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A double-focus lens interferometer for scanning force microscopy

Kazuya Goto
Department of Electronic Mechanical Engineering, Nagoya University, Nagoya 464-01, Japan

Minoru Sasaki and Shigeru Okuma
Department of Electronic Engineering and Electronics, Nagoya University, Nagoya 464-01, Japan

Kazuhiro Hane
Department of Mechatronics and Precision Engineering, Tohoku University, Sendai 980-77, Japan

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We present a laser interferometer for displacement measurement requiring high precision. Consisting of a small number of optical parts, the instrument is simple, compact, and not affected by environmental conditions. Further, with a birefringent double-focus lens, the two interfering beams share a common path and the interference signal is immune to fluctuations of the optical path length. Peak-to-peak noise in a dc to 1 kHz bandwidth is less than 0.02 Å. We applied this interferometer to scanning force microscopy and tested the performance. © *1995 American Institute of Physics.*

I. INTRODUCTION

In displacement sensing, higher sensitivity and precision have been increasingly needed. For example, a resolution of better than 1 Å is often required in scanning force microscopy (SFM). However, an interferometer is easily affected by environmental disturbances such as irregular air currents and inevitable vibration from the floor. To eliminate their influence, fiber-optic[1,2] and common-path[3–6] configurations are often used. In an optical system with a common path, unpredictable phase shifts caused by environmental disturbances can be canceled and a very high sensitivity on the order of 0.1 Å has been reported. To provide two interfering beams, optical devices such as gratings[5] and birefringent prisms[3,4] are used.

One of the best ways to apply the birefringent optical devices to common-path configurations is using a double-focus lens.[6,7] A double-focus lens gives two beams with different focal points because of its birefringence. Recently, the double-focus lens has been successfully used in a heterodyne interferometer for SFM.[8] In the microscopy using the heterodyne interferometry, the atomic images of graphite and mica surfaces have been first obtained.

In this pater, we report a modified version of the optical displacement sensor (interferometer) for SFM with a double-focus lens. With the homodyne detection technique, the interferometer is simple and compact. The arrangement of the optical parts, including a double-focus lens, is optimized to obtain the maximum signal to noise ratio. Unlike the previous common-path interferometers,[4,5] it is free to choose the size and the shape of a cantilever for the SFM because of the double focus of the lens. And compared to the SFM with the heterodyne interferometry,[8] it is easy to operate the SFM with the proposed interferometry in the constant pressure mode because a sample itself does not have to be used as the reference surface. The performance of the developed interferometer has been demonstrated in the SFM measurement.

II. OPTICAL DESIGN

The proposed instrument is based on polarization interferometry. The optical system and the ray trajectories are shown in Fig. 1. First, the polarized laser beam passes through the polarizing beam splitter (PBS). The PBS is set so that the beam is polarized at 45° to the optic axis of the calcite in the double-focus lens. The beam is divided into two orthogonally polarized beams at the double-focus lens[9] as shown in Fig. 2. The lens consists of a double concave lens of calcite and two double convex glass lens on each side. The lens of a calcite crystal has two different focal points because the crystal has two different diffractive indices depending on the polarizing state of the beams passing through it. The double-focus lens we used here is designed to have zero power for the ordinary ray and a focal length of 36.3 mm for the extraordinary ray. Next, each beam passes through the objective, which gives a focused beam and a parallel beam. The focused beam functions as the object beam to probe a small region and is reflected on the surface of the object such as a cantilever used for SFM. On the other hand, the parallel beam functions as the reference beam and is reflected on the reference surface. A right-angled prism is used as the reflector for the reference beam. In Fig. 1, the incident planes of the PBS and the prism are illustrated to be parallel for simplicity, but they should be oriented at 45° relative to each other so as not to change the polarization of the beam at the prism. In this arrangement, the incident beam (reference beam) to the prism is polarized to be parallel or perpendicular to the incident plane. Since the reference beam is parallel unlike the object beam, the distance between the objective and the reference surface can be determined separately from the object surface. As shown in Fig. 1, the axis of the reference beam is shifted at the prism. The axis of the object beam is also shifted. In this configuration, the laser is not affected by the backreflections from the surfaces. Thus no device such as an optical isolator is needed in this interferometer.

After the reflection, both beams pass through the objective and the double-focus lens and they share the same path. And at the PBS, two interference signals (p state and s state) are provided the phases of which are different from each other by 180°. The interference signals I_p and I_s are expressed as

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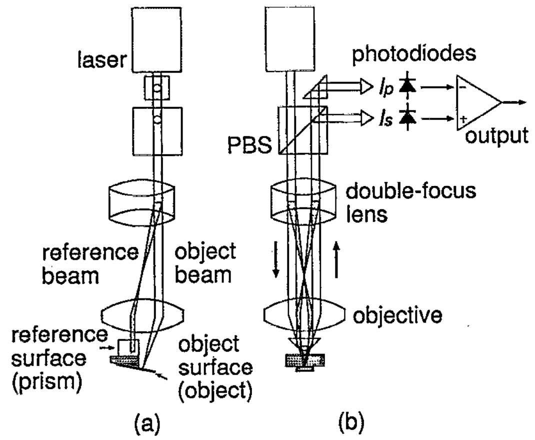

FIG. 1. Optical system. The sideview (a) and the front view (b).

$$I_p=\tfrac{1}{2}[I_o+I_e+2\sqrt{I_oI_e}\cos(\phi+\psi)], \tag{1}$$

$$I_s=\tfrac{1}{2}[I_o+I_e-2\sqrt{I_oI_e}\cos(\phi+\psi)], \tag{2}$$

where $I_o(I_e)$ is the intensity of the ordinary ray (extraordinary ray), ϕ is the phase shift by the displacement of the object surface, and ψ is the other unknown phase shifts. By adjusting ψ so that $\cos(\phi+\psi)=\sin\phi$ and assuming $I_o=I_e=I/2$, the interference signal I_p-I_s is given by

$$I_p-I_s=2\sqrt{I_oI_e}\sin\phi=\tfrac{1}{2}I\sin\phi\approx\tfrac{1}{2}I\phi, \tag{3}$$

where I is the intensity of the light from the laser. At this phase, the sensitivity to a small change of the phase ϕ is highest.

As the interfering beams take almost the same path, a phase shift by fluctuations of the atmosphere is eliminated. And as the object surface is fixed directly on the reference surface, the influence of vibration on the interfering beams is reduced. Thus a relative path difference alone is detected. Further, by subtracting one interference signal from the other as shown in Eq. (3), the fluctuation of the laser intensity are not detected as phase shifts. And as for the efficiency, there is no power loss in the proposed optical system because the light supplied by the laser is totally used for detection.

To compensate the phase shift, three methods can be used. First, as the object surface and the reference surface are separate, a piezoelectric actuator can be set between them to directly change the path difference. Second, since the paths of the object beam are not parallel to the reference beam, the path difference varies by adjusting the distance between the objective and the two surfaces (object surface and reference surface). The phase shift $\Delta\phi$ is given by

$$\Delta\phi=\frac{4\pi}{\lambda}\Delta d(1-\cos\theta), \tag{4}$$

where λ is the wavelength, Δd is the variation of the distance between the objective and the surfaces, and θ is the angle between the two beams. In other words, the influence of Δd on $\Delta\phi$ is not entirely eliminated. But it is reduced to 1/200–1/100 in our system since θ is approximately 6°–8°. Third, using a laser diode and taking advantage of the wavelength variation proportional to the injected current,[10]

$$\Delta\phi=\frac{2\pi}{\lambda^2}l\Delta\lambda, \tag{5}$$

where l is the optical path difference between the interfering beams and $\Delta\lambda$ is the wavelength change due to the injected current. To satisfy the required range of $\Delta\phi(\sim 2\pi)$, the value of l on the order of 1 or 10 mm is needed. It is not difficult to have such a spacing in our system.

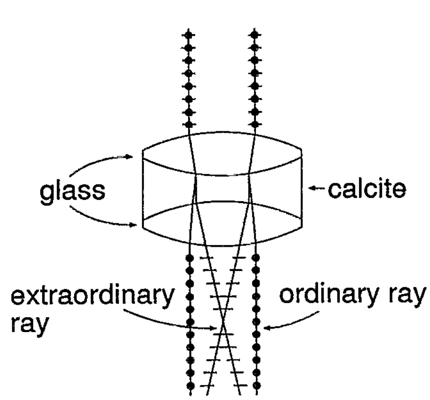

FIG. 2. Double-focus lens.

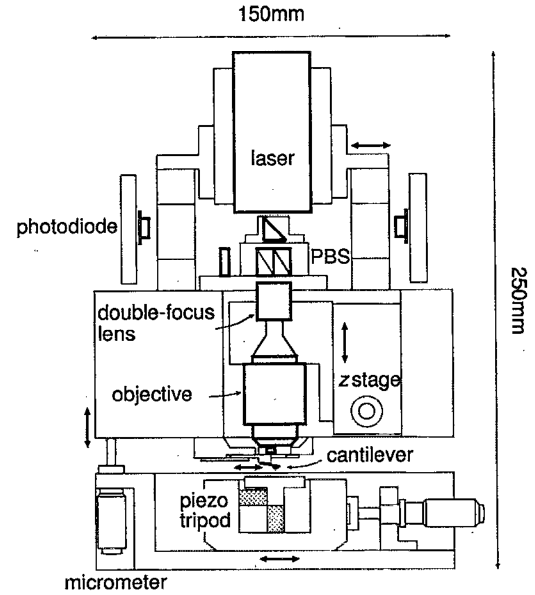

FIG. 3. Cross section of the SFM with the interferometer.

III. EXPERIMENTAL SYSTEM

Figure 3 shows the entire design of the instrument (SFM with the interferometer). It is 250 mm high and 150 mm in diameter. Since the interferometer is developed for SFM, a sample stage with positioners is also shown. The optical parts are assembled straight in a round body of the instrument. The body of the instrument is made of the low expansion cast iron (Enomoto, Nobinite). To make the axes of the interfering beams backreflected agree well with each other, the laser and the prism are shifted perpendicularly to the

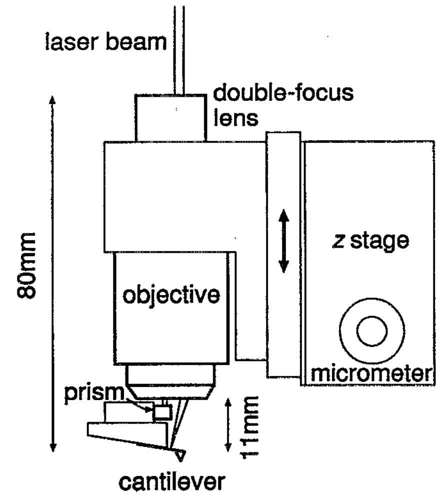

FIG. 4. Schematic diagram of the experimental setup around the objective.

optical path. Two reflectors are used to properly direct the beams (interference signals) to the photosensors.

In Fig. 4, the double-focus lens and the objective are shown with the prism (reference surface) and the cantilever (object surface). The position of the objective is changed together with the double-focus lens by the z stage so that the object beam can be focused on the object surface. The reference surface can be set freely within the working distance of the objective (11 mm). We set the prism 8 mm away from the surface of the object as shown in Fig. 4. Since the reference surface does not have to be in the same plane as the object surface, various kinds of cantilevers can be used, while in the conventional common-path interferometers,[4,5] the length of cantilevers (i.e., the distance between the two interfering beams on cantilevers) is determined by particular optical devices.

The laser used in the interferometer is a He–Ne laser (Uniphase, 1107P, $\lambda=633$ nm, 4 mW). The magnification and focal length of the objective (Olympus, ULWD MSplan) are 20× and 9 mm. The size of the prism is 2×2×2 mm. The photosensors are PIN silicon photodiodes (Hamamatsu, S2216-02) and the output signals are amplified by the operational amplifiers (Analog Device, AD549). In SFM measurement, a commercially available cantilever (Park Scientific Instruments) is used. In the sample stage of the SFM, the tripod is set up with three piezoelectric actuators (Tokin, NLA-5×5×9). The experiments were carried out on a vibration isolated bench in a room without a temperature controller.

IV. RESULTS AND DISCUSSION

The three methods of the phase compensation were examined. The phase difference was controlled by the piezoelectric actuator placed between the object surface and the reference surface in the manner similar to the conventional method.[11]

Next, the interference signal I_p-I_s was measured as a function of the spacing between the objective and the two surfaces. The objective was fixed to the z stage and the position was changed by rotating the micrometer attached to it. In the z stage, the rotation of 360° was converted into the displacement of 100 μm. As shown in Fig. 5, by changing the spacing between the objective and the surfaces, the interference signal varied sinusoidally. High contrast of the signal (the visibility reaches 0.8–0.9) is obtained when the position of the surface corresponds to the focal plane.

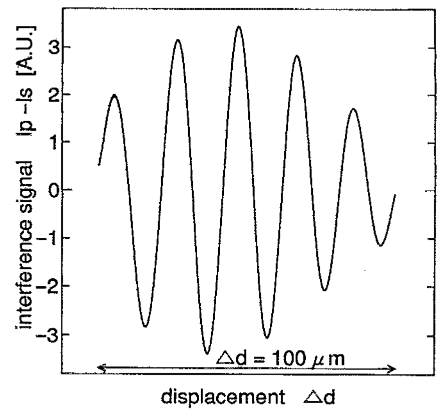

FIG. 5. Interference signal I_p-I_s measured as a function of the displacement Δd of the objective.

When a laser diode was used as the light source instead of the He–Ne laser, the phase difference between the two interfering beams was also compensated for by changing the injection current of the laser diode (single mode). The phase shift of 6π was obtained with the increase of the injection current from 33 to 43 mA at the path difference l of 17 mm.

Next, noise level of the interferometer was measured. The interference signal was measured under the condition given by Eq. (3). A stiff glass plate covered with gold was used as the object. Figure 6 shows the noise in the interference signal I_p-I_s for 100 ms in a dc to 1 kHz bandwidth. The measured peak-to-peak noise is less than 0.02 Å as shown in Fig. 6. This noise seems to be mainly caused by mechanical vibrations of the experimental setup. At higher frequencies, the noise level appeared to be governed by other noise sources, e.g., shot noise from the photodiodes, electronic noise, and laser noise. In a dc to 10 kHz bandwidth, the peak-to-peak noise was measured to be less than 0.06 Å. As for a slow drift in the interference signal, it was observed to be about 1 nm/min. The main causes of this were probably drifts in the aiming of the laser beam and variations in the laser frequency. Considering a rather large distance of 8 mm between the sample and the prism in the experiment, the

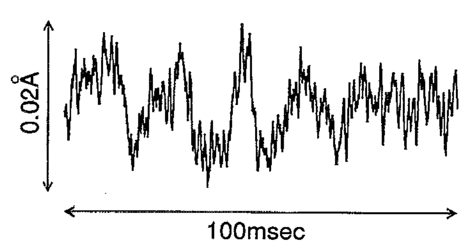

FIG. 6. Noise in the interference signal measured as a function of time.

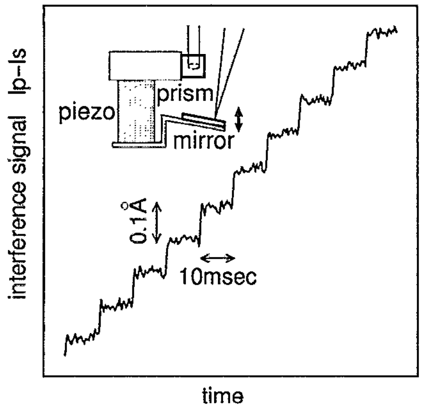

FIG. 7. Interference signal for step changes as a function of time.

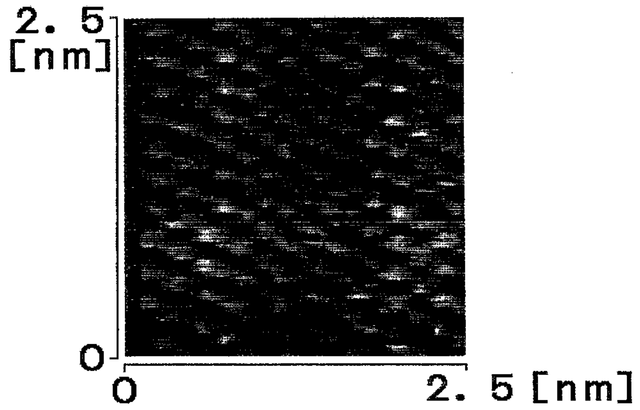

FIG. 8. Atomic image of an HOPG surface.

influence of the environmental disturbances was small.

To evaluate the resolution in the optical path difference, we displaced the plate stepwise with a piezoelectric actuator (NEC, AE0203D04) which was set between the prism and the plate and observed the interference signal for 100 ms. The signal to the actuator was sent from a computer and then the interference signal was recorded in the computer. Figure 7 shows the interference signal for the step changes of the path length. The displacement step was 0.1 Å at an interval of 10 ms. The displacement of 0.1 Å can be clearly distinguished as shown in Fig. 7.

As mentioned above, this interferometer was developed for SFM. We tested the performance as a microscope. The noise level is low enough to allow atomic resolution as demonstrated in Fig. 7. We observed a surface of highly oriented pyrolytic graphite (HOPG). The surface is scanned with the tip of the cantilever, the rear surface of which the objective beam is focused on. The cantilever used was 200 μm long and the rear surface of it was coated with gold for good reflection of the beam. Figure 8 shows the graphite surface imaged with atomic resolution by using the proposed interferometer. As shown in Fig. 8, the high resolution of the interferometer is demonstrated. The scanned area is approximately 2.5×2.5 nm.

Because the sample surface is not directly connected to the reference surface of the interferometer in the SFM measurement, relative displacement caused by vibration can easily disturb the interference signal. Though the system was already placed on a vibration isolated bench, we added a stack of sponge and rubber to obtain better stability. The measured noise level was approximately 0.2 Å at several hundred hertz and 0.4 Å at 1 or 2 Hz. The latter belonged to the resonance of our bench. For the further stability of the SFM, it is required to obtain the higher resonance frequency of the instrument by raising the spring constants of the positioners and by decreasing the weight of the body.

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