Interferometric method to characterize thermal elongation of near-field optics probes

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ABSTRACT

This paper presents a new method that exploits the interference and polarization properties of light to monitor, in real time, the rapid thermal elongation of near-field optical probes. The typically flat (nanometer in size) morphology of the probe apex serves as one "mirror" of a Fabry-Perot type cavity; a flat semitransparent metal coated surface constitutes the other mirror. The optical-interferometry set-up permits distance acquisition with a high frequency bandwidth (compared to other methods based on electronic feedback) while control of the light polarization allows an increase of the signal to noise ratio of the measurements.

1. INTRODUCTION

An accurate determination of the distance between a scanning probe microscope tip and a surface has been a goal for many years, leaving a trail of several methods. Tunnel current [1] provides very accurate distance control with speed limited by the high-gain current preamplifier, but has an extremely short range of useful working distances due to the fast (10 times current change for 0.1 nm motion) variation of current with tip-sample separation. Capacitance microscopy [2,3] is not as accurate, although it has a reasonable working range. Force microscopy [3] is limited in speed by the cantilever time response, which is slow for high sensitivity (high quality factor) probes unless special means are used. [4] We present here a very fast and very accurate method for monitoring the probe-sample separation, based upon a Fabry-Perot type cavity in which the end of the probe forms one end of the cavity. It has a long working range while retaining the ability to scan.

This instrument will impact three distinct areas that require the large working range, accuracy, and high-speed response. The first is probe-impact based data recording, [5,6] in which the probe is heated by a laser to lengthen the probe so that it impacts the surface and creates a hole – the data bit. The instrument can measure the various time responses of the probe, [7] and so determine the maximum writing rate. The second is optical metrology. Such a probe can be used as the sensor at the tip of a coordinate measuring machine. It could also be used in this mode as a read device for the data written by the above method. The benefit of such detection is that a constant height mode could be used, so that probe or piezoelectric response times are not limiting. The third area is that of time-resolved near-field optical microscopy (NSOM). When a pulsed laser is coupled into a NSOM probe, it will lengthen the fiber [6]. This could potentially crash the probe

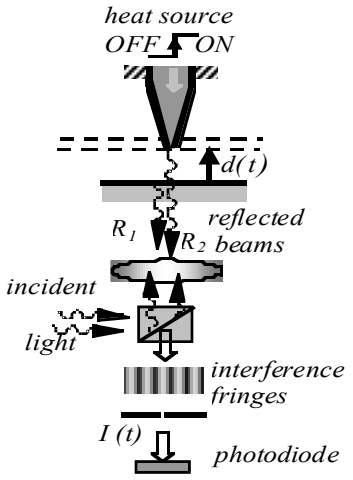

Figure 1. Schematic of the probe–sample distance d(t) measurement scheme. Light incident forms two reflected beams that interfere. A pinhole is used to select one interference fringe to monitor its light Intensity as the sample-tip separation variations are given by $|\Delta I|_{max} \sim 2\sqrt{I_1 I_2}\left(\frac{4\pi}{\lambda}\right)\Delta d$.

and destroy the probe or sample. The technique presented here could determine the power levels, operating height, and pulse repetition rate requirements for safe operation of such a system.

2. METHOD

The probe and cavity is shown in Fig. 1. Incident light from a microscope objective impinges on the semitransparent sample surface from below. A fraction reflects to give the R_1 beam in the figure. The remaining light is transmitted. Some of that light is reflected from the probe into the cavity between the probe and sample. The fraction of light that is reflected back from the cavity is given as R_2. Since the end of the probe is small, multiple reflections in the cavity do not contribute significantly to the signal at R_2, that is, the Fabry-Perot cavity has a low finesse. In this approximation, we model the system as a 2-beam interference, obtaining for a cavity length d that the irradiance is given by $I(d) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{4\pi}{\lambda}d + \phi\right)$, where ϕ accounts for any phase difference introduced by the mirrors. For $d = d_0 + \Delta d$, with fixed d_0 and small Δd compared to λ, we can use a Taylor's series to find the intensity variations as a function of Δd. Choosing d_0 such that it maximizes the interference signal, the maximum intensity

When a polarized He-Ne laser (λ_1 = 633 nm) is incident with few milliwatts of power, this predicts a few nanowatts/nanometer of motion. This small signal is hard to detect on a larger background, so we use the scheme shown in Fig. 2 to exploit the polarization of the light for the reduction of background.

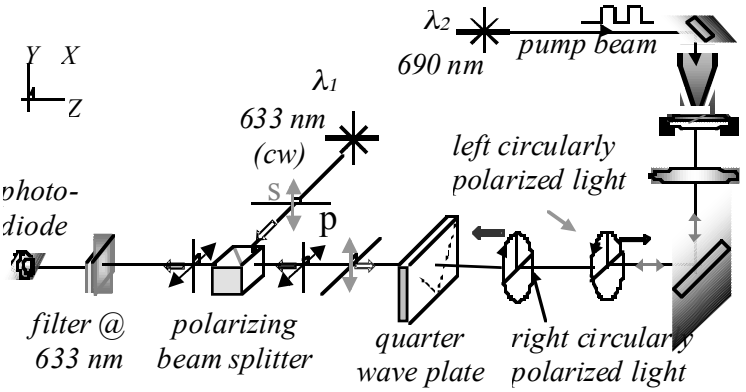

Figure 2. Optical setup that exploits light polarization properties to increase the signal to noise ratio in our measurement. Light reflected from the probe-sample cavity ends up as light polarized along the x-direction, which is the only polarization allowed by the polarizing beam splitter to reach the photodiode.

3. RESULTS

Next we measured the thermal elongation of chemically etched fibers having, typically, ~100 μm tapered region. A 690-nm laser was coupled into the probe. Losses [8] in the taper and aperture region heat the fiber probe and cause it to lengthen. The slower time constants of thermal processes in NSOM probes have previously been measured by monitoring the NSOM probe optical

throughput. [8] That system gave evidence of faster thermal time responses through a non-exponential frequency dependence when exposed to periodic thermal pulses, but was not able to accurately determine them. The system described here is more sensitive to the faster time constant than the slower ones, and can be used to measure their values and the amplitude associated with them.

Figure 3 shows the axial probe elongation as a function of time ('squares' curve), which was obtained by averaging 150 consecutive trials. The 'diamond' curve corresponds to a first order exponential fit that has the general form $y = y_0 + A_1\exp\{-(t-t_0)/\tau_1\}$, but fails to fit the experimental data accurately. The different factors (probe geometry, glass/aluminum composition) that can influence the probe's thermal response suggest the use of more than one time constant. We tried a second order exponential fit $y = y_0 + A_1\exp\{-(t-t_0)/\tau_1\} + A_2\exp\{-(t-t_0)/\tau_2\}$ and the result is indicated by the solid curve. The agreement with the experimental data is much better. The time constants obtained from the fitting curve are $\tau_1 = 0.540 \pm 0.016$ ms and $\tau_2 = 0.041 \pm 0.002$ ms, which are much smaller than the previously reported $\tau_{shank} \sim 10$ ms [8] associated with a thermal profile extending hundreds of microns – nearly the length of the tapered region of the probe.

4. DISCUSSION

The existence of several time constants in a thermal system is not surprising, since several materials are involved in a complicated geometry. The slower time constants result from setting up a thermal profile over most of the tapered region of the NSOM probe. Since the thermal mass is relatively large and the distances long, the relatively longer time constant is expected. The motion of the tip due to this slow effect should also be large, as we previously measured. [6] The faster time constants involve more local thermal problems. Possible physical descriptions involve: (1) the equilibration of the metal-coating temperature (the metal is what is heated by the laser shining into the probe) with the temperature of the silica fiber, and (2) the equilibration of the temperature of the metal film in a region whose size depends upon the coupling of energy along the film vs. into the silica, which is fast due to the high thermal conductivity of the metal. Thermal conduction in the silica and metal coating was found to be the dominate mode of heat transfer in this system, primarily due to the small surface areas and moderate temperatures involved. Both mechanisms are fast and could account for the measured responses. Since the size of the regions involved is smaller than the slow (10 ms)

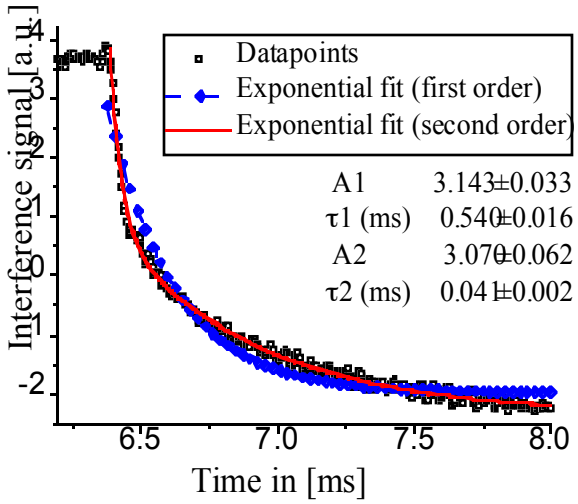

Figure 3. Interference time response curve. The sample-probe separation remains constant before a light pulse (from the 'pump' beam) is applied at t_0=6.39 sec. As the probe elongates the cavity length changes and the time response of the probe is extracted from the interference time response curve. Notice two time constants, τ_1 and τ_1, are necessary for the fitting curve to agree with the experimental data.

process, the amplitudes should be smaller. A τ_2 = 0.041 ms time constant gives a thermal diffusion length of L=15 μm and probe elongation $\Delta L \sim 2$ nm (assuming 50°K tip temperature rise and using a coefficient of thermal expansion for aluminum $\alpha_{Al} = 2.35 \times 10^{-6}$ /°K).

Our qualitative view of the thermal response of a NSOM probe is that small regions quickly equilibrate, giving small but non-negligible variations in the probe-sample distance, then a more large-scale expansion of the probe ensues as the larger portion of the taper is heated. If short-puled lasers are used, they should have a repetition rate that exceeds the slow thermalization rate. Then, the small scale, but fast, excursions must be accounted for before making conclusions about the optical response of the system. A careful choice of time constants for data acquisition should allow such measurements to be free from thermal artifacts in the probe.

5. CONCLUSION

A new optical method has been introduced to measure the variation of the distance between a NSOM-like probe tip and a sample. Measurement of the time response involved in thermal elongation of apertured NSOM probes was used to demonstrate the capabilities of the system. The corresponding instrumentation and implementation has been described in detail. We have measured, to the best of our knowledge, the fastest time response associated with thermal processes in NSOM probes. The high frequency bandwidth available in the new approach opens a new venue to study thermal processes in near-field probes. This is important, since it will expand the applications of NSOM in areas that involve short pulses of light. It will also help to evaluate the potential of using thermal probe elongation as a valid mechanism to create indents in polymers film in data storage applications.

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