# Simple and convenient nonoptical shear force sensor for shear force and near-field optical microscopes

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A simple, compact, and inexpensive method for shear force distance regulation is presented. A single piezoelectric cantilever is employed to both dither a fiber probe and to detect the decrease in piezotension-induced voltage as it approaches the sample surface. On resonance, the large piezotension-induced voltage ($\sim$0.2 mV/nm) allows for simple electronics to be used. It is expected to find application both in shear force microscopy and for shear force distance regulation in near-field optical microscopy. © *1999 American Institute of Physics.* [S0003-6951(99)05544-8]

The shear force and near-field optical microscope (NOM) are both members of the family of scanning probe microscopes. The former makes use of the damping effect of the sample–probe interaction on a laterally dithered tip to map topography of a sample surface. The latter, in many configurations, makes use of shear force feedback to maintain a constant separation between the fiber tip and sample (<10 nm). With a suitable fiber and stable distance control, resolutions greater than 20 nm can be expected in both optical[1] and shear force[2] modes.

Shear force detection is accomplished by using a piezoelectric element to excite the fiber or an assembly including the fiber at a resonance peak, and measuring the reduction of oscillation amplitude as the fiber approaches the sample surface. In most systems, the measurement is done optically by focusing a laser beam onto the tip and recording the scattered light.[2–5] Although this has proven to be robust, simple, and sensitive, there have been a number of proposals for nonoptical detection[6–11] motivated primarily by the desire to make the microscope system more convenient for the user (especially under nonambient, i.e., vacuum conditions) by eliminating the need for the optical alignment of an additional light source and detector. An additional advantage of a nonoptical technique is that it allows the fiber rather than the sample itself to be scanned during image acquisition.

From our experience, the ideal dither excitation/detection system would be nonoptical, have a small footprint, be simple and reliable mechanically and electronically, have a sensitivity and tip oscillation magnitude comparable to existing techniques and imaging resolutions (<10 nm), and a system $Q$ in the range of 50–200.[6] Ideally, the dither unit itself should be made from a single, low-cost piece. Finally, fiber replacement should be simple and convenient. In general, high scanning speed is not required as the available optical signal is usually the limiting factor rather than the shear force bandwidth in high-resolution imaging. Currently proposed nonoptical methods include using high-$Q$ tuning forks,[6,7] Wheatstone bridges to measure impedance change of the dither piezo,[8,9] asymmetric excitation detection,[10] and piezoelectric pickup from a sectioned laterally polarized piezoelectric tube.[11] Although all the above techniques meet the required sensitivity and tip oscillation magnitude constraints, as pointed out by Debarre,[10] they unfortunately suffer from various other drawbacks. The first technique, besides the inconvenience of fiber attachment, and relative complexity, suffers from having a $Q$ close to 1000. In the second method, excellent thermal stability is required to enable the complex electronics to compensate a large background signal. The third method suffers from the twin drawbacks of having a relatively large footprint and that two piezoelectric units are required.

The dither excitation/detection method described in this letter seeks to meet, and we believe successfully meets, all of the criteria for an ideal system—being a single, inexpensive, and sensitive unit that is convenient to use and fits conveniently within an ultrastable NOM head.[1]

Figure 1 presents a schematic illustration of the shear force detection system used in our combined shear force–near-field optical microscope. The fiber is both vibrated and

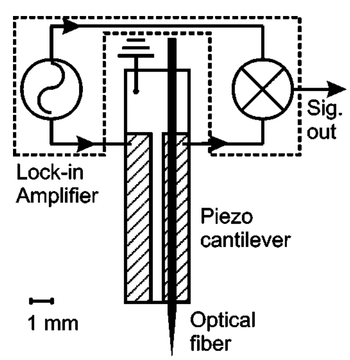


FIG. 1. Schematic representation of the dither excitation/detection method for shear force detection. The system itself consists of three parts: an optical fiber, low-cost lock-in amplifier, and the excitation/detection cantilever. The fiber is mounted on the side of the cantilever chosen for detection. An ac excitation voltage (lock-in oscillator) is applied between the left piezoceramic pad and ground (vibration occurs in the plane perpendicular to the page), while the piezotension-induced voltage between ground and the other piezoceramic pad is detected. Amplitude (or phase-sensitive) detection utilizing the lock-in amplifier's built-in oscillator provides the signal used for fiber tip-to-sample distance regulation.

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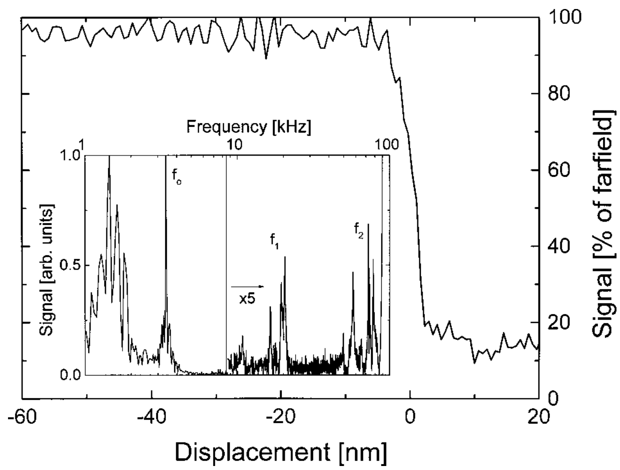


FIG. 2. Amplitude (in-phase component equivalent) of the piezotension-induced voltage as a function of fiber tip–sample separation for the fundamental (3.39 kHz) resonance of the combined fiber cantilever. The point where the signal drops to 50% of its far-field value is defined as zero displacement. The substrate is ethanol-cleaned silica glass. The lock-in time constant is 1 ms. Excitation amplitude corresponds to a fiber displacement of <7 nm for the fundamental. The primary source of noise is the lock-in amplifier itself. The inset presents the cantilever's response as a function of dither frequency with the fundamental, first, and second harmonics emphasized. Note the change in scale at 8.6 kHz.

has its vibration detected by means of a single piezoelectric cantilever polarized in the longitudinal direction. This cantilever is produced from the piezoelectric diaphragm of a miniature buzzer (a thin metal base plate covered on one side by a piezoceramic layer with electrodes)[12] as follows: An 11-mm-long (8 mm covered by piezoceramic) by 3-mm-wide rectangle is first cut out of the diaphragm. Second, the covering piezoceramic is cut into two pads. (cf. Fig. 1). Only three electrodes are required (excitation, detection, and ground). The excitation and detection electrodes are attached to the two piezoceramic pads and the metal base plate serves as a common ground. A sharpened fiber (produced, in our case, by chemical etching) is mounted on the surface of the detection electrode. An ac voltage is applied between ground and the excitation electrode at the combined fiber–cantilever resonance frequency. A piezotension-induced voltage (due to the piezoelectric effect), sensitive to both the magnitude and phase of the tip vibrational motion, appears between the detection electrode and ground. Amplitude (or phase-sensitive) detection, utilizing a low-cost lock-in amplifier, is used to provide a signal for a software feedback loop that maintains a constant separation between fiber tip and sample.

Probably the most important characteristic of any shear force-based distance control method is that it be sensitive to the shear force interaction as one approaches the surface, and that it do this with small tip dither amplitude (<10 nm). The approach curve (amplitude; in-phase component is equivalent) at the fundamental as the fiber approaches an ethanol-cleaned glass surface, is plotted in Fig. 2. The inset shows the cantilever resonances as a function of frequency with the fundamental and first two harmonics emphasized. Two things are important to note. First is the fact that the decay occurs over a distance of ~5 nm as would be expected for a hydrophobic sample at low humidity with a low dither amplitude (the curve is more gradual at higher levels of excitation).[13] This is similar to approach curves taken with other detection methods. The second is that the piezotension-induced voltage drops to a very small percentage of its far-field value upon contact with the surface. The percentage of residual signal is constant for a given piezo and substrate (i.e., independent of fiber). It does not seriously affect the distance resolution as it can easily be taken into account when setting the feedback threshold voltage. In relation to the tip excursion question, we have evaluated the tip excursion by means of the optical method proposed by Wei, Wei, and Fann.[14] In the case of the excitation at the fundamental resonance, tip excursion was evaluated as: $\Delta x_{\mathrm{tip}}\,(\mathrm{nm}) = 4.6(4) V_{\mathrm{excitation}}\,(\mathrm{mV})$. Thus, at the 1–2 mV excitation voltages, which we typically use during imaging (cf. Ref. 15 for images of the substrate of a pirated CD), the tip dither amplitude remains below 10 nm.

Having satisfied the primary requirements for any shear force-based distance control method, the secondary characteristics of the system will be addressed. The $Q$ factor for the assembly lies in the range of 50–60 at both the fundamental and first-harmonic resonance. As the vibration of the whole cantilever, which is asymmetric in the two lateral directions, is monitored, the problem of bistability,[2] wherein the two lateral vibrational modes of the fiber contribute to the signal, is largely mitigated (cf. Fig. 2, inset).

Fiber change is convenient as acetone quickly dissolves the glue holding the fiber in place, and a new fiber can be easily set in position. As the resonance frequency of the assembly changes little with fiber change (<100 Hz), experiments can be quickly resumed once the glue dries, without loss of time spent looking for a suitable resonance peak.

A key advantage of this method, relative to other techniques relying on piezotension-induced voltage,[11] is the large magnitude of the piezotension-induced voltage. For a tip excursion of 1 nm the piezotension-induced voltage is ~0.2(1) mV. This large signal, which is due to use of longitudinal rather than lateral geometry, greatly simplifies the electronics used.

In conclusion, a dither excitation/detection method utilizing a single head with three electrodes has been presented. Its simple mechanical structure and electronics, combined with its low cost and high signal level, make it an attractive alternative for distance control feedback mechanisms. Its small footprint allows convenient mounting at the center of an axial-symmetric tube piezoelectric scanning system.

At the 1–2 mV excitation we use in scanning at the fundamental, tip excursion is less than 10 nm. Where higher sensitivity or scanning speeds are required, the fiber can be vibrated at a higher harmonic, a better lock-in amplifier used, or additional electronics incorporated.

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