Near-field optical microscope based on local perturbation of a diffraction spot

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Using a vibrating opaque metallic tip, which periodically and locally modifies the electromagnetic field distribution of a diffraction spot focused onto a sample surface through a microscope objective lens, we have observed optical resolution better than the diffraction limit both with topographical features and with purely optical ones. This procedure simultaneously generates a reflection-mode near-field optical signal and a tapping-mode atomic force microscope signal and can therefore map independently the topography and the optical properties of a specimen. © 1995 Optical Society of America

Since the introduction of local probe microscopy, a large variety of new techniques have been invented or revisited. Among them, scanning near-field optical microscopy (SNOM) has demonstrated its ability to break the resolution limit imposed by diffraction. In the classical implementation, the electromagnetic radiation (wavelength \( \lambda \)) is confined within a cone and irradiates the sample under examination through a small aperture. An alternative way of achieving a local selection of a field distribution much smaller than \( \lambda \) by using an apertureless tip has been proposed and preliminary results have been demonstrated. In aperture SNOM the presence of the opaque screen surrounding the aperture often limits study to flat samples. Inouye and Kawata used a gold probe to convert the evanescent photons localized near the sample surface into a propagating scattered light wave. More recently, a transmission–diffusion configuration was used by Zenhausern et al., who report that nanometric resolution has been achieved on a phase object with a 2-nm-radius silicon tip and interferometric detection. In general, apertureless systems work in transmission, which limits studies to transparent samples. The systems that work in reflection are not combined with atomic force microscopy (AFM) and thus are as sensitive to the local sample topography as to its optical characteristics.

We describe an apertureless SNOM that uses reflected light (important when one is testing microelectronic or magneto-optic components) and generates an optical signal much more dependent on the local optical characteristics of the sample than on its topography.

The main idea (Fig. 1, bottom) is to use the periodic vibration of a metallic apertureless tip above a diffraction spot of a laser beam focused onto the sample. The tip, whose point has been etched to less than 100 nm in radius, vibrates perpendicularly to the sample surface with an amplitude in the 50–200-nm range. During the vibration cycle, the tip is more than 100 nm away from the sample at the top of its trajectory, and it only slightly perturbs the incident light field on the sample. At the bottom of its trajectory the tip is very near the sample and generates a much greater and more local perturbation of the field, canceling this field on a submicrometer area of the sample. In this way the tip periodically greatly weakens the light field at a specific portion of the sample, which alternately does or does not take part in the detected reflected light. This concept of local perturbation of the diffraction spot was confirmed by a Rayleigh–Sommerfeld scalar field calculation that we have performed. The reflected detected optical signal thus has two components: a continuous one, which represents the far field and is associated with the laser spot diameter (~1 \( \mu \)m), and a time-varying near-field one that depends on the opti-
cal properties of a small region beneath the probe. In fact, our idea is the complementary principle of that suggested by Synge \textsuperscript{13} in 1928; instead of using a small hole in a metallic screen, we use a small metallic screen in a large air aperture.

Our experimental setup (Fig. 1, top) uses a commercial microscope equipped with a 100× objective lens (N.A., 0.85). It simultaneously permits the focusing of laser diode 1 (\(\lambda = 670 \text{ nm}\)) and the collecting of the reflected light and lets the user observe the working field (spot, tip, and sample). The tip is a tungsten cone whose point has been etched to \(\sim 100 \text{ nm}\), bent, and attached to a piezoelectric ceramic, which excites it at its resonant frequency (\(\sim 5 \text{ kHz}\)). The force constant \(k_f\) of this cantilever is 20 N/m. The amplitude of vibration is measured by a transverse probe beam focused onto the lever arm, which acts as a knife edge, and detected by photodiode 2, whose signal is processed by a lock-in amplifier.

The vibrating tip is moved near the sample, and when it reaches the surface its vibration amplitude suddenly decreases and becomes proportional to the tip–sample average distance. In fact, the tip periodically crosses the adhesion force layer (the stiffness constant \(k_f\) and the vibration amplitude are large enough so the probe does not get stuck in the adhesion layer) and taps within the repulsive atomic force field of the sample. Numerical and analytic models have allowed us to understand the behavior of the tip in interaction with a repulsive and attractive force field.\textsuperscript{14}

This tapping mode\textsuperscript{15,16} presents several advantages. First, we are sure that at the bottom of the tip trajectory the tip–sample distance is very small. Second, the linear distance–amplitude dependence easily allows the distance between the sample and the average position of the tip to be stabilized at a constant value during scanning. This prevents damage to the tip and the sample and renders the SNOM signal nearly independent of sample’s topography. Third, the output signal of the feedback loop provides a topographic image of the sample. Finally, the tapping mode almost eliminates the shear forces on the tip and their destructive influence.

The reflected light field passes through the microscope and is detected by photodiode 1 in Fig. 1. Lock-in detection provides the SNOM periodic signal measurement, and direct detection with a low-pass filter provides the continuous far-field optical signal. The large numerical aperture of the objective lens used permits the concentration of the light power at the point of the tip and prevents a background ac signal from light scattered from other parts of the wire. This fact is experimentally verified: if the diffraction spot is moved and placed next to (and not beneath) the point of the tip, then the ac optical signal goes to zero.

To demonstrate the optical resolution, we first studied a test sample whose topographic and optical properties are known. It is made up of several nanostructures prepared by x-ray lithography. In particular, we have studied two kinds of structure: a single groove, 100 nm wide and 100 nm deep; and two grooves, each 100 nm wide, 100 nm deep, and separated by 300 nm [Figs. 2(c) and 2(f)]. Each groove (Si) has an optical reflection coefficient three times smaller than that of the surrounding material (Au). Figure 2 shows the measured 870 nm \(\times\) 500 nm and 1100 nm \(\times\) 500 nm SNOM and AFM images of the sample. The expected geometric (depth, width) and optical characteristics are obtained. The apparent triangular shape of the grooves is the convolution between the 100-nm probe tip and the 100-nm structure. The resolution in the optical image is comparable with that of the AFM image: better than 100 nm.

![Fig. 2. (c), (f) Test samples; one or two grooves engraved by x-ray lithography. At the bottom of each groove (Si), the optical reflection coefficient is three times smaller than that of the surrounding material (Au). (a), (b), (d), (e) Near-field images of the test samples. One groove: (a) relief determined by AFM, (b) SNOM (amplitude). Two grooves: (d) AFM, (e) SNOM (amplitude).](image-url)
In Fig. 3 the SNOM profile of a Si groove indicates that the expected ratio of 3 between the two optical reflection coefficients is roughly achieved.

We next studied a sample made from a heterostructure of layers that exhibits different optical properties and that is cleaved so its surface is flat. Figure 4 shows the SNOM, optical far-field, and AFM profiles when we scanned from a GaAlAs layer to a GaAs area. The GaAlAs optical reflection coefficient is weaker than that of GaAs by ~5%. Despite the weak contrast between the two zones, we can clearly see the improvement in resolution when going from the far-field to the near-field response; this improvement from the SNOM signal markedly steepens the step from the lower optical average level A to the higher level B. In this case, one can consider that the near-field optical profile is purely optical and that the negligible relief contrast of the sample surface has not taken part in the variation of the SNOM signal.

In conclusion, this reflection SNOM configuration has allowed us to reach a lateral optical resolution of ~100 nm. This resolution is still modest (\(\lambda/7\)), but for the time being it is limited only by the probe size. Assuming that the skin depth of the tip material is the fundamental limit for our SNOM resolution, we can hope for a 15-mm optical resolution, which corresponds to the skin depth of tungsten at \(\lambda = 0.67 \mu m\). The combination of this system with a tapping-mode AFM allows us to keep the probe–sample separation constant. This is an advantage over most SNOM configurations, in which the relief is confounded with optical properties because the feedback loop uses an optical signal that depends on both local topographic and optical properties of the surface sample. More recently, we have studied samples (20-nm iron oxide bumps on a Si substrate) having a topography inverse that of the lithographic samples. The SNOM signal drops in response to the bumps, demonstrating the independence of the SNOM and AFM signals.

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References