Improved fiber-optic interferometer for atomic force microscopy

D. Rugar, H. J. Mamin, and P. Guethner[a)]
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120-6099

(Received 7 August 1989; accepted for publication 16 October 1989)

A high-sensitivity fiber-optic displacement sensor for atomic force microscopy is described. The sensor is based on the optical interference occurring in the micron-sized cavity formed between the cleaved end of a single-mode optical fiber and the microscope cantilever. As a result of using a diode laser light source and all-fiber construction, the sensor is compact, mechanically robust, and exhibits good low-frequency noise behavior. Peak-to-peak noise in a dc to 1 kHz bandwidth is less than 0.1 Å. Images are presented demonstrating atomic resolution of graphite and magnetic force imaging of bits written on a magnetic disk.

Scanning force microscopies, of which atomic force microscopy[1] (AFM) is one example, measure the interaction between the sample and a sharp tip mounted on a weak cantilever. Two main modes of operation have been developed, which we will call dc detection and ac detection. In dc detection mode, the interaction force is determined by measuring the amplitude of the static deflection of the cantilever. This mode has been used for profilometry type applications with atomic[2,3] or molecular scale resolution,[4] as well as for mapping magnetic[5] and frictional forces.[6] In ac detection mode,[7,8] the cantilever is mechanically driven to vibrate with an amplitude of 1–100 Å at a frequency close to the cantilever resonance frequency. The presence of a force derivative shifts the resonance frequency and causes a change in the amplitude and/or phase of vibration. This mode of force microscopy has been successfully used for detection of magnetic,[9,10] electrostatic,[11,12] and van der Waals forces.

In the original AFM work,[1] cantilever deflection was detected using a tunneling probe. More recently, a number of alternative detection methods have been developed, including capacitive[13] and optical techniques. The optical techniques include homodyne[7,14,15] and heterodyne[8] interferometry, optical beam deflection,[16,17] and diode laser feedback detection.[18] All of these techniques have their relative merits and demerits with respect to complexity, sensitivity, low-frequency stability, the types of cantilevers that can be used, and the applicability to the two modes of force microscopy.

In this letter, we describe a new interferometric displacement sensor that is well suited for both dc and ac modes of force microscopy. The sensor exhibits high sensitivity, good low-frequency stability, and is simple, compact, and mechanically robust. The sensor does not require a specular reflection from the cantilever and, thus, is compatible with both microfabricated thin-film cantilevers as well as fine wire cantilevers.

The design of the instrument is shown in Fig. 1. A multimode GaAlAs diode laser[19] ($\lambda = 830$ nm) with a direct single-mode fiber output is used as a light source. The light is coupled into the input (labeled "1") of a 2×2 single-mode directional coupler.[20] The coupler splits the incident optical power equally between leads 2 and 3, which carry the light to the AFM cantilever and the "reference" photodiode, respectively. Approximately 4% of the light in lead 2 is reflected from the glass-air interface at the cleaved end of the fiber. This reflected light comprises one of the two interfering beams. The other 96% of the light exits the fiber and impinges on the force microscope cantilever with a spot size on the order of 5 μm. Part of this light is scattered back into the fiber and interferes with the light reflected from the fiber end. The total optical power reflected back through the fiber depends on the phase difference between the fiber end reflection and the cantilever reflection. The coupler directs half of the total reflected light to lead 4 and into the "signal" photodiode, where the intensity of the optical interference is measured. To reduce reflections from the ends of leads 3 and 4, the fibers were cleaved at a nonorthogonal angle and index-matching liquid was placed between the photodiodes and the fiber ends.

The output of the signal photodiode can be used directly as the force microscope signal. However, better performance is obtained, especially at frequencies below 1 kHz, if laser amplitude noise is cancelled by either subtracting or dividing the output of the signal photodiode by the output of the reference photodiode. Since most commercially available divider circuits have a somewhat limited dynamic range, we chose the noise subtraction approach using a low-noise differential amplifier.

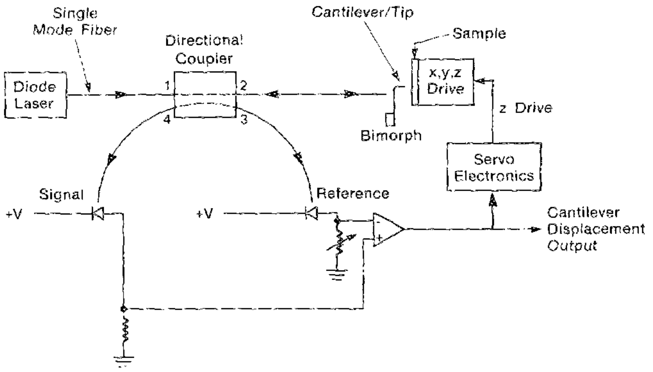

FIG. 1. Diagram of the fiber-optic interferometer and force microscope.

[a)] On leave from Dept. of Physics, University of Konstanz, D-7750 Konstanz, FRG.

The sensor described above has several advantages over the He-Ne laser-based fiber interferometer[14,21] used previously for force microscopy. First, the use of the diode laser light source and the all-fiber construction results in smaller size, improved mechanical robustness, and reduced heat dissipation. Since there is no air path between optical components (except for the micron-sized path to the cantilever), the instrument is much less susceptible to instabilities caused by air currents and acoustic noise. Also, the use of a short coherence length diode laser improves the low-frequency stability by eliminating interference effects of stray reflections. (In a long coherence length system, stray reflections can cause substantial low-frequency noise since their phase relationship with respect to the signal light will vary with temperature, laser frequency, etc.) Finally, since the response of the directional coupler depends only weakly on polarization, birefringence introduced by fiber bends will not disturb the operation of the sensor.

The interferometer response can be modeled as a simple two-component interference since multiple reflections in the interferometer cavity can be ignored. The current from the signal photodiode is given by

$$i = i_0(1 - V\cos 4\pi d/\lambda), \tag{1}$$

where λ is the laser wavelength and d is the fiber-to-cantilever spacing. The quantities V and i_0 correspond to the fringe visibility and the midpoint current, respectively, and are given by $V = (i_{\max} - i_{\min})/(i_{\max} + i_{\min})$ and $i_0 = (i_{\max} + i_{\min})/2$, where $i_{\max}$ and $i_{\min}$ are the currents corresponding to maximum constructive and destructive interference, respectively. The most sensitive operating point is where the phases of the two reflected components are in quadrature, or $d = \lambda/8, 3\lambda/8, 5\lambda/8,...$. At quadrature, the response for small changes in distance, Δd, and wavelength, $\Delta\lambda$, is given by

$$\frac{\Delta i}{i_0} = 4\pi V \frac{\Delta d}{\lambda} - 4\pi d V \frac{\Delta\lambda}{\lambda^2}. \tag{2}$$

Typical noise level of the interferometer was evaluated for the case when a polished silicon wafer is used as the reflector. The reflector was placed close to the end of the fiber ($<1\,\mu$m) and adjusted so that the instrument was at its most sensitive operating point (quadrature). Fringe visibility was approximately 50% and the optical power incident on the signal photodiode was 3 μW. Figure 2 shows the interferometer noise for a 0.2 s record with a bandwidth of dc-1 kHz. The peak-to-peak noise is less than 0.1 Å. For longer time records, a slow drift on the order of 0–3 Å/min is observed. This is probably due to thermal expansion motion between the fiber and the reflector and dc drift of the electronics.

Figure 3 shows the frequency spectrum of the interferometer noise. Above 1 kHz, the noise spectrum is flat with a spectral density of 5.5×10^{-4} Å/$\sqrt{\text{Hz}}$. The noise in this region is primarily due to shot noise.[14] For frequencies below 1 kHz, the noise amplitude rises with a frequency dependence of approximately $f^{1/2}$.

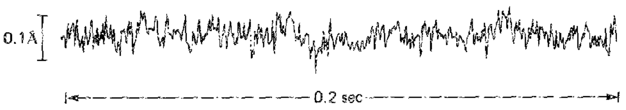

FIG. 2. Interferometer output for 0.2 s time record. Measurement bandwidth was dc-1 kHz.

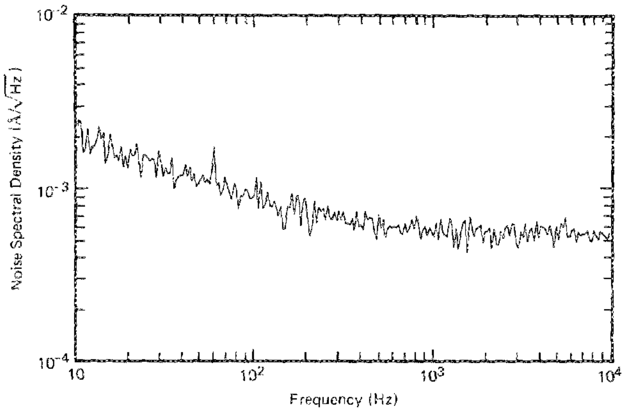

FIG. 3. Spectral density of the interferometer noise.

The low-frequency noise (1–1000 Hz) appears to be due to frequency (or phase) noise of the laser diode, a phenomenon that has been studied previously in Michelson interferometers.[22,23] As indicated in Eq. (2), small changes in laser wavelength will change the detected optical power and mimic a displacement. The rms noise (in terms of distance, Δd) resulting from a rms wavelength variation $\Delta\lambda$ is given by $\Delta d = d(\Delta\lambda/\lambda)$. Thus we expect the noise due to wavelength variations to increase linearly with increasing fiber-to-reflector spacing. This expected linear dependence of the noise on d is evident in the data shown in Fig. 4. The data are consistent with a rms wavelength variation of $\Delta\lambda/\lambda = 1.8\times10^{-6}$ in a 1–1000 Hz bandwidth.

For fiber-to-reflector spacings less than 4 μm, the rms noise in a 1000 Hz bandwidth is less than 0.1 Å. This noise level is sufficiently low to allow atomic resolution AFM imaging in the dc detection mode. Atomic resolution is demonstrated in Fig. 5, which shows graphite imaged using a lithographically fabricated Si_3N_4 cantilever.[24] One side of the cantilever was metallized with a thin gold layer to increase the optical reflectivity.

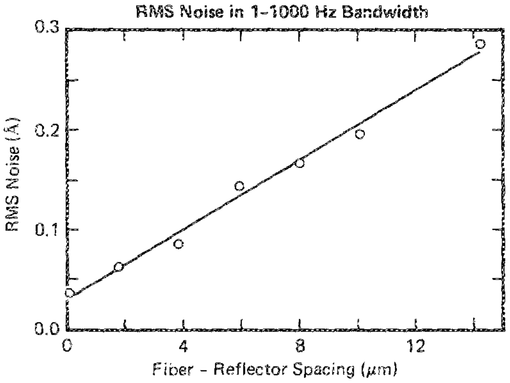

FIG. 4. Measured noise as a function of fiber-to-reflector spacing.

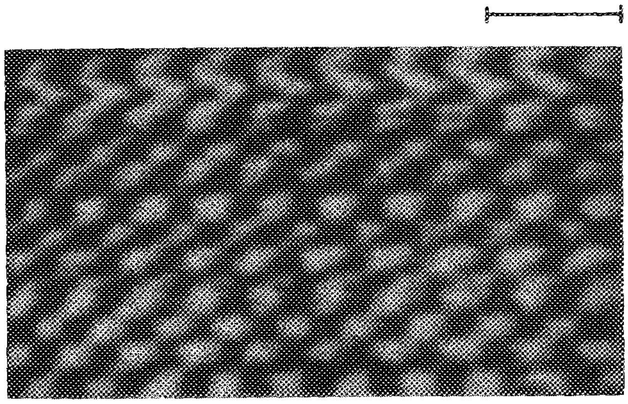

FIG. 5. AFM image taken in dc detection mode demonstrating atomic resolution of graphite. Scale bar is ~5 Å.

The fiber-optic sensor has also been used in ac detection mode for magnetic force microscopy. Figure 6 shows an example of magnetic imaging of bits on a Co-alloy disk using an etched nickel wire cantilever. Details of the imaging technique may be found in Refs. 9 and 10. The noise level of the interferometer is negligible when the ac detection mode is used since the thermal noise of a typical wire cantilever near resonance is relatively large, in the range of 10^{-3}–10^{-1} Å/$\sqrt{\text{Hz}}$.

In conclusion, we have demonstrated a simple fiber-optic interferometer which is suitable for force microscopy in both dc and ac detection modes. Because of the all-fiber construction, short coherence length light source, and polarization insensitivity of the directional coupler, the sensor has good noise characteristics, even at low frequencies. The sensor is mechanically robust, simple to construct, and does not require a specular reflection from the cantilever. The sensor can easily be adapted for other applications besides force microscopy, such as vibration analysis or acoustic wave detection.

We thank J. E. Stern and B. D. Terris for technical assistance and C. M. Mate for helpful suggestions. We also thank P. Wimmer for designing some of the microscope mechanics, T. Albrecht and C. F. Quate for cantilevers, and T. Yogi and S. E. Lambert for the magnetic disk sample.

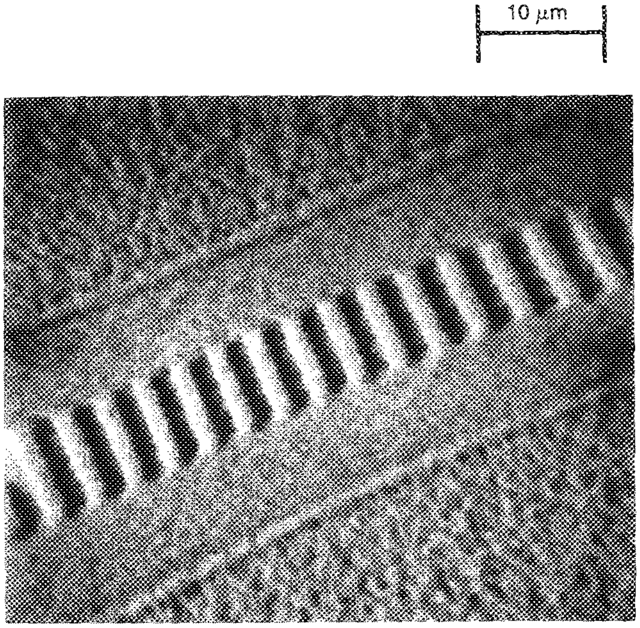

FIG. 6. Magnetic force micrograph taken in ac detection mode of a magnetic bit pattern on a Co-alloy disk. Spacing between magnetic transitions is ~2 µm.

[1] G. Binnig, C. F. Quate, and Ch. Gerber, Phys. Rev. Lett. **56**, 930 (1986).
[2] G. Binnig, Ch. Gerber, E. Stoll, T. R. Albrecht, and C. F. Quate, Europhys. Lett. **3**, 1281 (1987).
[3] O. Marti, B. Drake, and P. K. Hansma, Appl. Phys. Lett. **51**, 484 (1987).
[4] B. Drake, C. B. Prater, A. L. Weisenhorn, S. A. C. Gould, T. R. Albrecht, C. F. Quate, D. S. Cannell, H. G. Hansma, and P. K. Hansma, Science **243**, 1586 (1989).
[5] J. J. Saenz, N. Garcia, P. Grutter, E. Meyer, H. Heinzelmann, R. Wiesendanger, L. Rosenthaler, H. R. Hidber, and H.-J. Guntherodt, J. Appl. Phys. **62**, 4293 (1987).
[6] C. M. Mate, G. M. McClelland, R. Erlandsson, and S. Chiang, Phys. Rev. Lett. **59**, 1942 (1988).
[7] G. M. McClelland, R. Erlandsson, and S. Chiang, in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1987), Vol. 6B, p. 307.
[8] Y. Martin, C. C. Williams, H. K. Wickramasinghe, J. Appl. Phys. **61**, 4723 (1987).
[9] Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **50**, 1455 (1987).
[10] H. J. Mamin, D. Rugar, J. E. Stern, B. D. Terris, and S. E. Lambert, Appl. Phys. Lett. **53**, 1563 (1988).
[11] Y. Martin, D. W. Abraham, and H. K. Wickramasinghe, Appl. Phys. Lett. **52**, 1103 (1988).
[12] J. E. Stern, B. D. Terris, H. J. Mamin, and D. Rugar, Appl. Phys. Lett. **53**, 2717 (1988).
[13] G. Neubauer, S. R. Cohen, and G. M. McClelland, to be published in *Interfaces Between Polymers, Metals and Ceramics*, edited by B. M. DeKoven, A. J. Gellman, and R. Rosenberg, MRS Proceedings (Materials Research Society, Pittsburgh, to be published).
[14] D. Rugar, H. J. Mamin, R. Erlandsson, and B. D. Terris, Rev. Sci. Instrum. **59**, 2337 (1988).
[15] C. Schonenberger and S. F. Alvarado, Rev. Sci. Instrum. **60**, 3131 (1989).
[16] G. Meyer and N. M. Amer, Appl. Phys. Lett. **53**, 1045 (1988).
[17] S. Alexander, L. Hellemans, O. Marti, J. Schneir, V. Ealings, P. K. Hansma, M. Longmire, and J. Gurley, J. Appl. Phys. **65**, 164 (1989).
[18] D. Sarid, D. Iams, and V. Weissenberger, Opt. Lett. **13**, 1057 (1988).
[19] Model GO-DIP-1000-S-TC, General Optronics, 2 Olsen Ave., Edison, NJ 08820. Approximately 12 modes were active.
[20] Model SMC-03-50-2-A-2-S, Aster Inc., 113 Cedar St., Milford, MA 01757.
[21] A. D. Drake and D. C. Leiner, Rev. Sci. Instrum. **55**, 162 (1984).
[22] A. Dandridge, A. B. Tveten, R. O. Miles, D. A. Jackson, and T. G. Giallorenzi, Appl. Phys. Lett. **38**, 77 (1981).
[23] K. Petermann and E. Weidel, IEEE J. Quantum Electron. **QE-17**, 1251 (1981).
[24] Courtesy of T. Albrecht and C. F. Quate.