A Shear Force Feedback Control System for Near-field Scanning Optical Microscopes without Lock-in Detection

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We describe and demonstrate an improvement to the currently used ac impedance detection method for tip-sample distance control in near-field scanning optical microscopes. The output signal of the electronic bridge is increased by a factor of 5000 so that a root-mean-square chip can be used in place of sensitive lock-in detection. We show that the signal-to-noise ratio of this new method is high enough to detect 0.07 nm changes in topography. In addition, this modification makes the electronics for the shear force feedback compact and inexpensive.

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Introduction

Several non-optical methods[1,2,3,4,5,6] of detecting shear force changes, which are used to control tip-sample separation in near-field scanning optical microscopes (NSOM), have been put in practice during the past two years. Shear force refers to the effects of surface damping on a vibrating probe (tip), which is attached to and driven by a piezoelectric element (dither piezo), as the oscillating tip is brought within ~ 10 nm of a sample surface. One such method senses this force by measuring the change in the finite-frequency (ac) electrical impedance of the dither piezo in the piezo/tip electromechanical assembly.[2] Since the impedance change is about 1 part in 10^4, a bridge, either passive[2] or active,[3] is used to balance out most of the piezo/tip impedance with the tip far from the surface. The detection of small signals constitutes the biggest challenge in this method. Typically, the demodulated bridge output signal is 10 to 20 μV when the feedback is engaged. Even when great care is used to minimize noise, such small signals are susceptible to noise pickup and drift due to environmental changes. Furthermore, the nulled signal from the bridge is limited by the accuracy of the potentiometers used in the phase shifter. During a long scan, i.e., > 1 hr, the bridge output could drift by several microvolts, causing the tip to move out of the shear force feedback range. In this paper, we describe an improvement in the electronic bridge that gives a 50 time increase in the signal, while the background noise only increases by five fold. Consequently, the signal-to-noise ratio now ranges from 30 to 50. The larger signal is also less susceptible to noise pickup and drift. When combined with 100x gain, the signal now is in the 10 to 100 mV range. Thus, a commercially available root-mean-square (rms) chip can be used instead of a lock-in amplifier to demodulate the ac signal. This makes the electronics compact, as well as reduces the cost significantly.

Description of Instruments

We made three modifications to the circuits in Ref. 3 for detecting ac impedance changes.

(1) The 1 kΩ resistors and input followers for the piezo and the 180° phase-shifted signals are changed to transconductance amplifiers.[7] The rest of the electronic bridge is the same as what was published in Fig. 1 of Ref. 3.
(2) Another stage of 10x gain is added after the summing junction.
(3) An rms chip, instead of a lock-in amplifier, is used to demodulate the bridge output signal.

The reason for the first modification is to boost the input signal. The impedance change of the dither piezo is measured by monitoring the change in the ac current (I) flow across the dither piezo for a fixed amplitude drive voltage (V) at frequency f. In Ref. 3, I is monitored by measuring the voltage across a 1 kΩ sampling resistor, which acts as a voltage divider in series with the piezo. In the transconductance amplifier scheme, the output voltage is proportional to the current through a feedback resistor. Because impedance is reduced by the open-loop gain of the operational amplifier at the operating frequency,[7] a larger feedback resistor results in a signal gain without increasing the input impedance. In addition, the Johnson current noise associated with a larger feedback resistor is lower. The value of the feedback resistor depends on the piezo impedance, the desired bandwidth and gain. In our NSOM setup, the dither piezo is a tube made of EBL#2 material with dimensions 1/8" o.d., 1/8" length, and 0.01" wall. Its capacitance is ~ 200 pF, corresponding to an ac impedance of ~ 10 kΩ, nearly all capacitive, at 80 kHz, the midrange of the operating frequencies for NSOM tips. We chose a feedback resistor ($R_{feedback}$) value of 100 kΩ for moderate gain without significantly decreasing the bandwidth.[8] However, without an external feedback capacitor (parallel to the feedback resistor), we observe a signal at the second harmonic frequency (2*f*) when the bridge is close to the balance point. Because the rms chip has a wide bandwidth, the second harmonic signals are also demodulated and contribute to a dc offset. This can be avoided by adding a capacitor to increase $C_{feedback}$ in the transconductance amplifiers. With a 47 pF feedback capacitor, the 2*f* signal when the bridge is balanced is sufficiently suppressed with respect to the feedback signal. This circuit alteration from Ref. 3 increases the bridge output by a factor of ~ 50 at 60 kHz, i.e. the feedback signal is now ~ 500 µV instead of ~ 10 µV. This gain enhancement agrees well with the calculated result for the values of components we used. The increase in the background noise, from 18 $nV/\sqrt{Hz}$ to 90 $nV/\sqrt{Hz}$, however, is not proportional to the gain. Therefore, the signal to noise ratio is significantly enhanced.

The purpose of the lock-in amplifier in Refs. 2 and 3 is mainly to demodulate the small bridge output signal. Since in the distance control application, the lock-in output time constant used is typically less than 100 µs, the bandwidth narrowing feature of lock-in detection is not really used. Moreover, since the phase of the bridge signal depends on the tip, the sample, and environmental conditions and is not known *a priori*, a wide-bandwidth magnitude converter was added to make the tip-sample approach reliable.[3] Therefore, it would be simpler and more direct to use an rms chip for demodulation provided the signal is large enough. However, 500 µV is still well beneath the minimum resolution for commercial rms chips of sufficient bandwidth (≥ ~ 50 kHz); such chips typically require 10 to 50 mV minimum signal levels. An 100 fold increase is needed. To preserve the wide bandwidth required by the feedback in scanning microscopy, we chose a two-stage amplification (using OP-27s) with 10x gain each. The output is then AC coupled and sent into the input of a commercial rms chip (AD636).[9] The output from the rms chip is compared with a reference signal, and the difference goes in the feedback circuit of a commercial scanning probe microscope (PSI AutoProbe CP). Fig. 1 shows the block diagram of our new electronic setup for sensing AC impedance changes of the piezo/tip electromechanical system. The bandwidth of the electronic bridge combined with the rms demodulator is estimated to be ~ 34 kHz, limited by $R_{feedback}C_{feedback}$, for a feedback signal of 10 to 100 mV. The actual bandwidth of the entire feedback system is much smaller, given by the time constant and gain of the actual (digital) feedback circuit.[10]

Results and Discussion

An example of a topographic image taken with a tapered NSOM fiber probe using the circuit described above is depicted in Fig. 2(a) for a two-dimensional (2D) grating. A line cut, as indicated on Fig. 2(a), of the topographic image is shown on Fig. 2(b). The error signal as a function of tip-sample separation (*z*) is shown in Fig. 2(c). All data were taken with 25 mV drive voltage applied to the piezo. Far away from the surface, the demodulated rms signal is 10 to 20 mV, depending on the frequency, when the bridge is nulled. As seen in Fig. 2(c), the total noise when the tip is far from the sample is about ± 10 mV. This noise can be reduced by proper grounding and shielding to ± 2 mV. Even with a 10 mV noise level, for an approach curve distance of 6 nm, this circuit is sensitive enough to detect 0.07 nm height changes.[4] With better electronics and careful isolation from noise pickup, an improvement on the sensitivity can be expected.

When the bridge is near the balanced point, the signal is very sensitive to slight changes in impedance and to pickups. We found that temperature changes of the dither piezo and of the electronic components are responsible for most of the signal drift. To minimize drift, we placed the NSOMs away from any air drafts and encased them in Styrofoam boxes. Using the old setup, the drift could still be as large as the feedback signal (~ 10 µV) sometimes. However, using the setup described in this paper, the drift during a 30-minute scan was measured to be ~ 6 mV on average while the feedback signal was ~ 70 mV. Hence, the tip will not drift out of the feedback range during a long scan. We also tested the two bridges under identical conditions using 200 pF capacitors. After the bridges were balanced, the drift over 3 hours using the old bridge was ~ 2 µV while using the new one (in this paper) was ~ 4 mV.[11] Thus, the percentage of the drift signal to the feedback signal is significantly smaller when using this new improved design, 4 mV/70 mV versus 2 µV/10 µV.

An added advantage of this new ac impedance sensing circuit is that it no longer requires a lock-in amplifier. This not only reduces cost, but also makes the electronics much more compact. It is now possible to build all the electronics on an NSOM head, similarly to commercial scanning force microscopes. Having the electronic bridge physically close to the piezo further reduces drift and noise pickup.

Summary

In summary, we report an improved circuit on a method currently used to control tip-sample separation in NSOM. The input stage in the electronic bridge was modified to achieve higher gain. A commercial rms chip instead of a lock-in amplifier is used to demodulate the bridge output signal. While the sensitivity and bandwidth are comparable to previous setup,[3] the advantages of the new circuit are it (1) has a higher signal-to-noise ratio, (2) is less susceptible to drift, (3) is low cost, and (4) is compact and self-contained.

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[8] The bandwidth is set by $1/(2\pi R_{feedback}C_{feedback})$ and is stable if the op-amp is fast enough. We chose to use an OP-270 to minimize drift; temperature coefficients between the two op-amps on the same chip are closely matched, resulting in much smaller drift compared to using two separate single op-amps.
[9] The AD636 is used in the standard configuration as given on page 4-18 of Special Linear Reference Manual pubished by Analog Devices.
[10] The time constant for amplitude response measurement is $\tau = 2Q/2\pi f_0$, where Q is the quality factor of the system at resonance and f_0 is the resonant frequency. The Q values for NSOM fiber tips are typically ~ 100. Taking f_0 = 80 kHz, we obtain a settling time 5τ of 2 ms. Therefore, the feedback cirucuit bandwidth only needs to be a few hundred Hz.
[11] We can routinely balance the bridges better and observe a smaller drift with capacitors than with the piezo/tip on the tip resonance. The difference lies in that we operate the shear force feedback at the resonant frequency of the piezo/tip electromechanical system, whereas the impedance-equivalent capacitors have no resonances in this frequency regime. Near the resonances, both the magnitude and the phase of the ac impedance vary rapidly as a function of frequency (see Ref. 2). On the contrary, the ac impedance of the capacitors is a slow varying function.

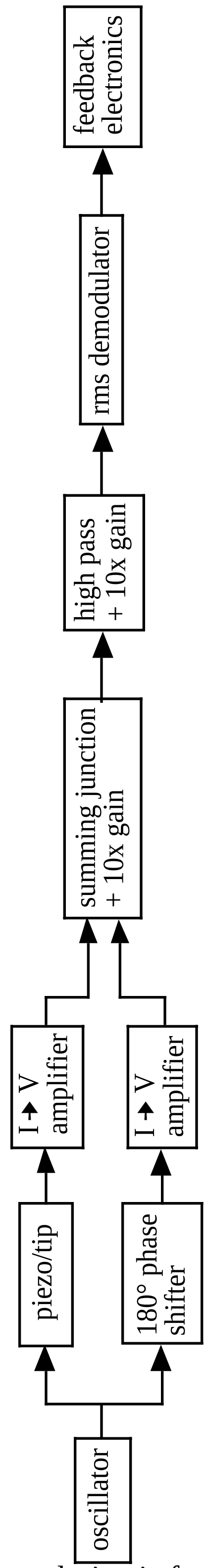

Figure 1: Block diagram of the improved circuit for detecting ac impedance changes in the piezo/tip electromechanical assembly. It no longer requires a lock-in amplifier and a fast magnitude converter as used in Ref. 3. Instead an rms chip is used to demodulate the bridge output signal.

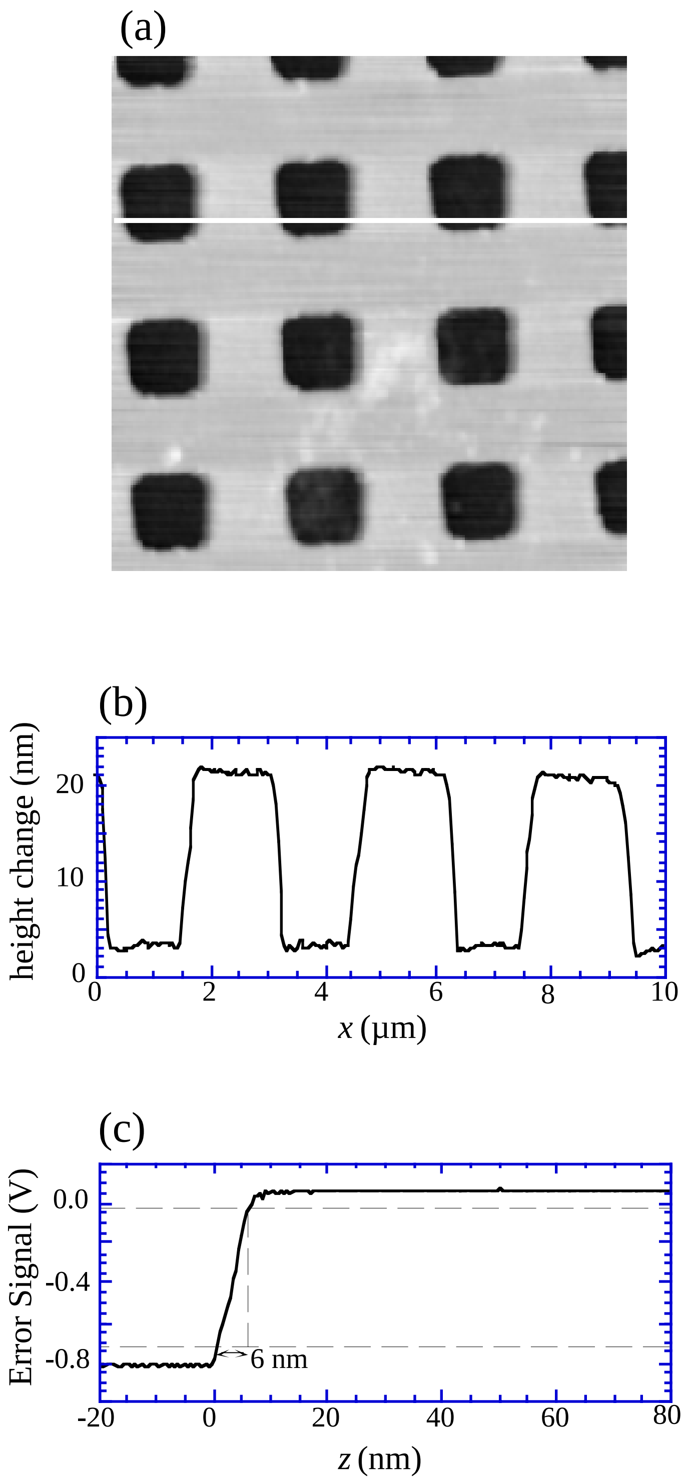

Figure 2: (a) An image of a 2D grating taken with an NSOM tip using the new circuit. The grayscale represents 25 nm height difference. (b) A line cut of height changes versus distance (*x*), as indicated in Fig. 2(a). (c) Error signal as a function of tip-sample separation (*z*). The zero of *z* is defined by the position at which the bridge output signal saturates, i.e., tip-sample "contact" point. The 10% and 90% of the transition are marked on the graph. The corresponding tip-sample separation is ~ 6 nm.