Interactions with a photonic crystal micro-cavity using an AFM in contact or tapping mode operation

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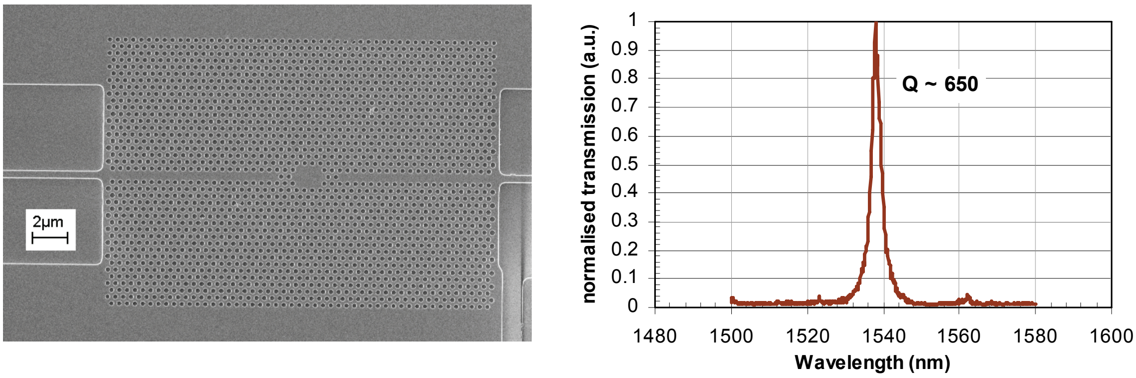
In this paper we show how the evanescent field of a localized mode in a photonic crystal micro-cavity can be perturbed by a nano-sized AFM tip. Due to the high field intensities in the cavity, we can see a significant change in output power when the tip is brought into the evanescent field in either contact or tapping mode operation. We find a 4 dB modulation, when using a Si_3N_4 tip and we show that the transmittance can be tuned from 0.32 to 0.8 by varying the average tapping height.

Introduction

Photonic crystal (PhC) micro-cavities (MC) are increasingly important building blocks in integrated optics. However, the strong dependence on the geometry of the MC cavity properties demands high-resolution fabrication processes to satisfy the designers' criteria. Even though nanotechnology-based fabrication advances rapidly, errors in the fabrication process are still inevitable due to variations in the fabrication process. This has led to an increase in attention for mechanical tuning [1, 2]. In this research we focused on mechano-optical interactions through the evanescent field, which have been utilized in, for example, sensors [3] and actuators [4]. In traditional mechano-optical approaches, the size of the object placed in the evanescent field is much larger than the optical wavelength to obtain a sufficiently large phase shift while avoiding strong attenuation. However, an optical micro-resonator providing a strongly enhanced field in a small volume (that is, having a high quality factor to modal volume ratio Q/V [5]) can have a strong mechano-optical interaction with sub-wavelength-sized dielectric objects. For example, the optical transfer function of an MC realized in silicon on insulator (SOI) can be strongly affected by an object with a minimum radius as small as 10 nm in close proximity to the resonator. In this research we use a scanning atomic force microscope (AFM) [6] with a dielectric tip for the mechano-optical interactions with the MC. We show that the AFM can be used in both contact mode and tapping mode to achieve strong interactions with the PhC MC.

Design and Setup

The experiments reported in this paper were performed on a PhC MC design in SOI (220 nm device layer thickness on 1 μm buried oxide) in a triangular lattice with 440 nm period and 270 nm hole radius. For practical purposes we designed a relatively large Fabry-Perot-like cavity (~ 2 μm) terminated by two holes on each side in a PhC waveguide (see Fig. 1a). This high-finesse cavity has a Q of about 650. This Q value was sufficient for our purpose, showing already a strong interaction of the probe with the cavity resonance, although much higher Q's can be attained, if needed, by optimizing the cavity design [5]. For feeding the PhC cavity we simply used W1 waveguides (i.e. one row of holes left out). The connecting photonic wires had a width of 600 nm, which ensures single TE-mode operation for wavelengths around 1550 nm. The structure as shown in the SEM photo in Fig. 1a, was fabricated (at IMEC, Belgium) using a process [7] involving deep UV lithography (λ = 248 nm) and reactive ion etching. The resonance wavelength was measured to be 1539.25 nm, see Fig. 1b.



(a) (b)

Fig. 1. ***(a)*** *SEM photo of the PhC MC.* ***(b)*** *The normalized spectral response.*

A scanning probe AFM was combined with a standard end-fire transmission setup for performing the nano-mechano-optical tuning experiments. A schematic representation of the setup is shown in Fig. 2.

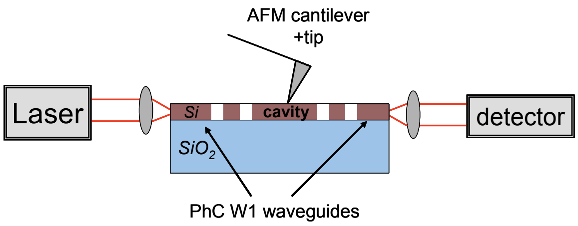
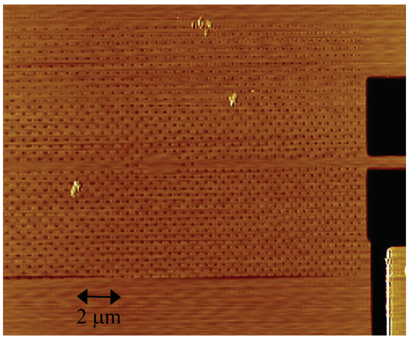


Fig.2 *A schematic representation of the dual-measurement setup.*

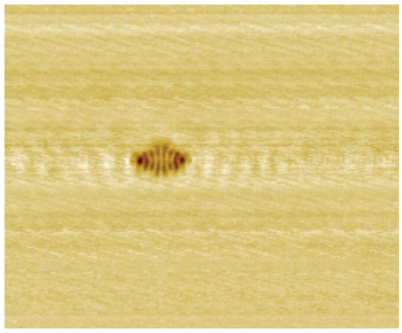
The AFM could be operated both in contact mode (dragging the tip over the sample) and in tapping mode. The cantilever was driven at its resonance frequency (~ 63 kHz) for tapping mode operation. The tip was scanned over the sample in a raster scan (256 x 256 points). The height (obtained from the AFM deflection signal) and the optical transmission could be determined at each raster point. By experiments [2] and modeling it was found that a small silicon nitride probe having a relatively low refractive index n (Si_3N_4, $n \cong 2.0$) can be used to map out the standing wave pattern in a PhC resonator. The probe induces a local phase shift, which results in a shift of the resonance to higher wavelengths. A drop in transmitted power can be observed, when the laser wavelength remains constant (at the initial resonance wavelength). A silicon (Si, $n \cong 3.5$) probe tip can be selected for obtaining an even higher interaction with the MC. This was also done for the tapping experiments presented in this paper.

Experiments

The size of the scanning window was set to its maximum value (20 µm) to locate the MC. By scanning in contact mode with a Si_3N_4 tip (minimum radius 10 nm) over the sample, we obtained the structure geometry from the AFM as shown in Fig. 3a and simultaneously the transmitted power, shown in Fig. 3b. This latter figure can be interpreted as the 2-D representation of the transmitted power at the resonance wavelength versus the tip position. The dark spots corresponding to a position inside the resonator represent dips in the transmission. Outside the resonator we only find a light color, with almost no variation, because the field intensity is low at those locations.



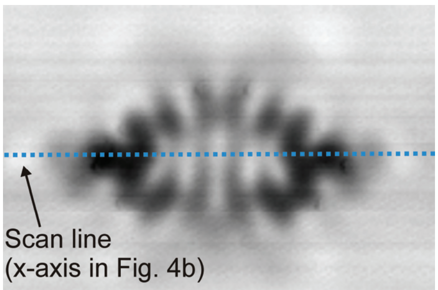
(a)



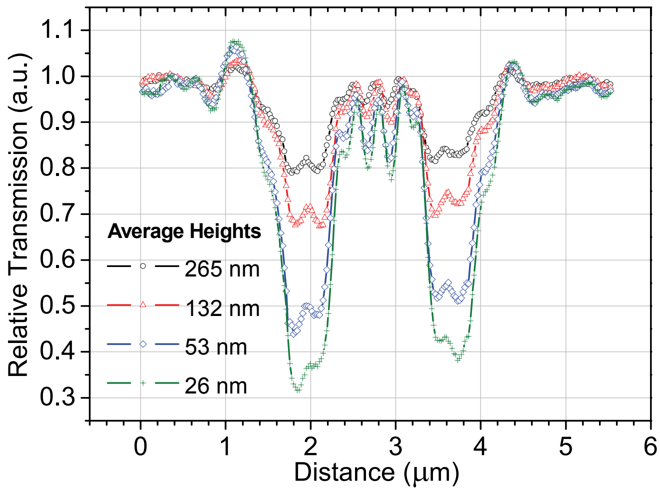
(b)

Fig. 3. (a) *AFM height data, obtained by scanning a Si_3N_4 tip over the PhC structure in contact mode.* ***(b)*** *While scanning, the transmitted power was monitored and graphically visualized in a 2D image.*

This type of resonance imaging in a PhC MC was for the first time demonstrated in [2], where a maximum modulation of about 4 dB was found for a nano-sized Si_3N_4 probe. In principle there are two ways to improve the interaction with the cavity: the first is by increasing the size of the tip, this can for example be established by focused ion beam milling [8] of the tip; the second alternative is to select a probe having a higher refractive index, for example silicon. The disadvantage of a Si probe in contact mode compared to a Si_3N_4 probe is that the Si probe wears off at a much faster rate. As a consequence, the probe size is slightly increased at each successive scan. However, this can be avoided by operating the AFM in tapping mode if the cantilever is stiff enough.



(a)



(b)

Fig. 4. (a) *A 2D representation of the transmitted power when a Si tip is scanned over the sample in tapping mode.* ***(b)*** *The graph shows the transmission over the scan line, see (a), for 4 average tapping heights. Lowering the tapping height increases the impact on the resonance, as expected.*

The result of the scan over the MC in tapping mode is shown in Fig. 4a. The tapping amplitude for this measurement was 52 nm, resulting in an average height of 26 nm. Due to the decay of the evanescent field above the cavity, the effect of the tip on average transmitted power depends on the average tip height. Because the field has an exponentially decaying shape above the cavity, the interaction between the tip and the MC resonance will also be approximately exponentially in shape. By varying the tapping amplitude above a pre-selected position, the transmission can be carefully tuned. The shift in transmission can be related approximately to a wavelength by using the transmission spectrum shown in Fig. 1b with the assumption that the scattering losses can be neglected, which is consistent with modeling (not shown in this paper). The on/off ratio of the transmitted power can be tuned from 0.8 (265 nm average height above the sample) to a value as low as 0.32 (26 nm). The minimum value is limited here by the minimum feasible tapping amplitude (2 x 26 nm = 52 nm).

Conclusions

We have shown that it is possible to interact with a PhC MC resonance using a nano-sized dielectric AFM tip. In contact mode, using a Si_3N_4 tip, we were able to map-out the standing-wave pattern in the MC. The maximum modulation depth found was 4 dB. Furthermore we showed that the AFM can also be operated in tapping mode to tune the transmitted power and thus the resonance wavelength (neglecting scattering). The major advantage for future integrated applications is that a tip wears off at a much lower rate when operated in tapping mode. This is particularly interesting when a silicon tip is employed.

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