tip was withdrawn from the surface by 50 Å, both the average and the cross-correlation signals dropped to zero. This means that the observed cross-correlation signal has no contribution from stray capacitance in the leads or from radiative coupling.

Figure 1(c) shows a $0.7 \times 0.7\ \mu m^2$ image of one of the transmission line conductors acquired as the fast pulse passed under the tip. By collecting a series of such STM images for increasing values of time delays, we expect to be able to "produce" ultrafast movies on the atomic scale. The technique will be a powerful new tool for the observation of processes and excitations that propagate at velocities of a few Angstrom per femtosecond. We believe that it will be possible to spatially and temporally resolve many dynamic phenomena on an atomic scale. Future investigations will focus on vibronic motion of atoms on surfaces, carrier transport in semiconductors, molecules and semiconductor devices, and hot carrier effects.

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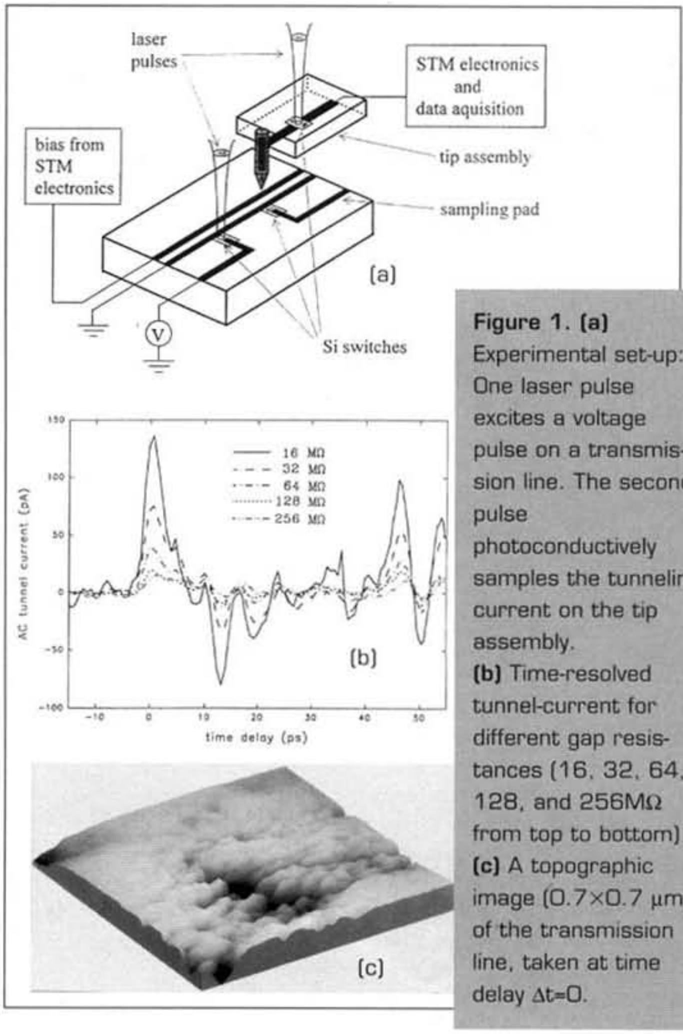

Figure 1. (a) Experimental set-up: One laser pulse excites a voltage pulse on a transmission line. The second pulse photoconductively samples the tunneling current on the tip assembly. **(b)** Time-resolved tunnel-current for different gap resistances (16, 32, 64, 128, and 256MΩ from top to bottom) **(c)** A topographic image ($0.7 \times 0.7\ \mu m^2$) of the transmission line, taken at time delay $\Delta t = 0$.

Intrinsic Thermal Phase Noise Limit in Optical Fiber Interferometers

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Optical fiber interferometers are used for several high sensitivity measurement applications, such as acoustic sensors, magnetometers, accelerometers, and gyroscopes.[1] A variety of noise sources limit the phase shift detection sensitivity attainable using fiber interferometric sensors. The most often quoted (and desired) intrinsic minimum detectable phase shift in interferometric optical systems is the shot, or quantum noise limit. In interferometric optical fiber sensors, the shot noise limit often can be realized; minimum detectable phase shifts of a few $\mu rad/\sqrt{Hz}$ at frequencies above a few hundred Hz are readily achieved with modest detectable power levels of a few microwatts.[1] When shot noise dominates, minimum detectable phase shift performance improvements can be obtained simply by increasing the detected power levels.

With the availability of more powerful and extremely low phase noise laser sources such as diode-pumped YAG, considerably lower shot-noise-limited minimum detectable phase shifts should be achievable. The shot noise limit is $\sim 1.5 \times 10^{-8}$ rad rms/$\sqrt{Hz}$ for 1.8 mW detected power at 1319 nm. However, workers in the field have not been able to achieve minimum detectable phase shifts below $\sim 2\text{–}7 \times 10^{-7}$ rad rms/$\sqrt{Hz}$ in the important 1-25 kHz band for fiber optic Mach-Zehnder interferometers, regardless of detected optical power. In addition, researchers did not understand why the 1-100 kHz phase noise spectra of fiber optic interferometers exhibits an extremely slow roll off with frequency. This phenomena could not be attributed to laser, electronics, or environmental noise.

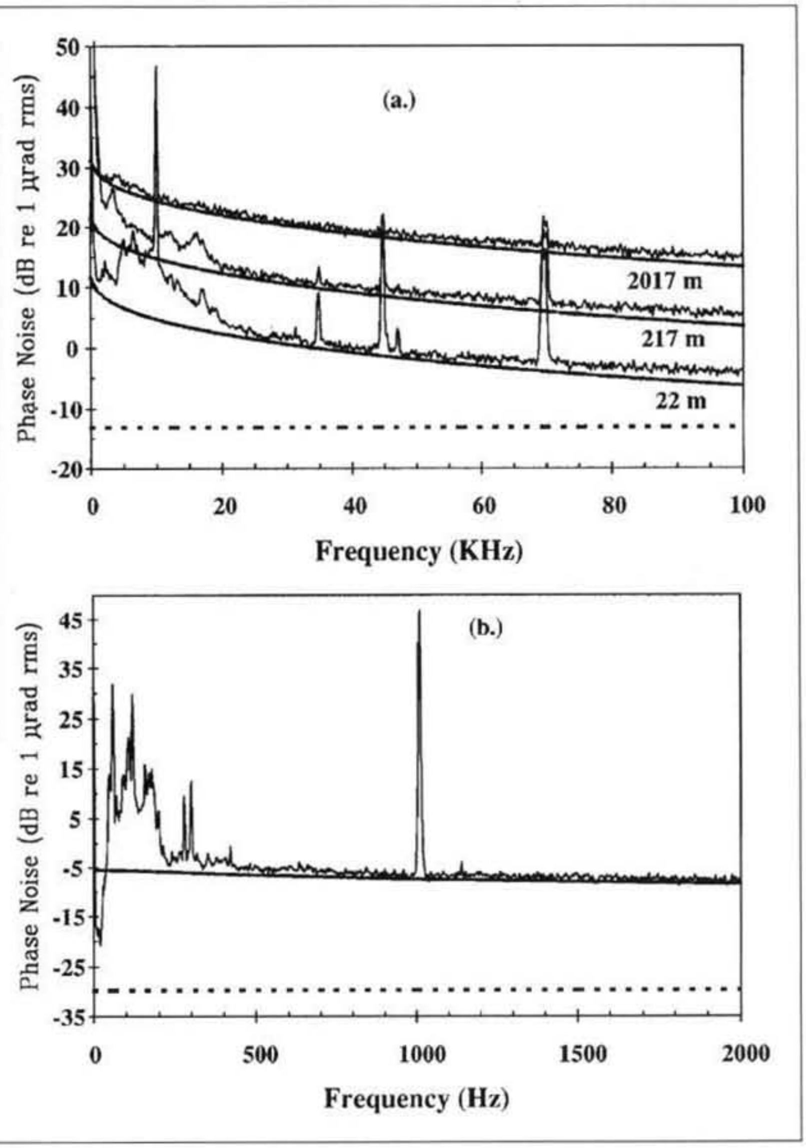

Figure 1. Phase noise spectra of Mach-Zehnder interferometers. Smooth curves are the theoretical thermal phase noise limits for the respective fiber lengths; dashed lines indicate the shot noise level. **(a)** 187 Hz measurement bandwidth for total fiber arm lengths of 2017 m, 217 m, and 22 m. The component at 10 kHz represents a calibration phase shift of 2.2×10^{4} radians rms. The components at 35, 44, and 70 kHz are thermally excited resonances of the piezoelectric cylinders.[4] Broad features from 5-20 kHz for two lower curves are thermally excited vibrational modes associated with fiber loops and arcs.
(b) 22 m Mach-Zehnder interferometer in 3.75 Hz measurement bandwidth, showing achievement of the thermal phase noise limit for frequencies as low as a few hundred Hz. 2.2×10^{4} rad rms calibration signal at 1000 Hz.

We have made careful measurements of the phase noise in different length Mach-Zehnder fiber optic interferometers and reported the first experimental observations and characterization of the intrinsic phase noise level induced by thermal fluctuations in the fiber itself.[2] The measurements over the frequency range of 250 Hz - 100 kHz are in excellent agreement with a theory developed earlier by one of the authors,[3] with no adjustable parameters. Figure 1(a) shows that the experimentally measured phase noise (above ~20 kHz) falls off at a rate of −10 dB for each factor of 10 reduction in fiber length, in good agreement with the theoretically predicted $\sqrt{L}$ dependence. We have investigated the excess noise in the 5-20 kHz band in the lower curve of (a) and shown that it is associated with thermally excited vibrations[4] of fiber loops and arcs. Figure 1(b) shows achievement of the thermal phase noise limit for the 22-m interferometer in the frequency range of 250-2000 kHz, using a more elaborate acoustic shielding package than in (a).

These measurements represent the lowest phase noise levels achievable in Mach-Zehnder fiber optic interferometers at room temperature, regardless of the light source used. The practical significance of this is that light sources that use squeezed or more exotic states of light[5] will not offer any improvement in phase measurement sensitivity in room temperature fiber optic Mach-Zhender interferometers in the important 0-100 kHz band, since the thermal phase noise limit can be achieved with currently available light sources. Future work will address the thermal phase noise limitations in multiple beam and retracing path fiber interferometers, such as the Michelson and ring resonator configurations.

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