Simulation and Analysis of SNOM Measurements using Rigorous Coupled-Wave Analysis

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Rigorous Coupled-Wave Analysis (RCWA) is applied to analyze different influences on the resolution of Near-field Scanning Optical Microscopy (SNOM) images. Furthermore, we simulate how the presence of a fiber tip alters the electromagnetic field during a measurement and compare the numerical result to the undisturbed electric field intensity.

1 Introduction

Near-field scanning optical microscopy (SNOM) is a method, which acquires evanescent field information, thus overcoming the Abbe resolution limit. It is a technique used for sub-lambda imaging at optical frequencies in experimental physics [1]. SNOM is generally thought to be understood well, since it works well in practice and experimentally one finds that the resolution is in the order of few tens of nm [2]. In the past, several attempts have been made to simulate the coupling of light into a fiber tip, using for example the beam propagation method [3] or the Finite Difference Time Domain method [4]. In this publication we apply Rigorous Coupled-Wave Analysis (RCWA) [5] and the recently developed Localized Input Field (LIF)-RCWA [6] to simulate SNOM measurements. In Sec. 2 we model the scanning of a narrow focal spot and we investigate how different parameters influence the resolution of SNOM images. In Sec. 3 we study how the presence of the SNOM-probe changes the electromagnetic field during a measurement. To this end we compare the undisturbed electric field intensity to the field distribution altered by retroactive effects.

2 Scanning a narrow focal spot

In this section we conduct a simulated SNOM-measurement, where a narrow focal spot serves as a sample. Fig. 1 illustrates the permittivity distribution of the fiber tip, where d_{ap} denotes the aperture diameter, α corresponds to the apex angle of the fiber tip, Δz denotes the vertical distance between sample and aperture and Δx is the lateral offset of the sample with respect to aperture. In the following we move the focus laterally across the aperture and conduct a RCWA calculation at each Δx. We obtain an intensity profile by plotting the amount of power coupled into the fiber core versus Δx. In all simulations we assume a wavelength of $\lambda = 850\,nm$, a calculation period of $P = 2\,\mu m$ and a total mode count of 101. In order to obtain a narrow focus in front of the SNOM-tip, we use the LIF-RCWA [6] to excite the 81 central modes of the incident field in TM polarization. This results in a peak width of $\sim 40\,nm$.

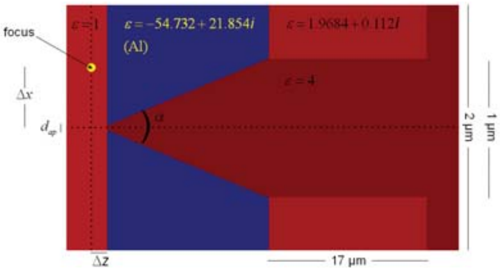

Fig. 1 *Permittivity distribution of the fiber tip.*

The power density distribution of one simulation is shown in Fig. 2. It can be clearly seen how light couples through the tip into the fiber. Also, one can see that the amount of energy coupled into the fiber is small compared to the incident power.

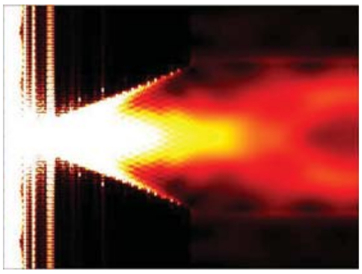

Fig. 2 *Clipped power density distribution inside a SNOM-probe for* $d_{ap} = 40\,nm$, $\alpha = 25°$, $\Delta x = 0\,nm$, *and* $\Delta z = 30\,nm$.

In the following we investigate the influence of the parameters d_{ap}, α, and Δz on the width of the resulting intensity profile. We observe that the width of the recorded peak follows the width of the aperture. The Gaussian width ranges from

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$\sigma = 24\,nm$ at $d_{ap} = 40\,nm$ to $\sigma = 84\,nm$ at $d_{ap} = 300\,nm$. As expected, the amount of intensity coupled into the fiber core increases significantly for larger aperture diameters. Varying the apex angle does not significantly change the width of the recorded peak, but the amount of intensity coupled into the fiber increases significantly for larger α. Varying Δz, we observe a peak width, which grows with Δz. The Gaussian width ranges from $\sigma = 24\,nm$ at $\Delta z = 30\,nm$ to $\sigma = 143\,nm$ at $\Delta z = 200\,nm$. The latter observation can be explained by the characteristic exponential decay of evanescent modes, which are the modes where the sub-lambda spatial characteristics are encoded. Due to the exponential decay of their amplitudes, propagation acts as a low-pass filter.

3 Scanning a grating structure

In this section we conduct a simulated SNOM-measurement of a back-illuminated grating structure in order to investigate the influence of the presence of the fiber tip on the measurement. Fig. 3 illustrates the simulated permittivity distribution. Furthermore, we assume fixed $d_{ap} = 40\,nm$ and $\Delta z = 30\,nm$. All remaining parameters are chosen in the same way as in Sec. 2.

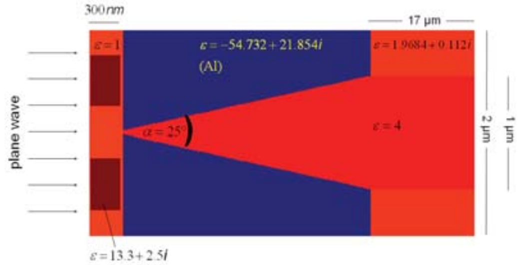

Fig. 3 *Permittivity distribution of the grating structure and the fiber tip.*

In Fig. 4 the power density distribution is shown (a) without and (b) with the fiber tip for one particular tip position Δx. It can be seen that the presence of the tip severely disturbs the power density distribution. Therefore, one might expect that the amount of light coupled into the fiber is proportional to the disturbed power. Fig. 5a shows a lateral line scan of the undisturbed power density distribution at $\Delta z = 30\,nm$. In contrast, Fig. 5b shows the amount of power, which is coupled into the fiber core as a function of Δx. It can be clearly seen that both curves are not in agreement. The width and position of the 'step' in Fig. 5b are determined by a least squares fit of a smoothened step function. We find that the width of the step $\sigma \approx 43\,nm \approx \lambda/20$ is small, but its position is shifted by approximately $\delta x \approx 82\,nm$ with respect to the original step position of the grating.

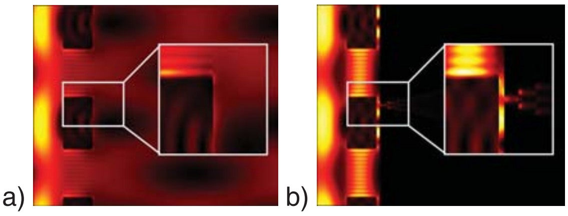

Fig. 4 *a) Undisturbed power density distribution with only the grating and b) power density distribution with fiber probe inserted.*

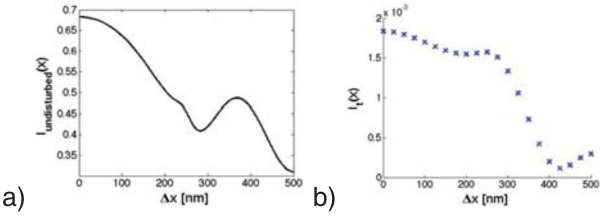

Fig. 5 *a) Line scan of the undisturbed power density distribution at $\Delta z = 30\,nm$, and b) amount of power coupled into the fiber, both vs. Δx.*

4 Summary

We simulated SNOM measurements using RCWA [5] and LIF-RCWA [6]. We find that the aperture size, the apex angle of the fiber tip, and the distance between sample and tip play a critical role when it comes to resolution and intensity coupling. Furthermore, our simulations show that retroactive effects of the fiber tip on the power density distribution are important and consequently, the intensity profile of the measurement may deviate from the true underlying structure of the sample.

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