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Fiber-Tip Displacement Sensor Using a Sinusoidal FM-Based Technique

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sensor; fibrositis; fiber-tip; frequency modulation, tunable source

A frequency modulated dual-electrode DFB laser is used as the optical source for a sensor which is immune to polarization and acoustic fluctuations affecting its fiberoptic leads. Detection of the quadrature components of the reflected signal allows unambiguous direction determination. A measurement accuracy of ±20 nm is demonstrated over a range of several millimeters.

1 Introduction

There is a class of interferometric fiberoptic sensors which uses the cleaved endface of an optical fiber as one interface of a low finesse Fabry-Perot cavity, and an external reflecting surface as the other [1]-[3]. These fiber-tip interferometric sensors have the advantage of lead-insensitivity, as any environmental fluctuations affecting optical phase or polarization along the fiberoptic system are common to both of the interfering optical fields; only the small region between the fiber-tip and the mirror is susceptible to external disturbance. In their most fundamental configuration, interferometric sensors have directional ambiguity and regions of zero measurement sensitivity. These problems have been addressed by using feedback control loops [1],[4], by using two orthogonal polarization modes [5], by using dual wavelengths [2], or by a coherence multiplexing approach [3].

In this letter we describe a method which uses a sinusoidally frequency modulated dual-electrode DFB laser [6] to generate a pair of quadrature signals that can be used to eliminate the directional ambiguity and regions of zero sensitivity in the interferometric output. A fiber-tip system of this type may have potential in applications requiring lead insensitive displacement measurements with accuracies of the order of nanometers.

2 Theory

Figure 1 shows the arrangement of the fiber-tip interferometeric sensor. For a frequency modulated source with no intensity modulation the reflected signals returning to the detector can be expressed as $E_1(t) = \sqrt{R_1}E_o \exp j[\omega_o t + \phi(t)]$ and $E_2(t) = \sqrt{R_2}E_o \exp j[\omega_o[t-\tau] + \phi(t-\tau)]$ where $\tau = 2x/c$, and R_1 and R_2 are the fractional optical powers coupled back into the single mode fiber after reflection from the fiber endface and the external reflector respectively.

For sinusoidal frequency modulation, the phase delay can be written as $\phi(t) = [\Delta\omega_o/\omega_m]\cos\omega_m t$ where $\Delta\omega_o$ is the amplitude of the frequency modulation, and ω_m is the modulation frequency.

After coherent mixing and square law detection, the output signal V_{op} can be expressed as

$$\begin{aligned} V_{op} \propto R_1 + R_2 &+ 2\sqrt{R_1R_2}\cos\omega_o\tau[J_0(\tau\Delta\omega_o) + 2J_2(\tau\Delta\omega_o)\cos 2\omega_m[t-\tau/2] + ...] \\ &+ 2\sqrt{R_1R_2}\sin\omega_o\tau[2J_1(\tau\Delta\omega_o)\cos\omega_m[t-\tau/2] + ...] \end{aligned} \quad (1)$$

where the approximation $\omega_m\tau/2 << 1$ is assumed. Filtering out the DC term, we get

$$V_{dc} \propto R_1 + R_2 + 2\sqrt{R_1R_2}J_0(\tau\Delta\omega_o)\cos\omega_o\tau \quad (2)$$

And the amplitude V_{ac} of the lowest frequency component, at ω_m, is

$$V_{ac} \propto 4\sqrt{R_1R_2}J_1(\tau\Delta\omega_o)\sin\omega_o\tau \quad (3)$$

With the appropriate choice of $\Delta\omega_o$ and appropriate limits on τ, equations (2) and (3) show that a pair of signals may be derived which are in quadrature in terms of the quantity $\omega_o\tau$. The arctangent of the ratio of these signals will be directly proportional to $\omega_o\tau$ and so to the measurand x.

3 Experiment

Figure 2 shows the experimental system. An isolated two-electrode DFB laser, emitting at 1.54μm, was driven by a pair of sinusoidal current waveforms in the kHz range. Optical feedback was used in a control loop to keep the current waveforms 180^o out of phase and adjust their relative amplitudes to minimise intensity modulation while maximising frequency modulation. In order to change the fiber to mirror distance in a well-controlled pattern, the sensing fiber was held near its tip in a piezoelectric micropositioner, driven by a sawtooth waveform in the 0.05 to 1 Hz range. A low pass filter was used to extract the DC component of the detected photocurrent, while a lock-in amplifier filtered out the component at the modulation frequency. A digitizing oscilloscope displayed the two signals as a function of time, confirming their quadrature relationship. The digitized signals were passed on to a computer, which calculated the phase angle $\omega_o\tau$, and so the change in distance between the fiber-tip and the mirror, as a function of time. Plotting the calculated distance against time showed that the motion of the fiber-tip was not perfectly linear through each half-cycle of the sawtooth ramp, due to non-linearity in the piezoelectric transduction in the micropositioner. However, this non-linearity could itself be monitored by tracking the zero-crossings of either one of the two filtered signals, to yield a wavelength-referenced calibration curve, and so in turn a plot of measured dispacement v. calibrated displacement.

Figure 3 shows the result for a displacement of 17 μm, during which the optical signal parameters had been set to a modulation frequency, $\omega_m/2\pi$, of 7 kHz, and a frequency modulation amplitude, $\Delta\omega_0/2\pi$, of approximately 16 GHz. The residual intensity modulation on the optical signal was observed to be approximately 10%. The sensor response appears linear to the eye on the scale shown, but taking the difference between corresponding data values of measured and calibrated displacements, and plotting the results against calibrated displcement reveals the residual measurement error. Figure 4 is the result for the same data used in Figure 3. The rms distance error typically found from such data was under 20nm over the 17μm range achievable in a single piezoelectrically driven run. The range was extended manually over more than 3mm, and further 17μm runs were made, without increasing the rms measurement error.

4 Discussion

The measurements described above demonstrate the feasibility of displacement monitoring over a range of a few millimeters with an accuracy of better than 20 nm, using sinusoidal frequency modulation in a relatively simple fiberoptic system. Absolute distance measurement can also be achieved with this system in situations where taking a "zero" reading with the fiber-tip touching the target is acceptable.

The residual error in the distance measurement typically has a strong cyclic component, as Figure 4 shows. The model outlined above was extended to take optical intensity modulation into account, and it was found that inserting the values relevant to these measurements led to predicted errors of the order observed experimentally. The measurement error in the general case was predicted to be directly proportional to the intensity modulation index. A tunable source subject to lower intensity modulation index than the 10% typical with our laser system might therefore allow distance measurement with correspondingly reduced error.

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5 References

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Figures

Figure 1. Schematic diagram of fiber-tip sensor head, showing the fiber endface (FT), the external reflector (M) a distance (x) away, and the input and output optical fields.

Figure 2. Experimental system used to demonstrate sensor. L: Laser; I: Isolator; PD1: Monitoring photodiode; PD2: Output photodetector; M: Target reflector; FG: Function generator; LDC: Laser drive control; BPF: Band pass filter; LPF: Low pass filter; DO: Digitising oscilloscope/waveform recorder; C: Computer.

Figure 3. Sensor-measured displacement v. calibrated displacement (referenced to source wavelength).

Figure 4. Error in sensor-measured displacement v. calibrated displacement (referenced to source wavelength).

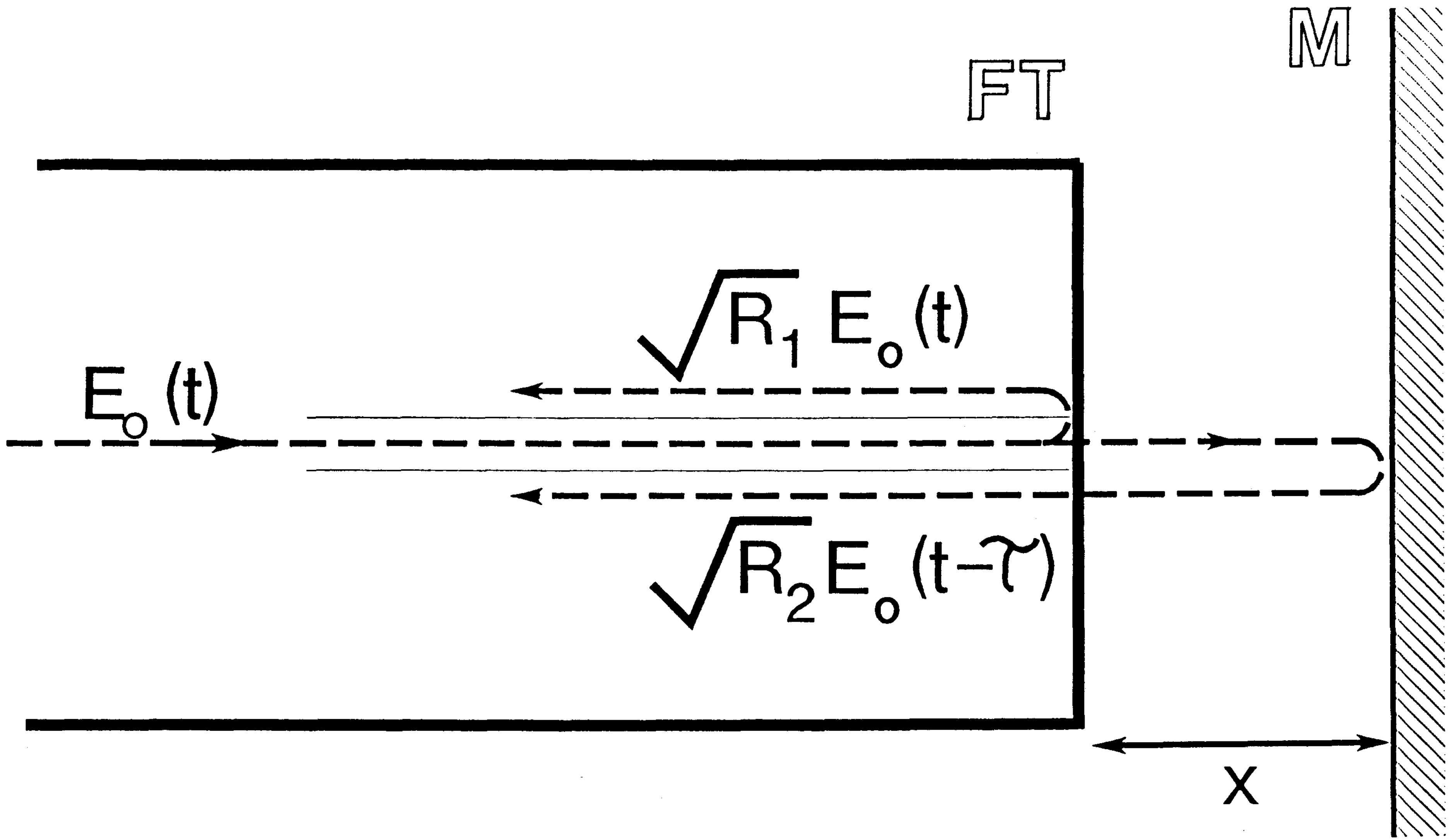


Figure 1

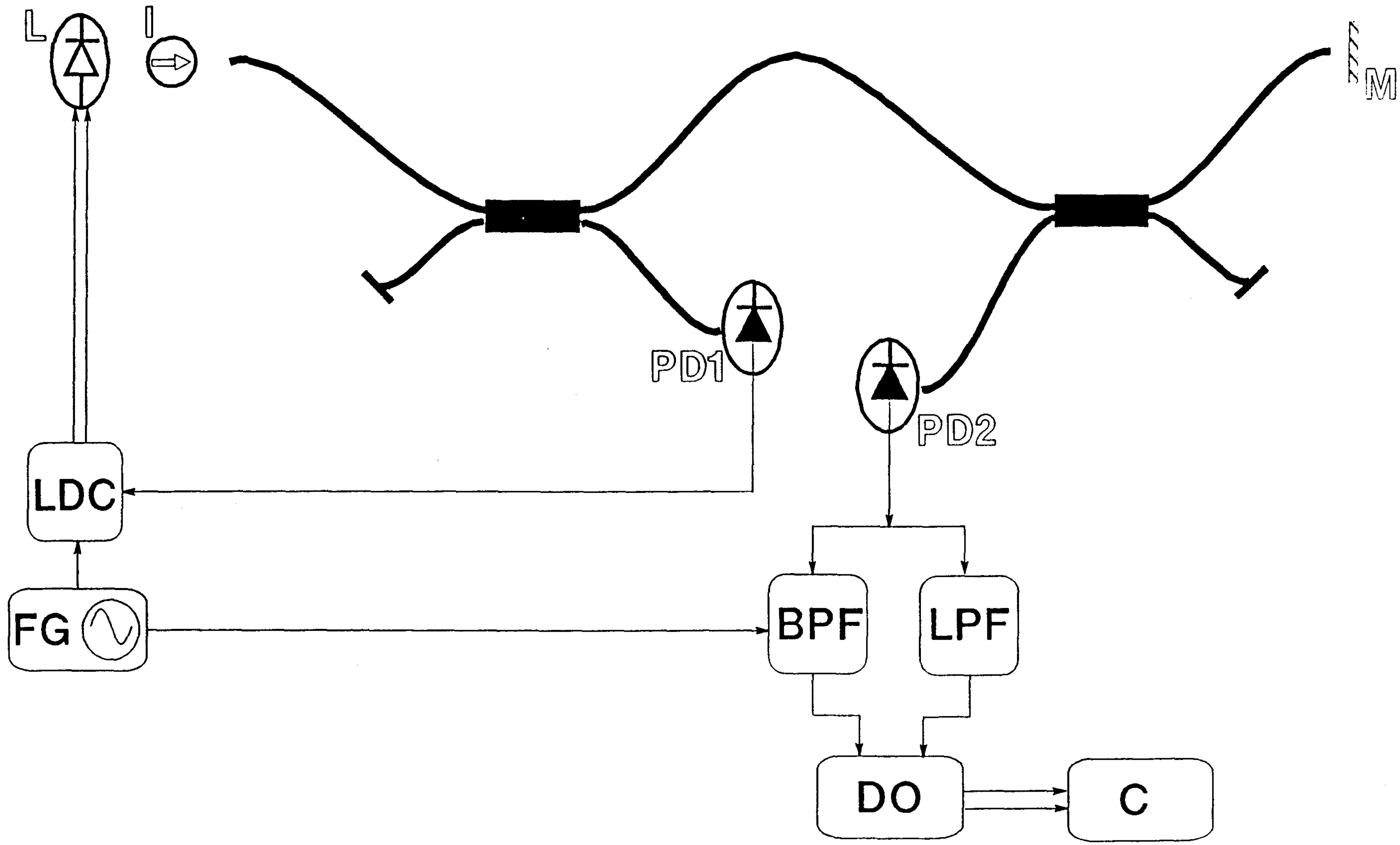
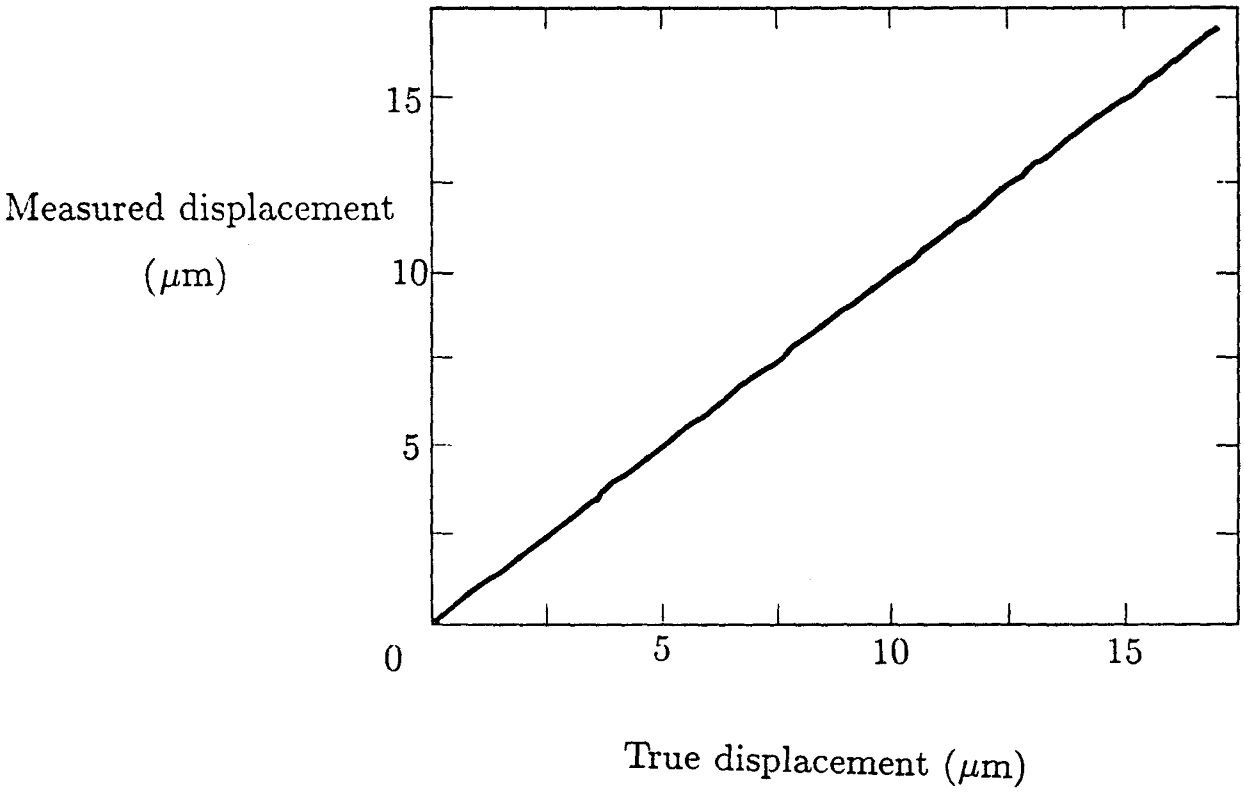


Figure 2



Measured displacement
(μm)
15
10
5
0
5
10
15
True displacement (μm)

Figure 3

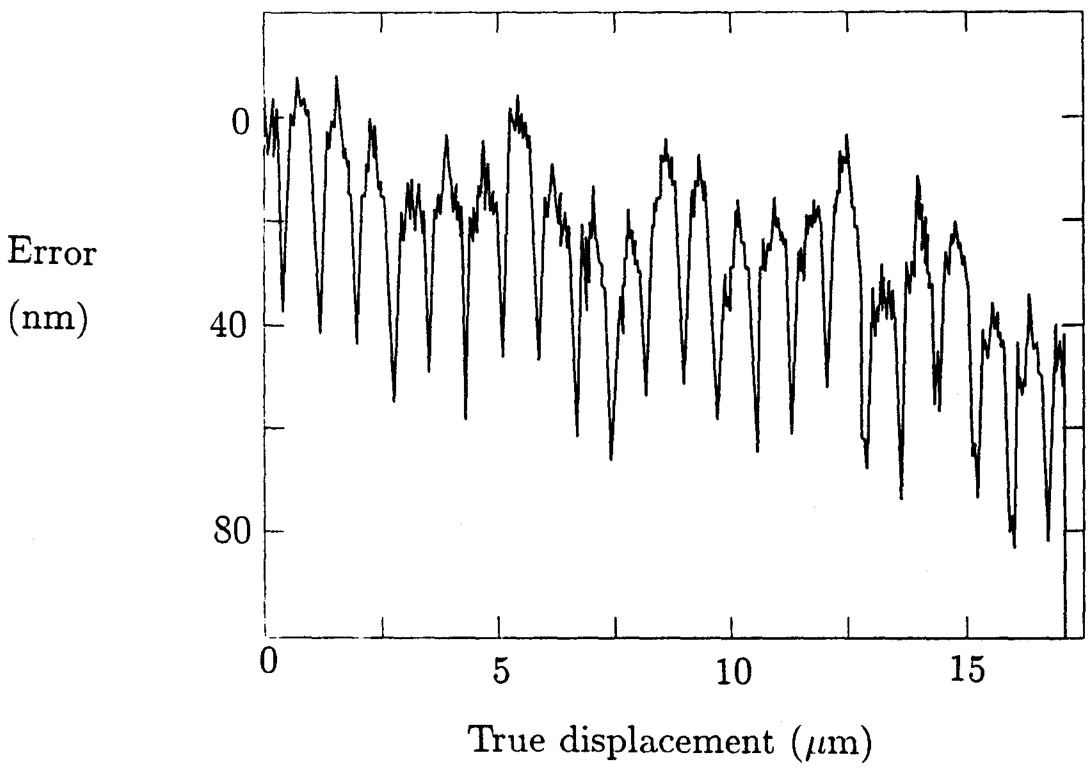


Figure 4