Phase locked laser diode interferometry for surface profile measurement

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We propose a new type phase locked interferometer which uses tunability of the wavelength of a laser diode. The phase lock is achieved by controlling the injection current of the laser diode. A CCD image sensor is used as a photodetector to scan electrically a measuring point along the surface of the object. Since this interferometer uses no mechanical elements such as a piezoelectric transducer and galvanomirror, the measurement accuracy is not limited by the mechanical properties. The characteristics of the feedback control system for the phase lock are examined through measurements of surface profiles of the diamond-turned aluminum disks.

I. Introduction

Optical interferometry has been used to measure surface profiles of optical parts. Recently as the properties of laser diodes improved,[1-3] a few interferometers adopted a laser diode. The laser diode has many *strong* points: small size, lightweight, and high efficiency. Moreover, the wavelength of the laser diode can be controlled by its injection current. Using this property, it is possible to constitute a heterodyne interferometer with mechanical elements such as a piezoelectric transducer (PZT).

A surface profile of an object can be measured with high accuracy by sinusoidal phase modulating (SPM) interferometry,[4-6] in which an injection current of the laser diode is modulated sinusoidally. But it is necessary to calculate the Fourier transform of an interference signal with a computer to obtain the surface profile of the object. This calculation takes a long time.

In this paper, we describe a phase locked laser diode (PLLD) interferometer in which the surface profile of the object is obtained from the sinusoidal phase modulated interference signal without a computer. In SPM interferometry, information on the surface profile of the object is in the phase term of the interference signal. Scanning a measuring point along the surface of the object, the phase term changes according to the surface profile of the object. If this phase displacement can be stabilized, the manipulated variable is proportional to the surface profile of the object. Since a laser diode is used as the light source in the interferometer proposed here, it is possible to stabilize phase displacement by controlling the injection current of the laser diode. To scan a measuring point along the surface of the object electrically, a charge coupled device (CCD) image sensor is used in this system. In the past, a phase locked interferometer was proposed,[7,8] where a PZT and a galvanomirror were used as the phase modulator and the scanner of measuring points, respectively. Since the PLLD interferometer uses no mechanical elements such as a PZT and galvanomirror, the measurement accuracy is not limited by the mechanical properties.

II. Principle

The configuration of a PLLD interferometer is shown in Fig. 1. A Twyman-Green interferometer is used as the optical system. The injection current of a laser diode consists of dc bias current I_0, modulation current $I_m(t)$, and control current $I_c(x)$. The central wavelength of the laser diode is λ_0 which is determined by the dc bias current I_0. The modulation current is given by

$$I_m(t) = a \cos\omega_c t. \qquad (1)$$

The reference wave reflected by mirror M and the object wave reflected on the surface of an object are imaged onto a CCD image sensor with lens $L2$. The surface profile of the object is represented by $D(x)$, where x denotes a measuring position on the surface of the object. The optical path difference between the two arms of the interferometer is $2D_0$ at the positions where $D(x) = 0$ and $I_c(x) = 0$. The ac component of the interference signal is written as

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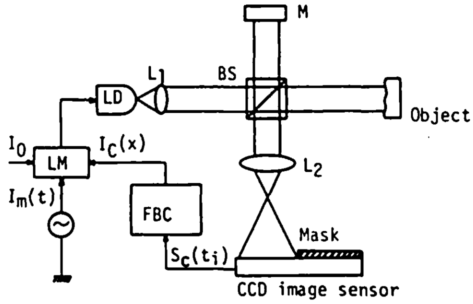

Fig. 1. Phase locked laser diode interferometer.

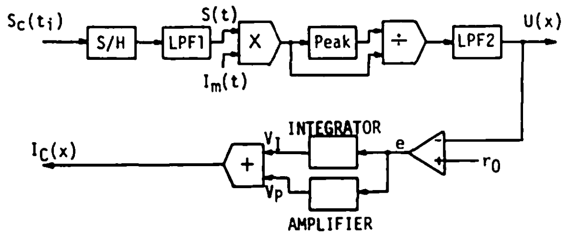

Fig. 2. Block diagram of the feedback control system.

$$S(t) = S_0 \cos[z \cos\omega_c t + \alpha(x)], \quad (2)$$

where $z = (4\pi/\lambda_0^2)a\beta D_0$, β is a proportional constant, and

$$\alpha(x) = (4\pi/\lambda_0)[D_0 + D(x)]. \quad (3)$$

In this interferometer, the surface profile can be measured by locking the phase $\alpha(x)$ at a desired phase α_L. Phase α_L is given by

$$\alpha_L = (4\pi/\lambda_0)D_0. \quad (4)$$

To lock phase $\alpha(x)$ to phase α_L, we change the wavelength of the laser diode from λ_0 to $\lambda_0 + \lambda_c$ by controlling its injection current $I_c(x)$. Then we obtain

$$(4\pi/\lambda_0)D_0 = [4\pi/(\lambda_0 + \lambda_c)][D_0 + D(x)], \quad (5)$$

where

$$\lambda_c = \beta I_c(x). \quad (6)$$

From Eqs. (5) and (6), we obtain $D(x)$ as follows:

$$D(x) = (D_0/\lambda_0)\beta I_c(x). \quad (7)$$

Equation (7) shows that we can measure the surface profile of the object by measuring the control current $I_c(x)$.

The phase lock is achieved by the feedback control of the injection current of the laser diode. We obtain a feedback signal from the interference signal. Expanding Eq. (2), we have

$$S(t) = S_0[\cos\alpha(x)][J_0(z) - 2J_2(z)\cos(2\omega_c t) + \ldots]$$
$$- S_0[\sin\alpha(x)][2J_1(z)\cos\omega_c t$$
$$- 2J_3(z)\cos(3\omega_c t) + \ldots], \quad (8)$$

where $J_n(z)$ is the nth order Bessel function. The amplitude of the component of $\cos\omega_c t$ is used as the feedback signal $U(x)$ as follows:

$$U(x) = -2J_1(z)\sin\alpha(x). \quad (9)$$

The injection current of the laser diode is controlled with a PI (proportional integral) controller by using the feedback signal $U(x)$. The signal $U(x)$ is kept at a constant value without steady state error even though phase $\alpha(x)$ is changed by scanning a measuring point along the surface of the object.

III. Feedback Control System

A block diagram of the feedback control (FBC) system is shown in Fig. 2. The output $S_c(t_i)$ of the CCD image sensor is a discrete signal in time, and it is an integration value of interference signal $S(t)$. We must convert it to a continuous signal which is equal to signal $S(t)$ for a specified measuring point. The period of integration is period T_a of the charge storage. If period T_a is much shorter than the period of phase modulation $2\pi/\omega_c$, we can get the continuous signal without the influence of integration. A sample–hold (S–H) circuit picks a signal concerned with a specified measuring point from output $S_c(t_i)$, and a low pass filter (*LPF*1) eliminates the undesired components. Signal $S(t)$ for a measuring point has been produced for a scanning time T_{scan}.

The signal $S(t)$ is multiplied by the modulation current $I_m(t)$ and divided by its amplitude S_0. Amplitude S_0 changes according to the distribution of the reflection factor on the object's surface. This division process removes the change of the gain in the control system which is caused by the change of amplitude S_0. Picking up the dc component of the output signal of the divider with a low pass filter (*LPF*2), we obtain the feedback signal $U(x)$ given by Eq. (9). A differential

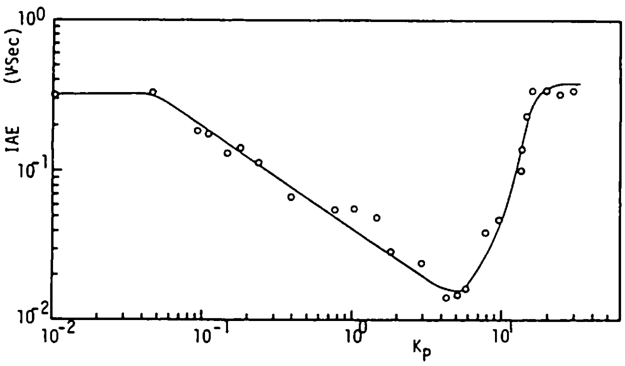

Fig. 3. Value of IAE for the various proportional gain K_P.

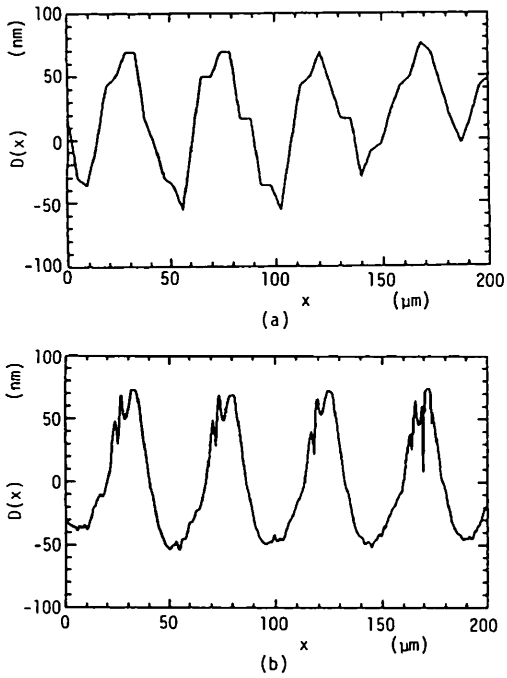

Fig. 4. Surface profiles of sample I measured with (a) the PLLD interferometer and (b) the Talystep instrument.

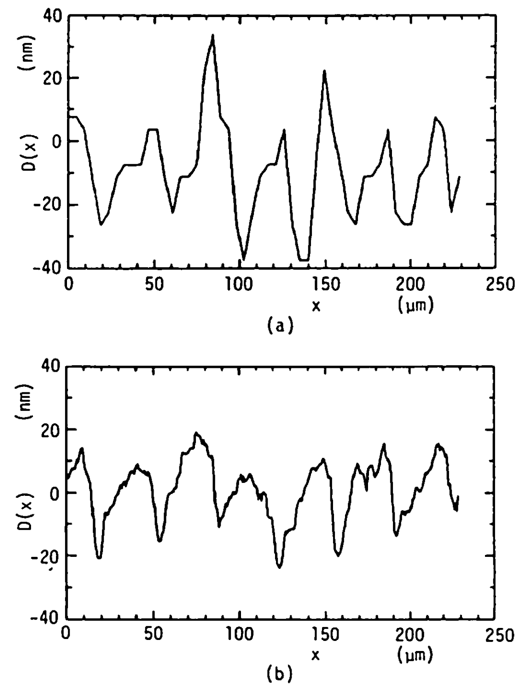

Fig. 5. Surface profiles of sample II measured with (a) the PLLD interferometer and (b) the Talystep instrument.

amplifier produces an error signal e which is the difference between the feedback signal $U(x)$ and a reference signal r_0. The desired phase α_L is determined by a reference signal r_0. The error signal is fed to an integrator and an amplifier whose integral time and proportional gain are T_I and K_P, respectively. The integral output V_I and the proportional output V_P are added and converted from a voltage signal to a current signal, which is the feedback current $I_c(x)$.

IV. Experiments

A. Optical System

We used a GaAlAs laser diode as the light source. Its maximum output power is 5 mW and peak wavelength is 780 nm. The modulation efficiency β is 6.0×10^{-3} nm/mA. The optical path difference $2D_0$ was 160 mm. The frequency of phase modulation $\omega_c/2\pi$ was 1.8 kHz. Its amplitude z was determined to be 1.2, which gives a maximum value to $J_1(z)$. The period of charge storage of the CCD image sensor was 40 μs, which resulted in a sampling frequency of 25 kHz for signal $S(t)$. The cutoff frequencies of the *LPF*1 and *LPF*2 were 5 kHz and 100 Hz, respectively. The size of the photodetector of the CCD image sensor is 9×14 μm, and the photodetectors are arranged at intervals of 14 μm. We used fifty elements of the photodetector in the CCD image sensor to detect interference signals along the surface of the object. The image of the surface of the object was formed on the CCD image sensor with a magnification of 3.0, so the spatial interval of the measuring points was ~4.7 μm.

B. Suppression of the Fluctuation of Wavelength

We observed the fluctuation of the error signal caused by the fluctuation of the wavelength of the laser diode. When the laser diode is used as a light source, it is necessary to suppress the fluctuation of its wave-

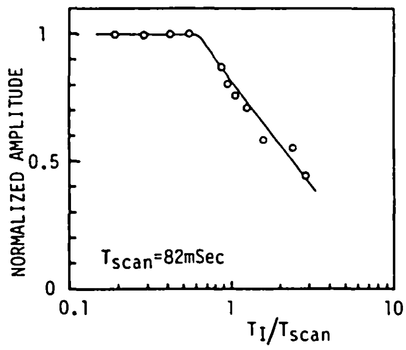

Fig. 6. Normalized value of the measured amplitude of sample I as a function of ratio T_I/T_{scan}.

length. We examined how to suppress the fluctuation with a proportional feedback control. We define an integral of absolute value of error (IAE) in a period of 1 s as follows:

$$\mathrm{IAE} = \int_0^1 |e(t) - e_s| dt, \tag{10}$$

where e_s is a mean value of the error $e(t)$. We estimate the effect of suppression by using the IAE. We measured the IAE in the feedback control system using only proportional control when a measuring point on the surface of the object was fixed. The experimental results are shown in Fig. 3. The IAE decreased monotonically as the proportional gain increased in the region of $K_P < 4.5$. When the K_P increases from 4.5, the control system becomes unstable and IAE increases rapidly. It is found that we have to determine a proportional gain smaller than 4.5. In the following experiments, the proportional gain K_P was kept at 4.3.

C. Measurement of the Surface Profile

We measured the surface profile of a diamond-turned aluminum disk. The integral time T_I of the integrator was 43 ms. The integral time was determined by taking account of the response time of low pass filter *LPF*2. In this system, the time required to achieve the phase lock is dependent on the integral time T_I. If scanning time T_{scan} is shorter than integral time T_I, a measuring point changes before the phase lock is achieved. So scanning time T_{scan} was selected to be 82 ms which is about twice the value of T_I.

First, the measured surface profile of sample I, whose cutting pitch is ~50 μm, is shown in Fig. 4(a). It is considered that the surface profile of the disk has a periodic structure determined by the cutting pitch. Figure 4(b) shows the surface profile of the same disk measured with a Talystep. The measuring points on the surface in Fig. 4(a) are different from those in Fig. 4(b). The surface profile of Fig. 4(a) agrees well with that of Fig. 4(b) as a whole.

Next, the measured surface profile about sample II, whose surface roughness is smaller than that of sample I and whose cutting pitch is ~35 μm, is shown in Fig. 5(a); the surface profile measured by a Talystep is shown in Fig. 5(b). Both measured results also agreed well with each other.

D. Integral Time and Scanning Time

We examined a suitable ratio T_I/T_{scan}. We measured the surface profile of sample I for various values of T_I and a fixed value of T_{scan}, 82 ms. The amplitude of roughness was calculated from the measured surface profile. The result is shown in Fig. 6, in which the amplitude of roughness is normalized by that measured at a small value of the ratio T_I/T_{scan}. Figure 6 shows that the measured amplitude is smaller than the true value of the amplitude when the ratio T_I/T_{scan} is larger than 0.6. It is found that the ratio T_I/T_{scan} must be fixed at a value <0.6.

V. Conclusions

We have proposed a phase locked laser diode interferometer which uses a laser diode as the light source and a CCD image sensor as the photodetector. No mechanical elements are required in this interferometer. We suppressed the fluctuation of wavelength of the laser diode with proportional feedback control. We measured the surface profiles of the diamond-turned aluminum disk with high accuracy.

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