Modeling and Experimental Verification of the Dynamic Interaction of an AFM-Tip With a Photonic Crystal Microcavity

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***Abstract*—We present a transmission model for estimating the effect of the atomic-force microscopy tapping tip height on a photonic crystal microcavity (MC). This model uses a fit of the measured tip-height-dependent transmission above a "hot spot" in the MC. The predicted transmission versus average tapping height is in good agreement with the values obtained from tapping mode experiments. Furthermore, we show that for the existing, nonoptimized structure, the transmission coefficient can be tuned between 0.32 and 0.8 by varying the average tapping height from 26 to 265 nm. A transmission larger than that of the undisturbed cavity at resonance was observed at specific tip locations just outside the cavity-terminating holes.**

***Index Terms*—Atomic-force microscopy (AFM), integrated optics, modeling, near-field microscopy, optical microcavities (MCs), optical variables measurement, photonic crystal (PhC).**

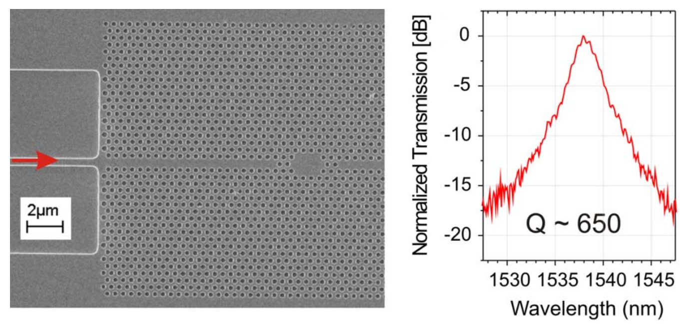

Fig. 1. Left: SEM picture of the PhC MC. Right: Corresponding normalized transmission.

I. Introduction

PHOTONIC crystal (PhC) microcavities (MCs) are key components in sensor, lasing, or nonlinear switching applications. More complex device functionalities can be achieved by modeling the PhC design by using, for example, a 3-D finite-difference time-domain method to predict its optical response characteristics. Besides the transmission and reflection of a PhC structure, a map of the field inside the MC can be helpful in experimental studies of device dynamics. Such field maps have been generated by scanning near-field optical microscopy (SNOM) [1]. However, for higher quality (Q)-factor PhC MC, SNOM is less suitable since it interferes with the field inside the cavity. We have recently proposed a novel method, now denoted as transmission-based SNOM or T-SNOM, to map the effect of nanomechanical interactions with the field within the PhC [2]. The method is based on mapping of the optical transmission while scanning an atomic-force microscopy (AFM) probe in contact over a PhC MC. The results show a close agreement with the calculated optical standing wave pattern. The disadvantage of contact mode operation is that the tip (especially when using a Si tip on a Si PhC device) may wear off at a fast rate [3]. To preserve the integrity of fragile PhC devices (e.g., containing polymer or other soft infiltrates), operating the AFM in the well-known tapping mode [4] would be preferable. The response of a PhC MC scanned in tapping mode is nontrivial because the height of the tip is varied in time in the exponentially decaying evanescent field of the optical mode. The tapping frequency (in our case 63 kHz) is much higher than the scan frequency (around ten pixels per second). In this letter, we show how the response of a PhC MC can be predicted as a function of the tapping amplitude using a simple model and a fit of the measured approach curve (height sensitivity curve).

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II. Model

A. Design and Setup

The device used for the experiments is a PhC MC in SOI (220-nm device layer thickness on 1-μm buried oxide) in a triangular lattice with 440-nm period and 270-nm hole diameter. For practical purposes, we designed a relatively large Fabry–Pérot-like cavity (~ 2 μm long), terminated by two holes at each side in a PhC waveguide (see Fig. 1). This high-finesse cavity has a $Q \sim 650$. This Q-value was sufficient for our purpose, showing already a strong interaction of the probe with the cavity resonance, although much higher Qs and thus interaction 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

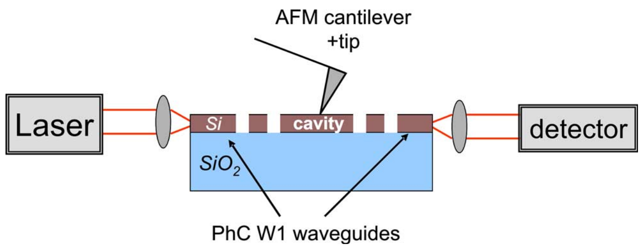

Fig. 2. Schematic representation of the dual-measurement setup.

had a width of 600 nm, which ensures single TE-mode operation for wavelengths around 1550 nm. The structure shown in Fig. 1 was fabricated (at IMEC, Belgium) using a process [6] involving deep UV lithography ($\lambda = 248$ nm) and reactive ion etching. The resonance wavelength was measured to be 1539.25 nm (Fig. 1).

The measurement setup was formed by combining a scanning cantilever AFM [7] with a standard end-fire transmission setup for performing the nanomechano-optical experiments. A schematic representation of the setup can be found in Fig. 2 (see also [8]). 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.

A raster scan was conducted by scanning the tip over a grid of 256×256 points. The height (obtained from the AFM height piezo at constant tapping amplitude) and the optical transmission could be synchronously determined at each raster point. By experiments [8] and modeling [2], it was found that a small silicon nitride probe having a relatively low refractive index n (Si_3N_4, $n{\sim}2.0$) can be used to map out the standing wave pattern in a PhC resonator. This can be explained by the local phase shift induced by the probe, which results in a shift of the resonance to higher wavelengths. Because of this shift, a drop in transmitted power can be observed if the laser wavelength remains constant (at the initial resonance wavelength). A silicon (Si, $n \sim 3.5$) probe tip yields an even stronger interaction with the MC [2], and was also used for the tapping experiments presented here.

B. Approach Curve

First the transmission as a function of the tip height above the sample was determined. This was not conducted in tapping mode, but by lifting the tip and cantilever assembly up and down over a scan line (shown later in Fig. 4) using a sawtooth-shaped vertical movement. The period of the sawtooth signal was chosen to be slightly larger than the time needed to measure a single scan line of 256 points. By repeating the measurement over this scan line for 256 times, we could determine the transmission at the resonance wavelength as a function of the tip height. The difference in periods should be small enough to shift one period over the 256 scanned lines to obtain the full approach curve, i.e., transmission values for tip heights in the range 0 to1 μm. The result of this experiment is displayed by the blue (interrupted) curve in Fig. 3. Since the evanescent field decays exponentially outside the resonator, we have chosen to fit the transmission (interaction) curve with a simple exponentially decaying function. This fit, characterized by the equation in Fig. 3, is represented by the red (solid) curve.

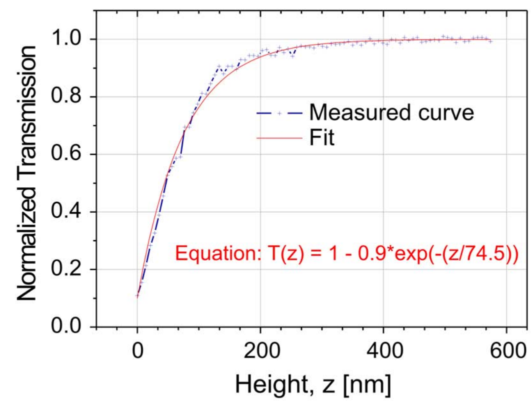

Fig. 3. Measured and fit transmission curve versus the height z of the tip above the sample.

C. The Model

The motion of the tip in tapping mode can be described by a cosine function which gives the tip height z as function of time t and average tip height h, where $z = 0$ corresponds to tip-specimen contact

$$z = h[1 + \cos(\omega t)]. \tag{1}$$

This function can be substituted in the fit for the height and time-dependent transmission function (approach curve) shown in Fig. 3 to yield

$$T(h,t) = B - A\exp(-\alpha h[1 + \cos(\omega t)]) \tag{2}$$

where A, B, and α are constants. The time averaged transmission T_{avg} can be calculated as follows:

$$T_{\text{avg}}(h) = \frac{1}{T_0}\int_0^{T_0} \{B - A\exp(-\alpha h[1 + \cos(\omega t)])\}\, dt \tag{3}$$

where T_0 is the period of one oscillation of the cantilever plus tip ensemble. Since the photodetector used in the measurement is relatively slow, having a time constant in the order of milliseconds, $T_{\text{avg}}\ (h)$ was automatically averaged over approximately 100 cycles.

III. Experimental Verification

A typical image of a tapping mode experiment at the cavity resonance wavelength is shown in Fig. 4. The dark areas in this two-dimensional representation of the transmitted power represent the places where the transmission drops due to the interaction with the tip [2], [8]. For an average tapping height of 53 nm, we find a maximum drop in transmission of ~3.5 dB, and for an average tapping amplitude of 26 nm ~5 dB (see Fig. 5).

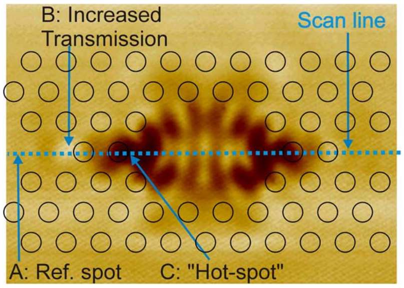

Fig. 4. A 2-D representation of the transmission for $h = 53$ nm. The mask layout (black circles) has been overlaid according to the measured AFM height data. The dark spots indicate a drop in transmission, i.e., the cavity is slightly off resonance for an AFM-tip at the dark spots [8]. The scan line corresponds to the distance axis in Fig. 5.

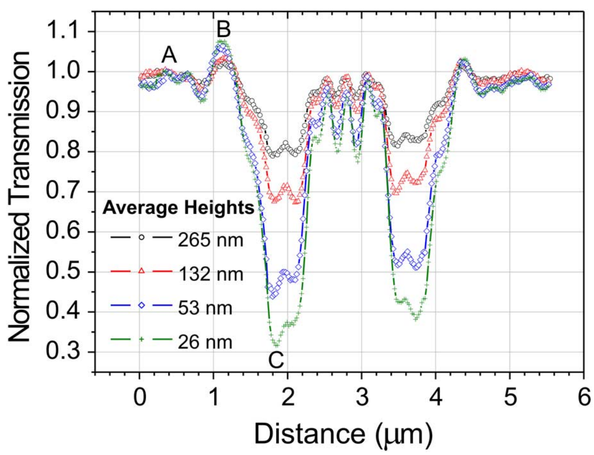

Fig. 5. Measured transmission on the scan line (see Fig. 4), normalized to the value at position A, for four different tapping heights.

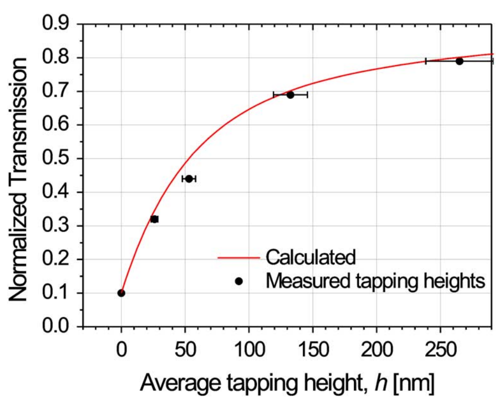

Fig. 6. Comparison between the calculated average tapping height dependent transmission curve and the values measured at five different tapping amplitudes, obtained from Fig. 5.

The scan line used for the tapping experiments presented in Fig. 5 is displayed as the dashed (blue) horizontal line in Fig. 4. Four different average tapping heights (1/2 the tapping amplitude) from 26 to 265 nm were chosen for verification of the presented model. The transmission was normalized to the transmission at a reference position exhibiting minimum interaction, indicated by A in Fig. 4. The transmission at this point was found equal (see Fig. 4) to the transmission found for the tip further outside the cavity and the waveguide. By reading the values at position C (the hot spot), we find the normalized transmission for verification with the model at the four average tapping eights.

We observe another interesting phenomenon in Fig. 5; just outside the cavity (before the two cavity-terminating holes, at spot B), we see an increase in transmission of up to 8% above the transmission at the low-interaction reference position A. In preliminary simulations, we find that three mechanisms may contribute to this effect: more light is coupled into the resonator by better matching of the wave-vector components in the W1 waveguide and the resonator, and/or the symmetry of cavity is improved by the presence of the tip, and/or the probe suppresses out of plane scattering at this spot. Further investigations of a similar effect can be found in [2].

In Fig. 6, we show both the results of the calculations and the measurements performed at four tapping amplitudes. The calculated curve was obtained from the model by calculating the average transmission as a function of h by using the measured approach curve (Fig. 3). We see that the transmission as a function of the average tapping height can well be approximated by the method presented in this letter. The small deviations could be explained by the uncertainty in the initial tapping amplitude of about 10%.

IV. Conclusion

We have shown that placing the AFM tip at the spot before the start of the cavity can increase the transmitted power above the level for the resonator without the presence of the AFM tip. Furthermore, we have shown a simple and fast way to determine the transmission as a function of the tapping amplitude using a simple model and an approach curve. These results are important for practical implementations of the T-SNOM characterization technique for optical resonators.

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