Surface Measurement by Dual-Probe Scanning Near-Field Optical Microscopy

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A dual-probe scanning near-field optical microscope was developed. The probe pair positioning was carried out using conventional microscopy with an accuracy beyond the diffraction limit. The distance dependence of the interference light transfer was measured to show the strong far-field influences. A dual-probe observation of an optical grating was performed. Gained two signals contained various information from the probe-pair and the sample. A method to process the two signals was suggested and discussed using three dimensional finite-difference time-domain simulations. Two independent signals specific to each probe were shown to be extracted by the procedure. [DOI: 10.1380/ejssnt.2012.426]

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I. INTRODUCTION

The serial nature of the conventional scanning probe microscopies (SPM) prevents us from utilizing the techniques in observing phenomena where it is essential to examine multiple points simultaneously. There has been many attempts to overcome this barrier by developing multiprobe SPMs – both in STM [1, 2] and AFM [3]. Also in scanning near-field optical microscopy (SNOM) [4–6] dual-probe setups will enable pump-probe [7] or correlation measurements, which are difficult in conventional SNOMs. We have developed a dual-probe scanning near-field optical microscope (D-SNOM), a pair of SNOM probes resting on mutually independent piezoelectric tubes, to investigate spatio-temporal correlations in optical phenomena in the sub-wavelength area.

Most of the recent studies on multiprobe SPM concerns their goal: applications to physical property measurements. But better applications could be made on the basis of deeper knowledge of what happens in normal SNOM measurements in dual-probe configurations. Here we concentrate on topological measurements in D-SNOM.

II. EXPERIMENTAL

Our D-SNOM setup was built on a conventional inverted microscope stage (Fig. 1). Each of the two probes (Al coated commercial SNOM fiber probes with a 200 nm diameter aperture) is fixed on a piezoelectric tube on an XYZ coarse-positioning stage.

Probe locations are observed using the conventional microscope. Introducing a probe-specific wavelength light (633 and 532 nm) into each probe (Al coated commercial SNOM fiber probe with 200 nm diameter aperture), and observing the far-field emitted from the aperture through a filter transmitting only one of the wavelengths, we can obtain the far-field image of only one of the apertures. By calculating the center of gravity of the intensity image from the CCD camera, the aperture position can be gained within the accuracy beyond the diffraction limit, since the diffraction dose not move the intensity peak.

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FIG. 1: Schematic of the D-SNOM experiment.

The accuracy of this positioning scheme depends on a variety of factors, one of the most significant of which is the effect of the discretization of the image into finite pixels. The center of gravity of the light intensity calculated using the image taken by the CCD camera is

\[ r_g = \sum_{mn} \int r_{mn} l_0(r - r_g) dS_{mn}. \]  

Here \( r_{mn} \) is the center of the \((m,n)\)-th pixel, \( l_0(r) = I(r + r_g) \) is the light intensity distribution around \( r_g \), and the surface integral is over each pixel.

The accuracy of our method can be estimated by evaluating \( \Delta \equiv r_g - \bar{r}_g \) for a point light source image. The \( l_0(r) \) of the image — a bright central disk (Airy disk) surrounded by a number of fainter rings — can be expressed using the Bessel function of the first kind of order 1. \( I(r) \) for the Airy disk, which is the essential part of the distribution, can be approximated by a Gaussian of the dispersion

\[ \sigma = \frac{3.83 M \lambda}{4 \pi N A}. \]

Here \( M \) is the magnitude of the lens defined as \( M \equiv d_g/d \), the ratio of the pixel width to the corresponding length on the plane containing the probe tip. NA is the numerical aperture of the objective lens. The value 3.83 is the first zero point of \( J_1(x) \). If both the width \( L_x \) and the height...
$L_y$ of the CCD camera is sufficiently larger than $\sigma$, we can treat the camera as the two dimensional array of detectors with infinite width and height. In this case $\Delta$ can be derived from the calculation in the reverse lattice space of $r_{nm}$. Its $x$ component is

$$
\Delta_x = d_p \sum_{m=1}^{\infty} \left( \frac{-1}{d_p} \right)^m \exp \left( - \left( \frac{\pi m \sigma}{d_p} \right)^2 \right) \sin \frac{2 \pi m r_{ex}}{d} \quad (3)
$$

when $\sigma \ll L_x$. Its first term can be used to estimate the position detection error:

$$
\Delta = \frac{d_p}{\pi} \exp \left( - \left( \frac{\pi \sigma}{d_p} \right)^2 \right) \quad (\sigma \ll L_x, L_y). \quad (4)
$$

From this relation we can see that a higher precision $\Delta/M$ in the probe position detection can be achieved either by raising the magnitude of the lens or by using longer wavelength light. Although the first condition is very natural, the second one may be against our intuition at first sight. Using light of sufficiently small $\lambda$ to give $\sigma \ll d_p$, only the single pixel in which the image drops detects a meaningful amount of light and so $\Delta \sim d_p/2$. When $\lambda$ is larger, the neighboring pixels also detect the signal with different weight which depends on the image center position in the central pixel, resulting in the finer accuracy. $\Delta$ decreases as $\lambda$ increases when $\sigma < L_x, L_y$ as is stated in Eq. (4). When $\sigma$ gets comparable to the pixel size, it is expected that $\Delta$ begins to increase with $\lambda$ because the amount of light detected by each pixel does not differ much any more and the intensity resolution of the device begins to give a large error in the calculation of the center of gravity.

With our system values $\text{NA} = 0.7$, $d = 620 \text{ nm}$, and $\lambda = 560 \text{ nm}$ (average of the two wavelengths), Eq. (4) gives the accuracy on the image plain $\Delta = 0.0696 d_p$. This value corresponds to the length $\Delta/M = 43 \text{ nm}$ at the probe tip, which is about an order smaller than the wavelength.

In order to demonstrate that the absolute position detection described here has subwavelength precision we used the technique in the hysteresis removal of the piezo tubes.

We applied oscillating voltage of various amplitudes to the piezo tube and measured the position of the probe. Figure 2(a) shows one of the voltage dependencies of the displacement of a probe. We can see that the hysteresis of the piezo tube was detected with the expected accuracy described above.

Afterward the parameters of experimental equations of this dependence are determined to fit the data, which is used to compensate the hysteresis. Then applying oscillating voltage to the tube once more, we measured the deviation of the probe position from the model equations for various oscillation amplitudes up from 500 nm to 5500 nm. Figure 2(b) shows one of such dependencies. In this case the hysteresis is compensated to give the absolute positioning accuracy of 90 nm, 3% of the amplitude. Throughout the amplitude range we get an accuracy of $2 \sim 6\%$ for each experimental amplitude.

After fixing the probe positions in this way, the sample stage was moved using three additional piezoceramic tubes. Instead of the positioning lights a $\lambda = 633$nm light was injected into the probe 1 for illumination/collection-mode imaging, while the probe 2 collected the field. The probe heights can be measured and adjusted by using the probe tip as an AFM probe. In order to prevent relative probe position variation, which would make it even more difficult to interpret the gained data, the measurements were executed in the constant height mode. The decrease in the returning light intensity from the probe 1 will be called $I_1$, while the intensity collected by the probe 2 will be called $I_2$.

In D-SNOM three bodies – two probes and the sample – will be located within the vicinity to each other. This makes it difficult to interpret the meanings of $I_1$ or $I_2$, which is the theme of this paper.

### III. SIMULATIONS

In parallel with experiments three dimensional finite-difference time-domain (FDTD) method simulations [8] were performed. Each probe was supposed to be a 17.6° tapered glass fiber coated with 200um thick conductive with a 200um diameter aperture at the apex. The probe tilt was set to 20°. The surrounding 5μm cubic area was divided into a $100 \times 100 \times 100$ lattice, combined with second order Liao absorbing boundaries [9], and used for simulations. An oscillating point electric field perpendicular to the plane containing the two probe axes was put in the probe 1 (on the probe axis, 1000nm from the

FIG. 2: Piezo-tube Hysteresis detection and its compensation: (a) voltage dependence of the displacement (b) preset value dependence of the displacement after compensation.
apture) as a 633nm light source. Field intensity at the center of each probe aperture is regarded as \( I_0 - I_1 \) or \( I_2 \), where \( I_0 \) is the single-probe-case light intensity at the center of the aperture of the probe 1.

IV. RESULTS AND DISCUSSIONS

A. Interprobe photon tunneling

To demonstrate our D-SNOM we measured the dependencies of \( I_1 \) and \( I_2 \) on the inter-probe distance \( \Delta x \) (Fig. 3(a)). The two probes were located at a same height \( (h = 500\text{nm}) \) over a flat glass plate and the probe 1 was driven to approach the probe 2. \( I_1 \) dose not alter much with \( \Delta x \), which suggests that \( I_1 \) may behave as a normal single-probe SNOM. The change itself indicates, that the field emitted by the probe 2, which was originated from the far-field pattern from the probe 1 itself, causes a significant disturbance in the electromagnetic field around the aperture 1. \( I_2 \) decreases with \( \Delta x \) and has several peaks. These peaks are located at the integer times of the half wavelength, which indicates the far-field interference of the field between the probe pair. For larger \( \Delta x \) you can even see the diffracted pattern of the far-field emitted from the probe 1 (About the far-field diffraction from SNOM probes see [10] for example). FDTD simulations (Fig. 3(b)) give a good conformance with the experiments.

B. Surface measurements

Next we imaged the surface of a 1\( \mu \text{m} \)-period polyester optical grating film with this microscope with the inter-probe distance of 1200 nm. In Fig. 4(c) its cross section (sinusoid-like surface) imaged by the D-SNOM is shown. Since our D-SNOM can properly image the grating when used in the single probe (illumination/collection) mode (See Fig. 4(b)), the dirtiness of the signal at a glance must have some physical meanings. Here we notice three things: (1) \( I_1 \) may show the surface topology but with some surplus peaks. The peaks are so narrow that they do not occupy plural sampling points, the sampling period of which was 80nm. (2) \( I_2 \) doubles in wavenumber to the surface up-downs (a double-peak in \( I_2 \) between \( 3.2\mu \text{m} < x < 4.2 \), for example, corresponds to the single peak in \( I_1 \) between \( 3.0\mu \text{m} < x < 3.6 \)). (3) When an abrupt peak occurs in \( I_1 \), \( I_2 \) shows an also narrow trough, which suggests that the increased emitted field are not collected by the other probe but probably radiated to the far-field.

In order to interpret these traits, and to get a pair of SNOM data from \( I_1 \) and \( I_2 \) if possible, we performed FDTD simulations of a D-SNOM system over a 1\( \mu \text{m} \)-period sinusoidally undulating glass surface (Fig. 5). As is shown in Fig. 5(a), \( I_1 \) is insensitive to \( \Delta x \) and always acts as a single-probe SNOM. This behavior of \( I_1 \) agrees well with the experimental results stated above.
Δx dependence of $I_2$, on the other hand, has two regions concerning Δx. When $Δx \lesssim 2λ$, $I_2$ also seems to be a single-probe SNOM, which means the probe pair can be regarded as a single body. The condition $Δx \lesssim 2λ$, however, cannot be easily satisfied with two metal coated probes because of the thickness of the coating.

If $Δx$ gets larger, the wavenumber doubles. Here $I_2$ should be proportional both to the “light source” $I_1 \propto e^{iKx}$ and the single-probe SNOM image of its location $I_2 \propto e^{iK(x+Δx)}$, where $K$ is the surface wavenumber. This gives the relation $I_2 \propto I_1I_2 \propto e^{2iKx}$ in conformity both with the experiments and the simulations. This agreement suggests that it would be safe to treat $I_2/I_1(=I_2)$ as the single-probe SNOM image at the point of the probe 2.

Then let us consider about the narrow peak/trough pairs that appeared in the surface imaging of the grating. They seem to be related to the fact that the imaging was in the constant height mode, where we directly detected various sub-wavelength Fourier components of the field localized around the surface [4]. In single-probe SNOM, such high spatial frequency light intensity distribution is averaged over the probe aperture and not detected. In dual-probe case, on the other hand, the probe pair is thought to be a kind of a resonator and amplifies some selected Fourier components, the spatial frequency of which is too high to be detected in single-probe cases.

A FDTD simulation of D-SNOM measurement of a single period sinusoidal pulse structure is shown in Fig. 6. There appear many peaks and troughs that were absent in the sinusoidal (so, periodic) cases. The grating used in the experiments is not an ideal periodic structure either. In D-SNOM, where no phase information but only the light intensities are measured, it is difficult to extract any useful information from such peaks. So, for now, we will try here to neglect them. As far as we neglect only single-sample-point peaks, which are narrower than the double sample length (160 nm) the topology information must not be much affected since they are narrower than the aperture diameter (200 nm) and should not be detected by SNOM.

Let us process the D-SNOM experimental data shown in Fig. 4(c) on the basis of the above discussions. We removed peak-trough pairs (peak in $I_1$ and trough in $I_2$) that are narrow enough to occupy only one sample point. The number of the omitted peak/trough pairs was five. This corresponds to only a single point per a period and arbitrary changes of the data could be avoided. Then $I_1$ and $I_2/I_1(=I_2)$ should be two independent SNOMs. The result is shown in Fig. 7. When $I_1$ is shifted right by $Δx = 1200$ nm, it gives rough agreement with $I_2/I_1$. Effects of our configuration where the probes tilt in the opposite directions, for example, might be considered in the further investigations to interpret this rather limited agreement.
V. CONCLUSION

A dual-probe SNOM was constructed to measure the surface structure. Gained two signals contain various in-
formation from the probes-sample system but they could be processed to give two independent SNOMs.

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