron beam lithographic definition and subsequent plasma etching of the nanopattern and wet underetching of the 200 nm thick membrane, the particle to be released is suspended in the substrates by two breakable tethers, as shown in Fig. 1(a). The cavity consists of a local defect of four modified neighbouring holes. Gently pressing a soft polymer to a pattern of such cavities (Fig. 1(b)) transfers the pattern to the polymer, which is then operated as a a stamp. Pressing this stamp again at an arbitrary substrate, e.g. glass in Fig. 1(c) transfers (a part of the) cavities to the glass.

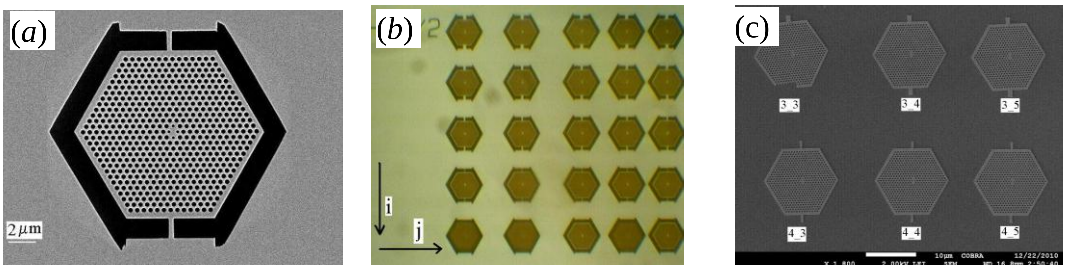

Fig. 1 (a) Top SEM image of PhC cavity suspended by two breakable tethers. (b) Optical microscope image of an array of cavities. (c) SEM-image of part of the array of (b) transfer printed to glass.

Individual cavities can be taken out of the array with a tapered glass fiber, pulled to a diameter of less than 1 μm, and mounted on a nanomanipulator as sketched in Fig. 2(a). The particles easily adhere to the tip, see optical image in Fig. 2(b), presumably due to electrostatic or Van der Waals forces. As expected, the resonance frequencies before and after release are unchanged, see Fig. 3, but the relative intensities are strongly modified. The latter is the result of the different orientation of the cavity and the directional radiation patterns of the different resonant modes. The observed resonances are well identified, but this will not be discussed here.

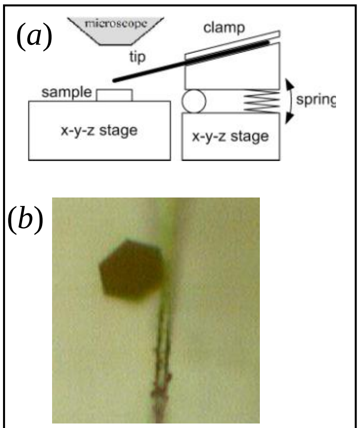

Fig. 2 (a) Schematic of the tapered fiber manipulator (b) Optical image of a microparticle attached to the fiber tip.

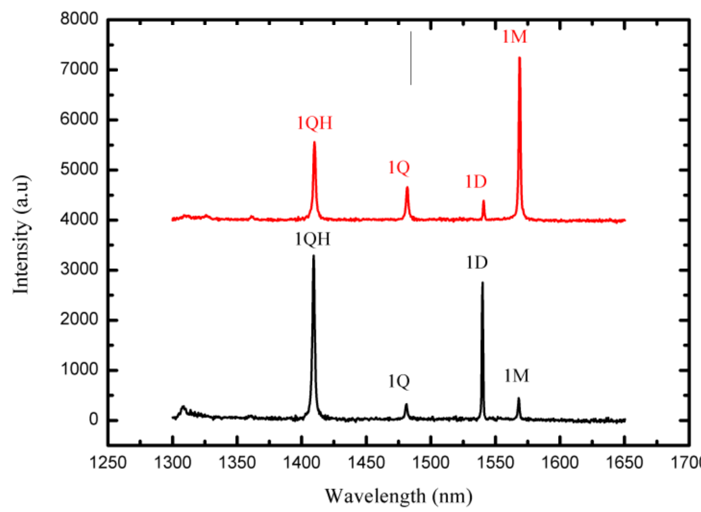

Fig. 3 Cavity PL spectra with cavity still in original position (lower) and cavity on fiber taper (upper).

Results and Discussion

The PL spectra of the cavity 4_3 (see Fig. 1(b,c)) is shown in Fig. 4. When that cavity membrane is pressed on a glass substrate with the stamp, and the stamp is still present, huge red-shifts are observed, see the two lower traces in Fig. 4. These redshifts result from the presence of the glass and polymer stamp dielectrics in the evanescent field of the resonant mode. From the magnitude of the shift, it follows that some glue used on the stamp has penetrated inside the holes. The shift that remains after removal of the stamp, upper trace of Fig. 4, can be fully explained by the presence of the glass alone. This betrays that the membrane is tightly bound to the substrate, with no substantial air gap in between.

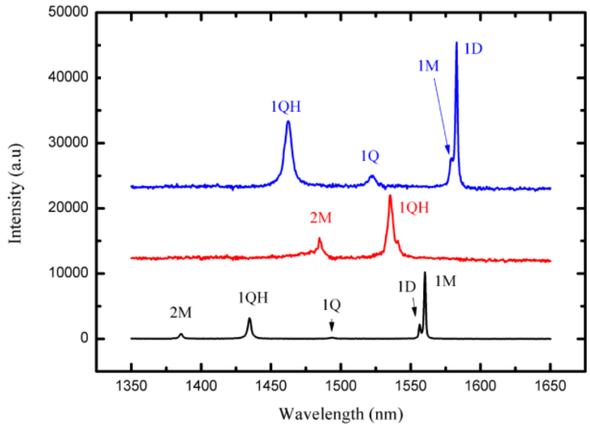

Fig. 4. Lower: Original spectrum, before release. Middle: On glass, stamp still present. Upper: On glass, stamp removed.

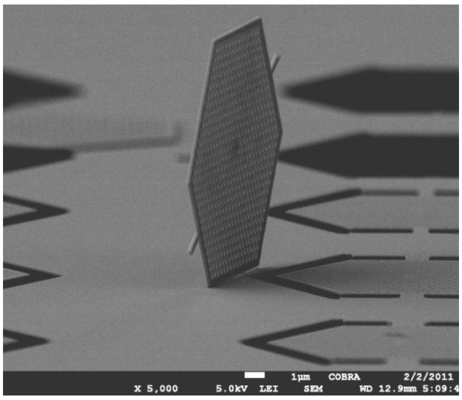

Fig. 5. SEM image of micro-manipulated particle standing upright on substrate.

Striking phenomena were observed when the cavities were released with the micromanipulator. They preferentially orient themselves with their face perpendicular to the substrate surface as shown in Fig. 5. This was the case when they were gently placed on the surface from the tip, but even after they were launched when the fiber was used as a spring. This spontaneous orientation probably results from the strong electrostatic or Van der waals interactions between the particles' edges and the surface, and could be useful for future 3D photonic structures fabrication.

Local sensors mounted at the very tip of an optical fiber would be useful for a large variety of applications. Micro- or nanostructured devices are difficult to fabricate on the tip, since standard lithographic techniques fail due to the impossibility to spin resist on such a small area. Here we exploit the micromanipulation technique to bond a prefabricated nanocavity membrane on the core of a standard SMF 28 single mode optical fiber with 8.2 μm core diameter. The core position is identified for alignment puposes by illuminating it with visible light from the other end. The core size is only slightly larger than the cavity mode, so that optical excitation of the cavity through the same fiber is reasonably efficient without additional focussing. Fig. 6(a) shows the cavity as mounted on specially prepared piece of fiber, suitable for inspection in a Scanning Electron Microscope (SEM). Fig. 6(b) shows two luminescence spectra from the mounted cavity as collected through the same fiber. The cavities were of a standard type used mostly in planar PhCs. This implies that the emission pattern is primarily along large angles with respect to the surface normal, and therefore largely not matching with the low numerical aperture (~ 0.14) of the fiber. Therefore the signals are very small and only just above the background.

To demonstrate the operation as a refractive index sensor, the spectrum was measured with the fiber tip in air or immersed in water. The red-shift due to the refractive index of water is clearly seen in Fig. 6(b), although the shift is less than expected for complete infiltration (expected from calculations ~ 50 nm, measured ~ 30 nm). A surface treatment to make the semiconductor more hydrophilic will enable complete infiltration. The strong decrease of signal starting near 1600 nm is due to a detector cut off. The bond to the surface was found to be very rugged and not affected by immersion in water. It is expected to be due to Van der waals forces.

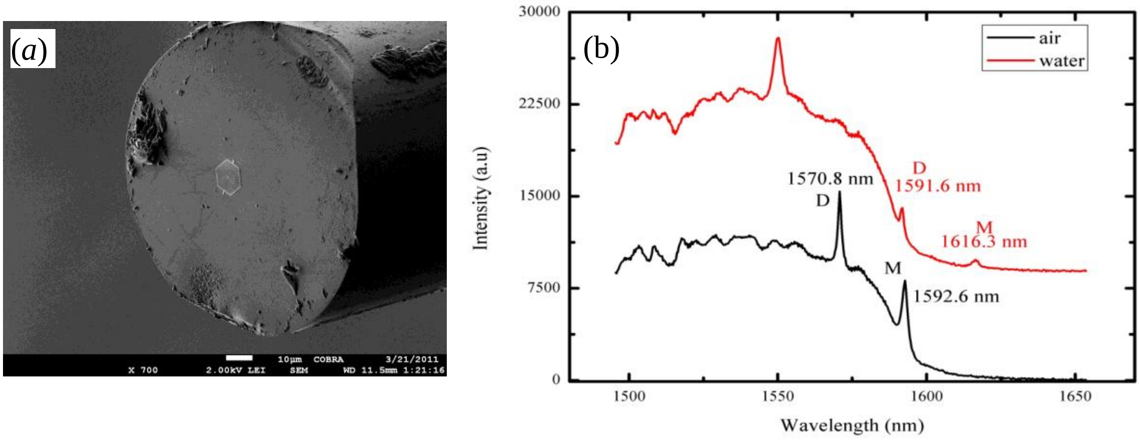

Fig. 6 (a) Fibertip with PhC cavity mounted. (b) Spectra from cavity on tip when in air (lower curve) and in water (upper curve).

Conclusions

Methods were presented to release membrane photonic crystal cavities after nanofabrication in the host semiconductor material and mount them onto arbitrary substrates. The microparticles naturally tend to align vertically on any host substrate, which could be useful for 3D manufacturing. The PL enables remote optical communication for sensing. A novel fiber-optic sensor with a PhC cavity mounted on the fiber tip was demonstrated.

References

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