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Optical method for distance and displacement measurements of the probe-sample separation in a scanning near-field optical microscope

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In this work, we present an alternative optical method to determine the probe-sample separation distance in a scanning near-field optical microscope. The experimental method is based in a Lloyd's mirror interferometer and offers a measurement precision deviation of ~ 100 nm using digital image processing and numerical analysis. The technique can also be strategically combined with the characterization of piezoelectric actuators and stability evaluation of the optical system. It also opens the possibility for the development of an automatic approximation control system valid for probe-sample distances from 5 to 500 μm . © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4947114>]

I. INTRODUCTION

Optical metrology has demonstrated over the last decades its efficacy in measuring various physical properties with high precision, contactless and ultra-fast speeds.^{1,2} Specifically, accurate distance measurements can be achieved with very high precision by using interferometric techniques.³ Scanning near-field optical microscopy (SNOM) is a visualization technique used to map the intensity distribution of evanescent electromagnetic fields.⁴ These types of fields do not radiate into free space and are confined to a surface in regions smaller than the operating wavelength. In SNOM, it is necessary to approximate a probe very close to the surface to be able to detect the signal. For visible light, the intensity of the evanescent waves decays exponentially over a distance of less than a micron from the surface. Therefore, it is clear that the positioning of the probe near the surface is a task that requires high precision. Moreover, in aperture type SNOMs a typical probe can be a tapered optical fiber with a conical tip used to collect the evanescent fields. A collision between the optical fiber and the sample usually destroys the conical shape of the tip, making it useless for SNOM measurements, and requiring a tip replacement. Bearing these reasons in mind, we propose an alternative optical method able to determine the probe-sample separation in SNOMs without adding new elements into the setup, i.e. using the same optical elements that already constitute the microscope. The developed approach provides a visual and safe alternative to approximate the optical fiber tip to ~ 5 μm above the sample in a fast and controllable way, with a measurement precision deviation of ~ 100 nm. This technique opens the possibility for the development of an automatic approximation control system which may notify the user the probe-sample separation in real time, for distances between 5 and 500 μm ; a feature that is not available in current SNOM systems. Moreover, the interference pattern can be used as a quality indicator of the probe.

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II. MATERIALS AND METHODS

The experimental setup consists of a non-commercial aperture type SNOM that is designed to work in collection mode with a tapered optical fiber as the probe (~ 100 nm radius of curvature). The tips are fabricated using chemical etching. For more details see Ref. 5. The optical fiber is glued along one arm of a quartz tuning fork that acts as a shear-force sensor [Fig 1(a)]. The other end of the fiber is connected to a photon counter to detect the optical signal of the evanescent fields.

We have complemented the setup with an additional fiber launch system for coupling a free space laser into the fiber, in such a way that it is possible to switch between detection and transmission of light through the fiber. Thus, it is possible to switch between both configurations by simply connecting the fiber in the detector or in the fiber launcher with an FC connector. This process does not modify the alignment, nor changes any other configuration of the SNOM. An He-Ne laser, at a wavelength of $\lambda = 594$ nm, is used to light up the tip of the probe [FIG. 1(c)]. The principle of operation of the proposed method consists of forming a Lloyd's mirror with the illuminated fiber tip (source) and its reflection with the sample (virtual source) [FIG. 2(a)]. The two light sources interfere and produce straight parallel interference fringes that can be observed in the back focal plane of a lens [FIG. 2(b)-2(d)]. A high resolution, charge-coupled device (CCD) camera is positioned at the focus length $f = 5$ cm of the lens to record the images. [FIG. 2(a)]. Next, the images are processed to obtain the frequency ν of the interference fringes. Since the pixel size, $s = 4.65$ μm , is given by the CCD manufacturer, we can obtain the frequency in inverse length units. To determine the frequency with the highest precision, we have developed a fitting algorithm based on Fourier transforms. Such algorithm also showed to be the fastest to converge when compared to an exact analytic intensity function fitting. After the frequency is calculated, the separation distance d can be found from the modified analytic expression of the intensity distribution⁶

$$I = I_0 \cos^2 \left(\frac{2\pi d}{\lambda f} y \right), \quad (1)$$

and since a squared cosine function has double the frequency of the original, we can find that $d(\nu) = (\nu f \lambda)/2$. It is important to note this method cannot be extrapolated to all existing kinds of SNOM systems due to its principle of operation, e.g. in cantilever based SNOMs or with metal-coated tips.

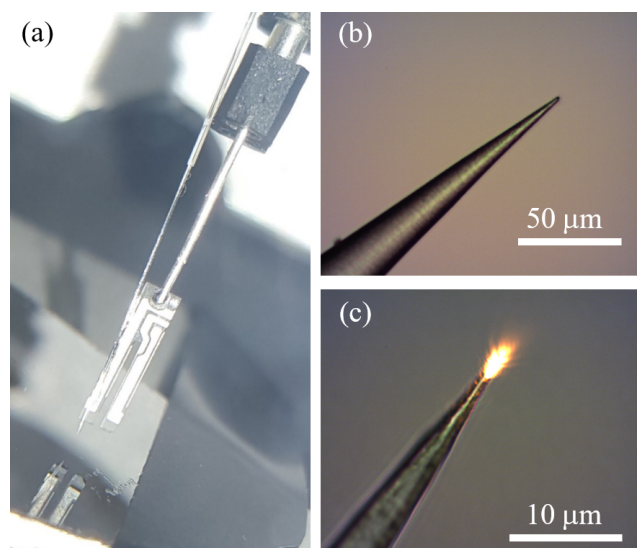


FIG. 1. (a) Digital photograph of the optical fiber glued to the tuning fork. Its reflection can be observed on the surface of the sample (down-left). (b) Optical microscope image (10x) of the tapered fiber tip. (c) Optical microscope image (100x) of the tapered fiber emitting light from the subwavelength-sized tip.

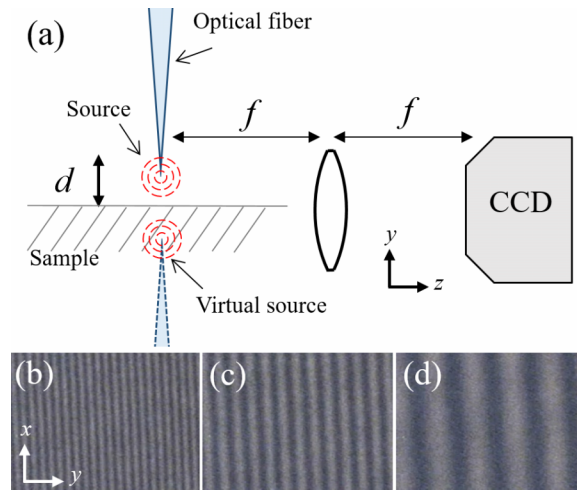


FIG. 2. (a) Schematic diagram of the proposed experimental setup used to produce the interference fringes. (b-d) Interference fringes corresponding to three different separation distances between the tip and the sample: (a) 140 μm , (b) 80 μm , and (c) 30 μm .

III. RESULTS AND DISCUSSION

Two sets of experiments were performed in order to demonstrate the reliability of the method. The first one corresponds to the characterization of the elongation of a piezoelectric actuator used for approximation in the SNOM. The second estimates the mechanical stability of the SNOM.

A. Piezoelectric actuator characterization

The characterization of a piezoelectric actuator is helpful if the parameters (maximum elongation, step resolution, voltage response, etc) are unknown a priori, e.g. when the detailed characteristics of a piezo are not available from the manufacturer, or if the piezo is already discontinued from the market. In such case, it is possible to use the aforementioned method to characterize it. The actuator is mainly used to approximate the sample to the fiber tip. As the probe-sample distance is reduced, the frequency of the interference fringes in the CCD camera decreases. The opposite occurs when the separation distance is increased. The images containing the interference fringes are recorded in the CCD camera, and are processed to obtain the frequency ν that is later translated to a separation distance d [FIG. 3(a)]. The results showed that the piezoelectric actuator elongated a maximum of 30 μm , and with a non-linear behavior, especially on both extremes, with an inflection point around 50% of the maximum input voltage [FIG. 3(a)]. Since the separation distance

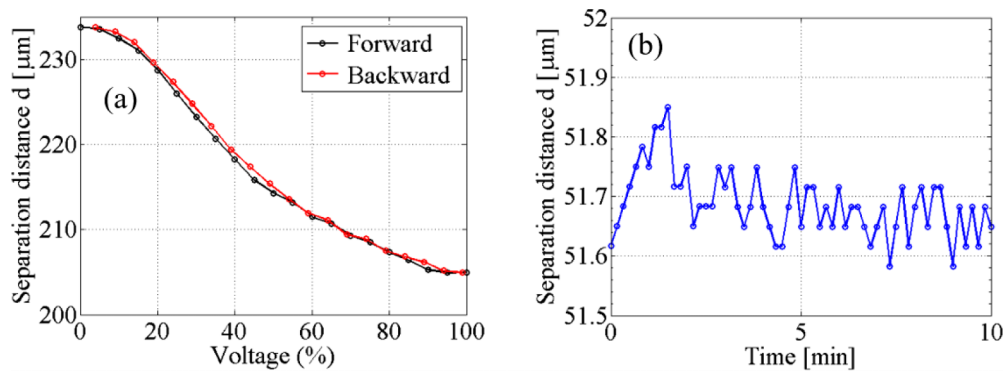


FIG. 3. (a) Separation distance between the sample and the fiber tip (probe) vs the applied voltage into the piezoelectric actuator. (b) Mechanical stability measurement obtained by measuring the separation distance in a time lapse of 10 minutes.

can be monitored in real-time using the CCD camera, it is possible to develop an approximation control system to determine the separation distance from 5 to 500 μm . It is important to note that this method does not intend to replace the current feedback control system used to maintain the probe-sample separation distance during imaging, but instead, to complement it by offering a safe and automatic alternative to approximate the fiber tip down to $\sim 5 \mu\text{m}$ above the sample.

B. Mechanical stability characterization

Mechanical stability is one of the most critical parameter when realizing SNOM measurements. Usually, floated optical tables are required for such sensitive experiments because of both the short sample-tip separation distances ($< 100 \text{ nm}$) and the high sensitivity of the shear-force zone.⁷ If the experimental setup does not meet this requirement, the imaging process will probably fail. In this context, we used our optical method to test the mechanical stability of the complete SNOM setup, including environmental parameters, such as floor vibrations, sound contamination, etc. The procedure consists of measuring the probe-sample separation distance over a period of time. We decided to measure the mechanical stability over 10 minutes [FIG. 3(b)]. During the first two minutes there was a higher instability of almost $\sim 200 \text{ nm}$, but the system gradually recovered stability with fluctuations in the separation distance of less than 100 nm .

IV. CONCLUSIONS

We presented an alternative experimental method to measure the probe-sample separation distance for application in a SNOM. The method has demonstrated to be an efficient alternative to determine the separation distance above $5 \mu\text{m}$, and a safe way to approximate the tapered optical fiber to the sample. This technique also serves as a quality indicator of the fiber tip. The interference pattern will not form straight uniform bands after the tip has suffered significant degradation, but instead, complicated interference patterns are observed. Although this method is only valid for reflective or semi-reflective surfaces or samples, it stills has a wide range of applications, e.g. in plasmonics, where reflective metal surfaces are used to excite surface plasmons.⁸ It was possible to characterize the electro-mechanical parameters of a piezoelectric actuator within the SNOM, but this method is not limited to actuators inside the microscope. The mechanical stability of the SNOM was characterized with a measurement precision deviation of $\sim 100 \text{ nm}$. The details obtained from such a meticulous characterization enrich the complete knowledge of the imaging system and opens the possibility for an automatic approximation control system with real-time knowledge of the probe-sample separation distance.

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