Imaging of photonic crystal cavity mode via refractive index sensing

Kumar Saurav [1,2] and N. Le Thomas [1,2]

[1] Photonics Research Group (INTEC), Ghent University - imec
[2] Center for Nano- and Biophotonics (NB-Photonics), Ghent University,
iGent - Universiteit Gent Vakgroep Informatietechnologie Technologiepark-Zwijnaarde 15, 9052 Gent.

Silicon (Si) based integrated Photonic Crystal (PhC) cavities show great promise for biosensing applications, owing to their high Quality (Q) factor, low mode volume and compatibility with Complementary metal–oxide–semiconductor (CMOS) fabrication. We present the development of a new experimental technique to experimentally determine the sensing properties of PhC cavity mode. It makes use of a silica nano-tip fiber that moves in the near field of the PhC cavity and of a high numerical microscope objective that collects the field radiated out-of plane from the cavity. Measuring the intensity fluctuations that are induced by the nano tip via local perturbation of the refractive index allows us to map the intensity profile of the cavity mode.

Introduction

Si based PhC cavities have attracted significant attention recently for their ability to strongly confine light in wavelength-scale volumes. The ultra-high Q factor, small mode volume, and CMOS compatibility properties of these cavities have fostered a broad range of applications in the field of sensing [1, 2]. The sensing principle of a PhC cavity is based on the strong overlap between the confined electromagnetic field and the surrounding medium, which allows a label-free detection based on the refractive index (RI) change. Due to the low cost and label-free aspects, this type of biosensors may play a significant role in cellular sensing and biochemical recognition [3-5]. Furthermore, the large-scale integration of PhC cavities can enable multiplexed, fast and sensitive detections in various fields such as biotechnology, pharmacology and colloidal sciences.

When a dielectric nano-object approaches the near field of an optical cavity, the local refractive index changes. It results in a redshift of the wavelength of the cavity resonance and a concomitant variation of the intensity stored in the cavity for an excitation at a single frequency. For weak perturbations, the intensity variation is proportional to the local cavity field intensity and to the volume of the nanoparticle. It follows that the spatially mapping the perturbation-induced intensity variation provides an image of the intensity distribution of the cavity field. The experimental knowledge of the three dimensional distribution of the cavity field is important to predict the sensing capabilities of the cavity. Here, we discuss the preliminary development of a new technique to map the interaction between a nano-object and a photonic crystal cavity mode. First, we describe a special technological post-processing of the photonic cavity that allows approaching the nano-object close to the cavity in a controlled way and to collecting at the same time the light scattered from the cavity. Then we discuss the fabrication of nano-tip fibers that are used as nano-objects to perturb the cavity mode. The last part presents the optical set-up and initial three dimensional mapping of the fundamental mode of a L3 PhC cavity.

Fabrication of PhC cavity

Integrated 2D PhC cavities were fabricated using a Multi Project Wafer (MPW) service in a 200 mm SOI-pilot line at imec using deep – UV lithography on SOI wafers. These wafers consist of a 220 nm top silicon layer on top of a 2-µm-thick buried silicon dioxide (BOX) layer. These layers are supported by a 740-µm-thick silicon substrate. Our PhC cavities are designed to operate with air on both sides of the PhC membrane. This kind of structures provides higher Q factors compared to silicon oxide cladded structures.
We have removed the silicon substrate below the PhC to have free accessibility to the cavity from both sides. The chip was thinned and polished using a chemical mechanical polishing machine. The chip is thinned by mounting it on a vacuum chuck on which the substrate is pressed down against a rotating pad. A chemical slurry that contains silica is flown continuously over the pad to mechanically remove the substrate. A hard mask made of layers of Plasma enhanced chemical vapor deposition (PECVD) silicon dioxide and PECVD silicon nitride has been used to remove the silicon substrate. Any scratch on polished side of chip has to be avoided as it can lead to the peeling of the hard mask during the silicon etching process. A window was patterned on the hard mask by photolithography. From the patterned window the silicon was etched with a KOH solution. Later, buried oxide below PhC was etched in hydrofluoric acid (HF).

Fabrication of fiber nano-tip

The fiber based nano-tip was fabricated from a standard silica fiber designed for single mode operation around a wavelength of 800 nm. First, the fiber facet was cleaved and properly cleaned in acetone and IPA. The cleaved fiber facet was then vertically immersed in aqueous HF and an organic overlayer. The fiber was carefully etched to fabricate nano-tip. Depending upon the use of organic overlayer, nano-tips of different size and shape at the fiber apex can be realized. Figure 1 shows the scanning electron microscope (SEM) images of typical nano-tip fibers fabricated with this process.

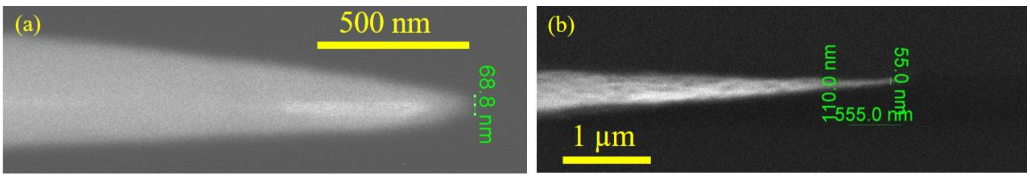

Figure 1. SEM images of fabricated silica nano-tip fiber (a) with organic overlayer, (b) without organic overlayer.

Imaging of PhC cavity modes

Figure 2(a) shows a schematic of the setup that we have developed to map the cavity response induced by a positioning a fiber nano-tip in the near field of the cavity. It highlights the V grooved opening of the sample at the bottom and the local light collection from the top side of the cavity. The photonic crystal structure is excited at a fixed frequency by a single mode tunable laser diode through a polarization controller,

which can excite TE or TM mode separately. The linearly TE polarized light is coupled into the waveguide by focusing it on the entrance facet via a lensed fiber. The light is then coupled into the PhC cavity by access waveguide. The light radiating out of the cavity surface is collected through a high numerical aperture (0.95) microscope objective and directed toward an infrared camera and InGaAs photodetector.
We have mapped the mode of a L3 cavity. Such standard PhC cavities are created by removing 3 holes along Γ-K direction. The current cavity has quality factor of approximately 3700. The cavity was excited through a W1 waveguide (line defect waveguide constructed by removing a row of air holes along Γ-K direction) separated by 4 rows of holes from the cavity in vertical direction (Γ-M).

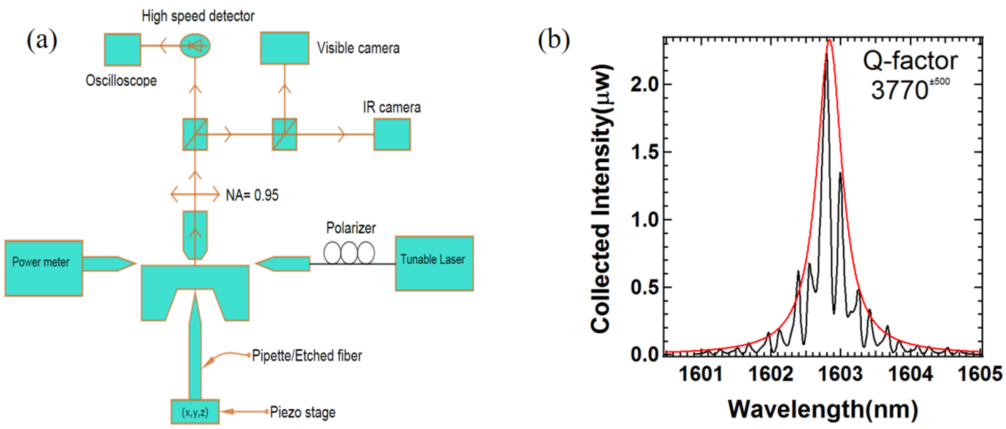

Figure 2. (a) Schematic of the experimental apparatus used for PhC mode map, (b) Transmission spectra of PhC cavity without substrate.

The nano-tip fiber is mounted on a piezoelectric stage to position it close to cavity surface. The other end of the fiber nano-tip is connected to a 780 nm laser diode which helps in controlling the position of the nano-tip. We first measured the cavity resonance which is at 1602.8 nm. Figure 2(b) shows the transmission spectrum (black line) together with Lorentzian fit (red line) of the cavity collected from cavity surface. While accurately keeping these alignments, the tip was raster scanned in the near field of the cavity in XY plane from the backside while simultaneously recording the cavity transmittance (I).

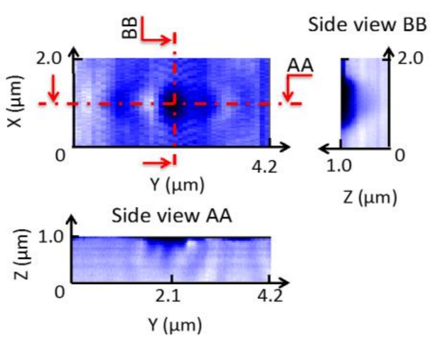

Figure 3. Three-dimensional map of the intensity variation induced by the interaction between the nano-tip fiber and the L3 cavity.

The interaction between the nano-tip fiber and the confined cavity field allows us to build a three dimensional map of the intensity variations of the intensity scattered from the cavity as shown in Fig. 3. As it can be seen in the Fig. 3, this map provides information about the maximum and minimum of electric field distribution inside the cavity. The scan step in X and Y direction is 100 nm and 10 nm respectively. The black color represents the minimum intensity whereas white color represents maximum intensity. The minimum of intensity at center of the cavity is due to redshift in cavity resonance wavelength. This mode mapping technique is very versatile and can be implemented to image the mode of various kinds of cavities and waveguide structures.

Conclusion

We have reported on the preliminary developments of a new technique to study the interaction between a nano-object and the fundamental resonant mode of a photonic crystal cavity. This technique relies on the measurement of the intensity variations of the out-of-plane losses of the mode, which are induced by the refractive index perturbation due to presence of the nano object in the near field of the cavity. Our initial results indicate that our approach is promising for investigating the fundamental sensing limits of photonic crystal cavities.

References

[1] Y. Lai, S. Pirotta, G. Urbinati, D. Gerace, M. Minkov, V. Savona, A. Badolato and M. Galli "Genetically designed L3 photonic crystal nanocavities with measured quality factor exceeding one million", Applied Physics Letters Vol. 104, 241101,2014

[2] Yoshihiro Akahane, Takashi Asano, Bong-Shik Song & Susumu Noda "High-Q photonic nanocavity in a two-dimensional photonic crystal" Nature, Vol. 425, 2003.

[3] Joel P. Goldena, Tamara M. Floyd-Smithb, David R. Mottc, Frances S. Liglera, "Target delivery in a microfluidic immunosensor", Biosensors and Bioelectronics, Vol. 22, Issue 11, 2763–2767, 2007.

[4] Costa Nicholaou, "Improving the Detection Limit of Planar 2D Photonic Crystal Slab Refractive Index Sensors", PhD thesis, University of Toronto, 2013.

[5] Daniel Pedone,Martin Langecker,Gerhard Abstreiter and Ulrich Rant, "A Pore-Cavity-Pore Device to Trap and Investigate Single Nanoparticles and DNA Molecules in a Femtoliter Compartment: Confined Diffusion and Narrow Escape", Nano Letters, Vol. 11, 1561–1567, 2011.