

Mapping the field distribution of a resonator in a photonic crystal slab, using transmission SNOM

René M. de Ridder, Wico C.L. Hopman, R. Stoffer, and Kees O. van der Werf
 University of Twente, MESA+ Institute for Nanotechnology, Enschede, The Netherlands
 R.M.deRidder@utwente.nl

Abstract: *Transmission scanning near-field optical microscopy (T-SNOM) is a recently introduced method for imaging optical intensity distributions in dielectric waveguiding structures, with a resolution below the diffraction limit. It is in particular suitable for mapping out standing-wave patterns in resonators. Application of the method to a Fabry-Perot-like cavity in a line-defect waveguide in a photonic crystal slab is demonstrated. Two different two-dimensional models have been used to verify that the T-SNOM image is a good representation of the optical intensity distribution in the resonator.*

Introduction

Scanning near-field optical microscopy (SNOM) methods [1], can provide the resolution below the diffraction limit that is required for measuring the field distribution in high-refractive-index microcavities, e.g. in photonic crystals. The interpretation of images obtained by such methods may be challenging because the probe that is used for local light collection and/or illumination also perturbs the optical structure under investigation. Although probe tips can have diameters below 100 nm, their effect can certainly not be neglected when small high-Q resonators are to be characterised. Especially metal-clad tips, that provide the best spatial resolution, may strongly affect the optical field, thus making the interpretation of such measurements difficult. In particular, this can be a problem with high-Q resonators which can be considerably detuned by the presence of a nano-sized probe [2, 3, 4]. The perturbation of the field by the probe is essential for obtaining resolution below the diffraction limit by converting part of the evanescent field to radiation. Recently we [4] and others [5] have demonstrated a related method, now called transmission scanning near-field optical microscopy (T-SNOM), where the functions of light collection and illumination on the one hand are separated from the function of perturbation on the other hand. The effect of this perturbation of the field by a dielectric or metallic probe is measured through the light that is transmitted through (or back-reflected from) the structure. The method is especially useful for mapping out standing-wave patterns. Although other SNOM types, like photon scanning tunnelling microscopy (PSTM) have a broader field of applicability (not requiring transmitted or back-reflected light to be available for analysis), T-SNOM has several advantages compared to PSTM. The scanning tip can be significantly smaller (potentially increasing the resolution) without necessarily decreasing the

sensitivity; there is a large freedom in choosing the tip material, allowing to select the strength of the mechano-optical interaction; the availability of a larger optical signal improves the signal-to-noise ratio, thus allowing less complicated detectors and signal processing electronics. In this paper we will explain the method, show some results for a Fabry-Perot-like cavity resonator in a photonic crystal slab, discuss the interpretation of the results, and show through simulations that the T-SNOM image indeed closely resembles the intensity distribution in the unperturbed resonator.

T-SNOM operation

The principle of the set-up is shown in Fig. 1. The tip of an atomic force microscope (AFM) probe is scanned over the surface of the photonic structure, while the light transmission through the structure is recorded for each tip position. The strongest interaction can be expected at those positions where the optical field has the largest intensity, so that the optical field distribution is effectively mapped out. The AFM probe can be scanned across the device either in contact mode or in tapping mode. In contact mode the highest sensitivity and resolution can be expected, but damage to the tip or the structure may easily occur. In tapping mode, damage is much less likely to occur, but resolution and sensitivity may be less because of the reduced optical intensity in the evanescent field compared to that of the diffraction limited radiation field. However, as was recently pointed out by Li et al. [6], this height-dependent differential sensitivity may be exploited for discriminating between the evanescent field and the radiation field by using the tapping mode with a suitable signal processing method.

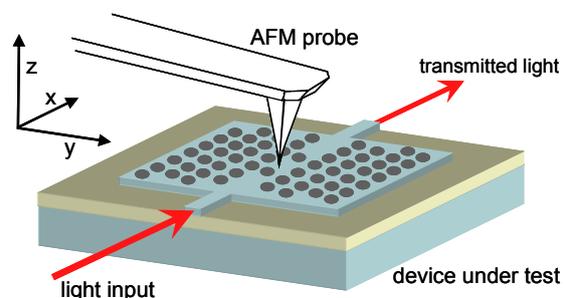


Fig. 1: T-SNOM set-up. Light from a tuneable laser is coupled into the device under test using a microscope objective. The transmitted light is collected on a photodetector, and the transmission is recorded for each position of the scanning AFM tip.

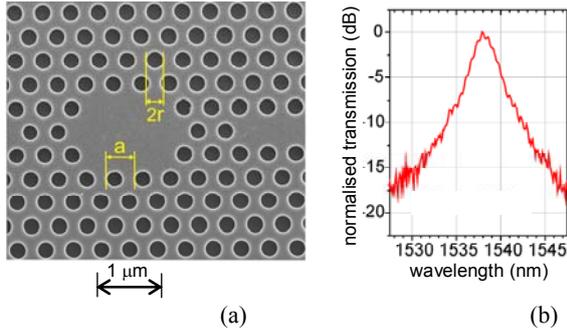


Fig. 2: Device under test. a) SEM image of the structure, a Fabry-Perot-type cavity formed between extra holes in a W1 waveguide in a photonic crystal slab. b) Transmission spectrum of the undisturbed device around a resonance wavelength. The quality factor $Q \cong 650$.

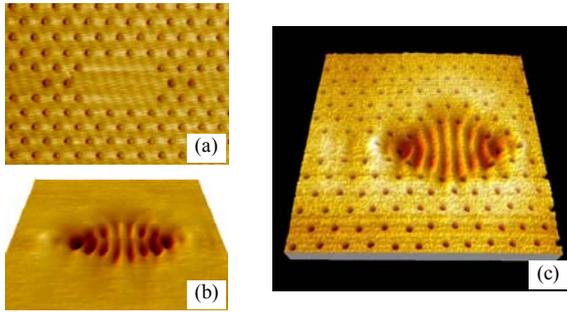


Fig. 3: Image formed by scanning an AFM tip over the top surface of the resonator structure. a) Height data (conventional AFM image). b) Optical transmission versus AFM tip position (T-SNOM image). c) Superposition of images a) and b), showing the location of interaction maxima relative to the structural device features (hole boundaries enhanced for clarity).

In Fig. 2a we show a SEM picture of a resonator in a silicon-on-insulator photonic crystal slab. The top silicon layer is 220 nm thick, the lattice parameter $a = 440$ nm, and the hole radius $r = 270$ nm. The fabrication process was described in [7].

Figure 3 shows that the combination of the height mapping (conventional AFM image, Fig. 3a) with the optical transmission mapping, Fig. 3b, results in a map, Fig. 3c, of the locations of maximum probe interaction with respect to the resonator topography. In this experiment we used a silicon nitride AFM tip with approximately 10 nm radius.

Modelling T-SNOM

As we demonstrated before [4], the presence of an AFM tip in the near field of a microcavity resonator may affect the losses (scattering, absorbing or guiding away part of the light) and the tuning (local increase of the average refractive index). The resulting change in Q-factor or resonance wavelength will affect the measured transmission through the device under test. Intuitively, this effect is expected to be maximum at locations of intensity maxima and to vanish at locations where the optical field is negligible. We investigated the validity of this assumption by modelling the optical microcavity in the photonic

crystal and its interaction with a dielectric AFM probe tip. Since the problem is essentially three-dimensional, the model should be 3-D in principle. However, for practical reasons of computing resources, we have chosen to test two different 2-D models in two cross-sectional planes of the composite resonator-probe structure.

The first model, illustrated by Fig. 4, is in the x-z plane, c.f. Fig. 1. This model translates our problem into a cavity between two short grating sections. The AFM-probe is modelled here as a semi-infinite 50 nm thick silicon slab in the y-z-plane. Using a quadririrectional eigenmode propagator (QUEP) [8], the power transmission T and reflection R are calculated, and, assuming no absorption, the loss due to scattering S is found from the energy balance $T + R + S = 1$. Figure 5 shows the spectra obtained for the unperturbed resonator (without AFM tip). Next, the wavelength is fixed at $\lambda_r = 1.5388$ nm, (resonance), and the tip is scanned along the x-direction, while being in contact with the top surface of the resonator. The resulting variation of T with the probe position is shown in Fig. 6. Assuming that the main effect of the probe is a detuning of the resonator, the T -curve in Fig. 5 is used for calculating a wavelength shift that is equivalent to the change in T . The assumption of detuning only is not completely valid, but the consequences of the resulting error are small as will be reported elsewhere [9]. Finally, this calculated wavelength shift is shown in Fig. 7, together with the intensity distribution in the unperturbed resonator. The horizontal position scale for both curves is identical, and the vertical intensity scale is matched to the wavelength shift scale for maximum visual correspondence. It can be seen that the AFM-probe induced wavelength shift matches the intensity distribution of the undisturbed resonator quite well.

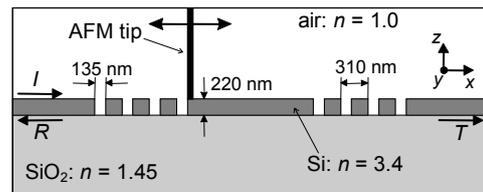


Fig. 4: Model used for simulating AFM-tip interaction with optical field in photonic-crystal microresonator.

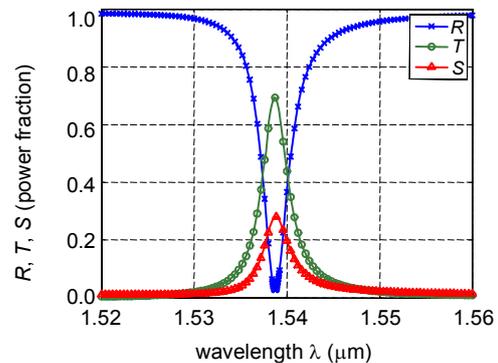


Fig. 5: Calculated transmission (T), reflection (R) and scattering ($S = 1 - T - R$) spectra of the unperturbed resonator.

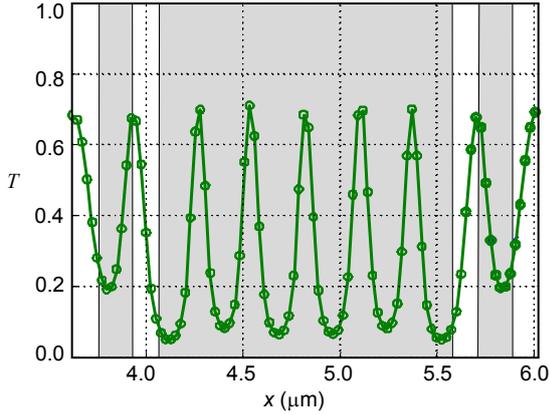


Fig. 6: Calculated transmission (T) through the resonator, versus the x -position (see Fig. 4) of an infinitely long, 50 nm wide silicon AFM tip. The white vertical bands indicate the hole locations. The calculation was done at the resonance wavelength of the unperturbed resonator.

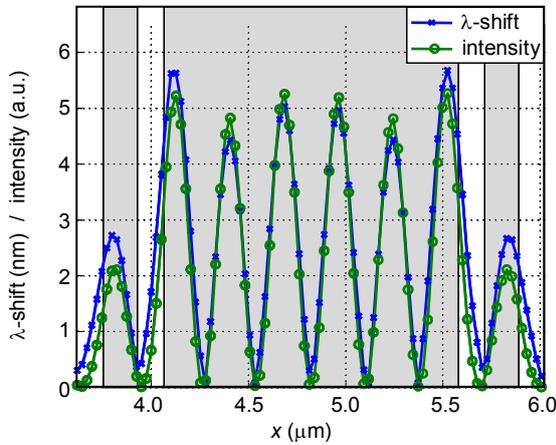


Fig. 7: Equivalent wavelength shift due to *local perturbation* by AFM tip, (calculated from Fig. 6, using Fig. 5), and calculated intensity distribution in the *unperturbed* device.

The second model maps the resonator and AFM probe on the x - y -plane, parallel to the photonic crystal slab. The photonic crystal structure is “flattened” using a kind of effective index approach. The refractive index values ($n_{\text{slab}} = 2.9$ and $n_{\text{hole}} = 1$) to be used in the simulation were chosen such that the calculated standing wave pattern in the undisturbed structure matched the experimental observation. Figure 8 shows this intensity distribution at resonance, calculated using a finite-difference time-domain (FDTD) method. The effect of the AFM-probe is modelled by introducing a small square (120 nm on a side) with a slightly increased refractive index superimposed on the refractive-index pattern of the resonator. The model was then recalculated many times, each time shifting the square representing the tip to a new position on a 40 nm grid overlaying the structure, thus mapping the power transmission versus probe position. The relatively large size of the square and the grid were chosen for keeping the computational effort within reasonable bounds. As this purely 2D model cannot account for out-of-plane scattering, it models just the detuning effect of the AFM tip.

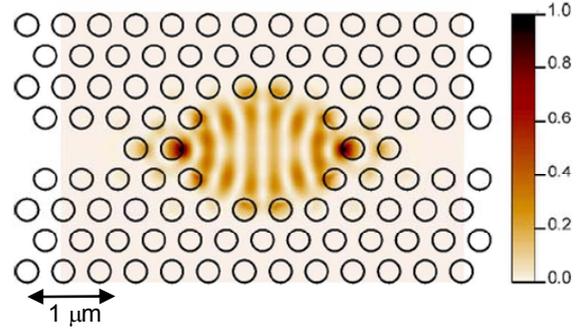


Fig. 8: Computed optical intensity distribution of the undisturbed resonant mode (2D FDTD).

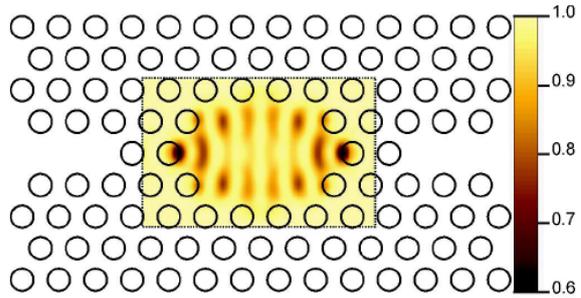


Fig. 9: Simulated T-SNOM image obtained by calculating (using 2D FDTD) the transmission through the resonator versus the position in the resonator plane of a small (120 nm x 120 nm) region of slightly increased refractive index ($\Delta n = 0.2$) representing the local effect of the AFM tip.

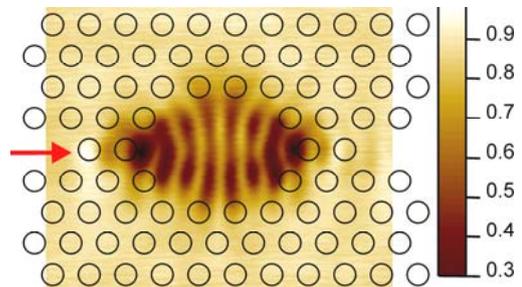


Fig. 10: Measured T-SNOM image, taken at the undisturbed resonance wavelength, using a silicon nitride AFM tip in contact mode.

The transmission value at each position of the square is converted to a colour of a pixel that is plotted at that position in a map of the structure. Figure 9 shows the result of such a sequence of calculations which simulates the scanning of the AFM tip over the resonator surface. Finally, Fig. 10 shows a T-SNOM measurement of the standing-wave pattern at resonance, at the surface of a photonic-crystal microcavity. Figures 9, 10 and 11 have been reproduced at the same scale in order to facilitate the comparison between the calculated intensity pattern, the simulation, and the measurement. A good agreement between these results can be seen, indicating that a T-SNOM mapping can give a good representation of the intensity distribution in a cavity. A more detailed account of these modelling methods and results will be published elsewhere [9].

The measurements presented here do not show the limits of resolution that can be obtained with T-SNOM. Of course, the demonstrated resolution (here about 100 nm) cannot be better than the finest detail in the intensity distribution that is mapped. Experiments at shorter wavelengths and with cavities in different materials are needed to explore the limit of resolution of this method.

Conclusions

Transmission scanning near-field optical microscopy (T-SNOM) was found to be a useful and convenient tool for mapping out the intensity distribution of a standing-wave pattern in an optical microcavity in a photonic crystal slab. Calculations using 2D models in cross-section and “top view”, simulating T-SNOM operation demonstrate that the obtained image is a good representation of the intensity distribution. The simulated pattern matched the actually measured data rather well. We believe that this method has a wider range of applicability.

Acknowledgments

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