Phase locked laser diode interferometer

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ABSTRACT

We propose a phase locked interferometer where tunability of the wavelength of a laser diode is utilized. A CCD image sensor detects an interference signal scanning electrically a measuring point along a surface of an object. The phase of the interference signal changes according to the surface profile. This phase is kept at a constant value by controlling the injection current of the laser diode with a feedback control system. The surface profile is obtained from the change in the injection current. The feedback signal is generated directly from the output of the CCD image sensor, which enables us to make high-speed measurements in real time. The scanning time required to complete the measurement for one measuring point was from ~2 msec to ~10 msec.

External disturbances such as mechanical vibrations cause phase variations in the interference signal, and accurate measurements become impossible. Detection of the phase variation at a fixed point on the surface of the object is added to the phase locked interferometer. The feedback control of the injection current is done alternately for the fixed point and the measuring point. An exact surface profile is obtained by subtracting the phase variation detected at the fixed point from the surface profile detected at the measuring points. We could improve the measurement accuracy from ~20 nm to ~5 nm in surface profile measurements of diamond turned aluminum disks.

1. INTRODUCTION

Laser diodes (LDs) have been used as a light source in interferometers. The phase modulation required by the interferometers is easily produced by modulating the injection current of the LD[1-3], where the tunability of the wavelength in the LD is utilized. By utilizing this aspect of the LD more effectively, we can construct a phase locked laser diode (PLLD) interferometer[4] without using any mechanical elements which were used in the conventional phase locked interferometers[5-7]. The PLLD interferometer detects the information about the phase of the interference signal with sinusoidal phase modulating interferometry[8,9]. Scanning a measuring point along the surface of the object, the phase changes according to the surface profile of the object. This phase change is stabilized by controlling the injection current of the LD. The surface profile is obtained from the change in the injection current.

The PLLD interferometer does not need any computer for computation. It uses feedback control system to obtain the surface profile. The feedback signal is directly generated from the output of the CCD image sensor. Then the construction of the PLLD interferometer is simple, and we can measure the surface profile in real time.

External disturbances such as mechanical vibrations of optical components cause phase variations in the interference signal. Since these variations are converted to a surface profile, it is impossible to measure an accurate surface profile. We detect the phase variations at a fixed point on the surface of the object, while we detect a surface profile at the measuring points. The feedback control of the injection current of a laser diode is done alternately for the fixed point and the measuring point. An exact surface profile is obtained by subtracting the phase variation detected at the fixed point from the surface profile detected at the measuring points. Thus we can measure a surface profile with a high accuracy eliminating the effects of external disturbances.

2. PRINCIPLE

Figure 1 shows the setup of the PLLD interferometer. Sinusoidal phase modulation is given by the modulation current[3]

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

The surface of the object is represented by $D(x)$, where x denotes the measurement position on the surface of the object. The optical path difference between the two arms is $2D_0$ at a position x_0, where $D(x_0)$ is regarded as zero. The central wavelength λ_0 of the LD is determined by its dc bias current I_0. The wavelength $\lambda_c(x)$ changes with the feedback control of the injection current $I_c(x)$ according to the relationship $\lambda_c(x)=\beta I_c(x)$, where β is a modulation efficiency of the LD. The interference signal on the CCD image sensor is

$$S(t,x) = S_1 + S_0\cos[z\cos\omega_c t + \alpha(x)] \ , \qquad (2)$$

where

$$z = (4\pi/\lambda_0^2)a\beta D_0 \ ,$$

$$\alpha(x) = \{4\pi/[\lambda_0 + \lambda_c(x)]\}\{D_0 + D(x)\} \ . \qquad (3)$$

and S_1 is a dc component. When we scan the measuring point along the surface of the object, the phase $\alpha(x)$ changes according to the surface profile if the current $I_c(x)$ is fixed. The current $I_c(x)$ must be controlled if the phase $\alpha(x)$ is to be locked to a specified value $\alpha(x_0)$. The phase lock is achieved by controlling the injection current $I_c(x)$ with a feedback system. We obtain the surface profile of the object $D(x)$ from the control current $I_c(x)$ as follows[4]:

$$D(x) = (D_0/\lambda_0)\beta I_c(x) \ , \qquad (4)$$

where $I_c(x_0)=0$.

3. FEEDBACK SIGNAL AND CONTROLLER

The CCD image sensor is driven synchronously with the modulation current $I_m(t)$. The signal $S(t,x)$ is integrated during a half period of the modulation current $I_m(t)$. The CCD image sensor produces the two different signals[9]

$$y_i(x) = \int_{(T/4)(2i-3)}^{(T/4)(2i-1)} S(t,x)\, dt \qquad (i = 1,2) \qquad (5)$$

during one period of the sinusoidal phase modulation.

A sample-hold circuit 1 (SH1) and 2 hold the signals $y_1(x)$ and $y_2(x)$, respectively, as shown in Fig.2. By subtracting $y_2(x)$ from $y_1(x)$, we obtain the feedback signal as follows:

$$Y(x) = y_1(x) - y_2(x) = K_1 \sin\alpha(x), \qquad (6)$$

where K ia a constant value. A SH3 holds the signal Y(x) between 3T/4 and 7T/4. This processing is done at intervals of T. So the signal Y(x) is discrete in time. The measurement for one measuring point is completed after the feedback signal is sampled N times at intervals of T sec. Hence the measuring point moves at intervals of T_{scan}=NT. Although the quantities in Fig.2 are functions of both measuring point x and time t, we give them only one of the two variables for the sake of simplicity.

The feedback control system adopts a proportional and integral (PI) controller to eliminate the steady state error as shown in Fig.2. A differential amplifier produces an error signal e(t) which is the difference between the feedback signal Y(x) and a reference signal r_0. The locked phase is determined by the reference signal r_0. For the feedback signal given by Eq.(6), the system gets stable easily at r_0=0. The error signal e(t) is fed to an amplifier with gain K_P and to an integrator with time constant T_I. The proportional output and the integral output are added, and the voltage output is converted to a control current $I_c(x)$.

4. MEASUREMENT OF SURFACE PROFILE

The experimental setup is shown in Fig.1. We used a GaAlAs laser diode as a light source. Its central operating wavelength λ_0 is 790 nm. The modulation efficiency β is 6×10^{-3} nm/mA. The optical path difference $2D_0$ was 140 mm. The frequency of phase modulation 1/T was 4 kHz. The feedback control system was stable when K_p and T_I were 2.0 and 0.5 msec, respectively, at T=0.25 msec.

In Fig.3, the error signal e(t) shows how the phase $\alpha(x)$ is locked at zero by the feedback control. The error signal increases immediately after the measuring point moves, and it reduces to zero after T_{scan}=4 msec which corresponds to N=14. Then the control current $I_c(x)$ is detected, and the surface profile is obtained using Eq.(4). Figure 4 shows a measured surface profile which agrees well with the surface profile measured with Talystep instrument. The number of the measuring points was 50, and the measurement time was 200 msec. The measurement accuracy was below 10 nm in this interferometer.

5. INTERFEROMETER INSENSITIVE TO EXTERNAL DISTURBANCE

External disturbances such as mechanical vibrations of optical components cause phase variations in the interference signal. We detect the phase variations at a fixed point on the surface of the object, while we detect a surface profile at the measuring points. An exact surface profile is obtained by subtracting the phase variation detected at the fixed point from the surface profile detected at the measuring points.

Figure 5 shows a block diagram of generator of the control currents. The fixed point and the measuring points are denoted by P and X. The interference signal is detected alternately for the fixed point and the measuring point at intervals of T. The feedback signal Y(X) for the measuring point X is sampled from t=T to t=2T, and it is held with the sample holder 1 until the next sampling begins at t=3T. The control current $I_c(X)$ is generated in the same way as that described in Sec.3, and it is fed to the LD from t=2T to t=3T through the switch 2. The feedback signal Y(P) for the fixed point P is sampled from t=2T to t=3T, and it is held with the sample hold 2 until the next sampling begins at t=4T. The control current $I_c(P)$ is fed to the LD from t=3T to 4T. This processing is repeated. Thus the feedback control for the point X is done between 2mT and (2m+1)T (m=0,1,2,…), while the feedback control for the point P is done between (2m+1)T to 2(m+1)T. The proportional gain K and the integral time T_I of the PI controller 2 are equal to those of the PI controller 1.

The control current $I_c(P)$ detects the external disturbance $d_P(t)= (D_0/\lambda_0)\beta I_c(P)$. We can eliminate the external disturbance $d_X(t)$ contained in the control current $I_c(X)$, since it is satisfied that $d_p(t) \sim d_X(t)$. Hence we measure the surface profile eliminating external disturbances as follows;

$$D(X)= (D_0/\lambda_0)\beta [I_c(X)-I_c(P)] \quad . \qquad (7)$$

6. MEASUREMENT OF SURFACE PROFILE WITH ELIMINATION OF EXTERNAL DISTURBANCE

The experimental setup is the same as that shown in Fig.1, if the feedback controller (FBC) given by Fig.5 is used. The frequency of the sinusoidal phase modulation was 7KHz, and the other conditions are the same as those described in Sec.4.

First we examined fundamental characteristics in eliminating external disturbances. We detected the difference $\varepsilon(t)$ between $d_P(t)$ and $d_X(t)$ when the measuring point was fixed. The root mean square of the difference $\varepsilon(t)$ was below ~5 nm when a sinusoidal vibration of an amplitude 100 nm was applied as external disturbance.

Next, we measured a surface profile of a diamond turned aluminum disk whose cutting pitch was 35 μm. Figure 6(a) shows a surface profile obtained from the control current $I_c(X)$ which contains the external disturbance. The external disturbance $d_P(t)$ detected at the fixed point is shown in Fig.6(b). Figure 6(c) shows a surface profile obtained from the difference between $I_c(X)$ and $I_c(P)$ using Eq.(7). We measured the same surface profile once more. The measured results are shown in FIgs.7(a), (b) and (c). In Figs.6(a) and 7(a), the periodic structure of the surface profile does not appears clearly, since the external disturbances shown in Figs.6(b) and 7(b) are added to the real surface profile. The root mean square R of the difference between the two measured surface profiles is 21 nm. The measured surface profile shown in Fig.6(c) is agree with that shown in Fig.7(c), and the value of R for these surface profiles is 5 nm. We could reduce the effect of the external disturbances from 21 nm to 5 nm.

7. CONCLUSION

The PLLD interferometer was constructed which used a laser diode and a CCD image sensor instead of mechanical elements such as a piezoelectronic transducer and galvanomirror. We could measure surface profiles in real time. The time required to complete the measurement for one measuring point was ~2 msec to ~10 msec.

We eliminated the effect of external disturbances such as mechanical vibrations of optical components by detecting phase variations of the interference signal at a fixed point on the surface of object. We could improve the measurement accuracy by subtrating the phase variation detected at the fixed point from the surface profile detected at the measuring points. The measurement accuracy decreased from ~20 nm to ~5 nm.

8. REFERENCES

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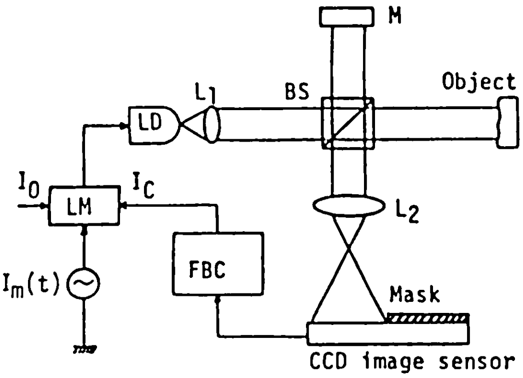


Fig.1. Phase locked laser diode interferometer.

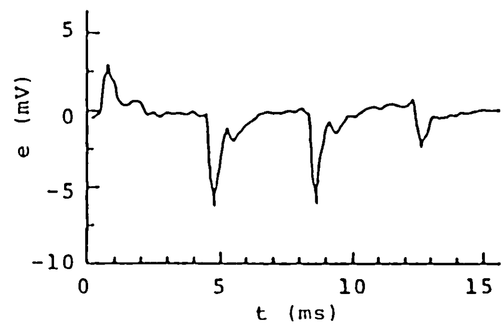


Fig.3. Error signal e(t) observed when the measuring point moves.

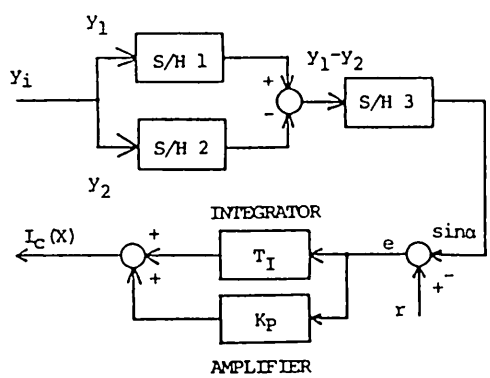


Fig.2. Block diagram of the feedback controller (FBC).

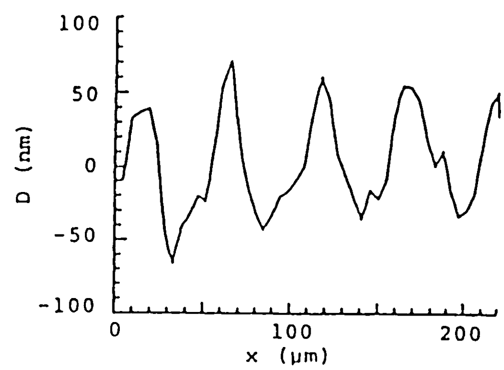


Fig.4. Measured surface profile.

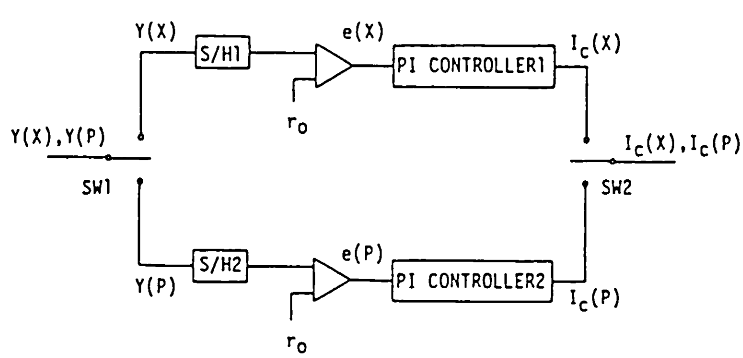
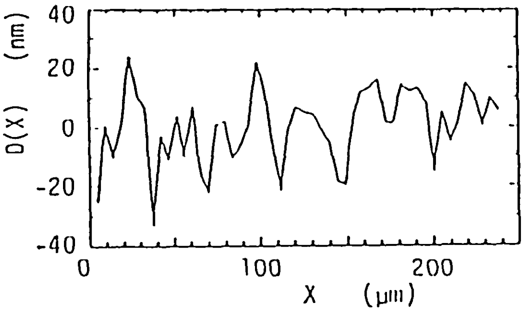
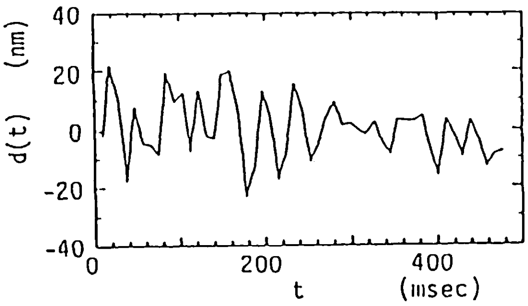


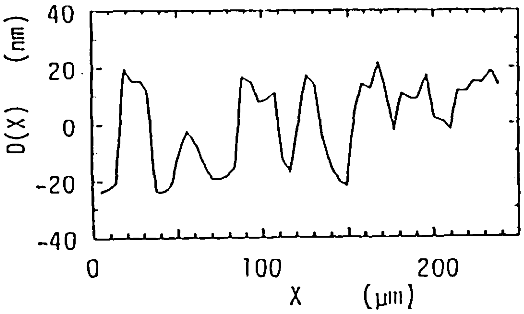
Fig.5. Block diagram of the feedback controller to eliminate external disturbance.



(a)

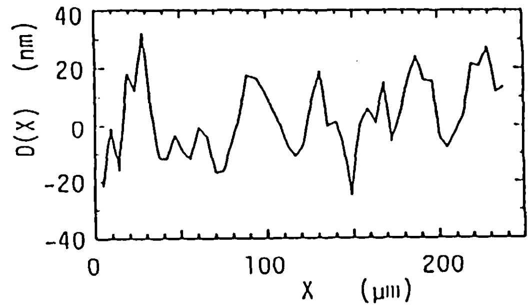


(b)

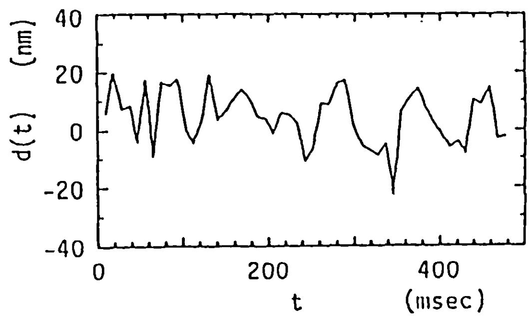


(c)

Fig.6. Experimental Results I : (a) Surface profile which contains external disturbance; (b) Detected external disturbance; (c) surface profile obtained by eliminating external disturbance (b) from (a).



(a)



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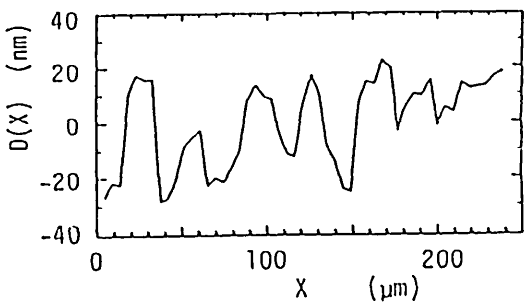

(c)

Fig.7. Experimental Results II : (a) Surface profile which contains external disturbance; (b) Detected external disturbance; (c) surface profile obtained by eliminating external disturbance (b) from (a).