Absolute distance measurement with a sampling type of double sinusoidal phase-modulating laser diode interferometer

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ABSTRACT

We propose a new range finding technique that uses two-wavelength interferometry. The system we propose uses a single laser diode to realize a two-wavelength interferometer, which expands measurement range. The single light-source allows us to simplify the optical setup. Our devise generates two independent interference signals with respect to the wavelengths generated by offset current. The external disturbances on these interference signals are eliminated by the feedback control. Although the feedback control eliminates disturbance as well as the information about the distance, we are able to detect the distance from the phase difference between those compensated interference signals.

Keywords: Interferometry, laser diode, two-wavelength method, feedback control, sinusoidal phase modulation

1. INTRODUCTION

When we measure distance that is larger than a half wavelength, more than two wavelengths are usually required. In this requirement, the laser diode (LD) is very useful because it has wavelength tunability. This feature enables us to use different wavelengths with a single LD. We have previously proposed the two-wavelength interferometers (TWIs) that use a single LD[1, 2]. In these interferometer, different two wavelengths, which provide different two phases, are generated by means of the feedback control. The phases of the interference signal are alternately controlled to the required value. This technique allowed us to eliminate the external disturbance to some degree. As the feedback control was mainly used for the phase locking, external disturbance affected the measurement accuracy.

We also proposed double sinusoidal phase-modulating (DSPM) interferometer[3]. In this interferometer, we modulate the LD with two different sinusoidal signals. Distance is measured through the frequency analysis of the obtained interference signal. As the feedback control is mainly used for the disturbance elimination, measurement accuracy is not affected from the disturbance very much. In the optical setup, however, mechanical modulating device, piezoelectric translator (PZT), is used. Thus, the static measurement is difficult in this interferometer.

In this paper, we propose a disturbance-free range finding technique based on the DSPM laser diode interferometry. As the feedback control is used only for the disturbance elimination in this technique, the disturbance is clearly eliminated. Our interferometer generates two interference signals that have different phases with a sampling technique. The distance is measured from the difference between the two phases that are detected by the sinusoidal phase modulating (SPM) interferometry.

2. PRINCIPLE

2.1 QUASI-TWO-WAVELENGTH INTERFEROMETRY

Schematic of the simplest optical system is shown in Fig. 1 to explain our technique. The injection current for the LD consists of bias current I_0, modulation current $I_L(t)$, and offset current $-\Delta i$ or $+\Delta i$ as shown in Fig. 1(a). The central

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wavelength λ_0 is determined by I_0. The offset current Δi changes wavelength by

$$\Delta\lambda=\beta\Delta i, \qquad (1)$$

where β is called modulation efficiency. Thus, we can shift the wavelength λ_0 by $-\Delta\lambda$ or $+\Delta\lambda$ with the offset current, and we can apply these two wavelengths to the TWI.

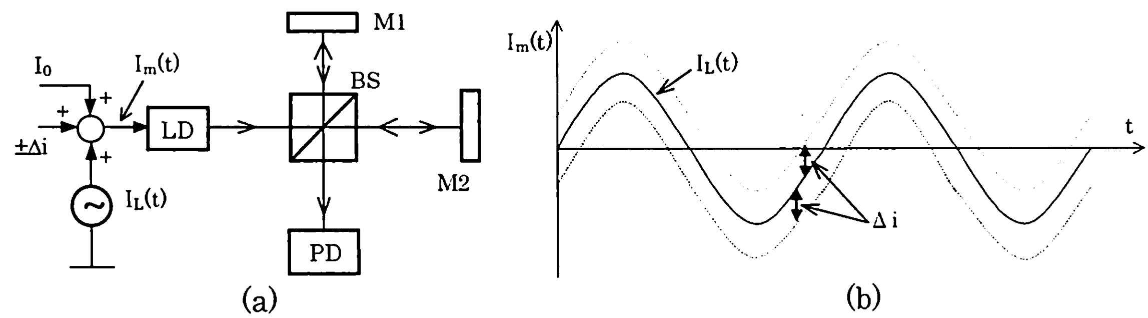
When we use a sinusoidal signal

$$I_L(t)=a\cos\omega_c t \qquad (2)$$

as the modulating current, injection current of the LD becomes $I_L(t)-\Delta i$ or $I_L(t)+\Delta i$ as shown in Fig. 1(b). Then, the SPM interference signal

$$S_i(t)=a_i+b_i\cos[z\cos\omega_c t+\alpha_i] \qquad (i=1, 2) \qquad (3)$$

is obtained independently, as shown in Fig. 1(c), where a_i, b_i, and z are dc components, amplitudes of the ac component, and modulation depth, respectively. The phases corresponding to the wavelength-shifts are given by



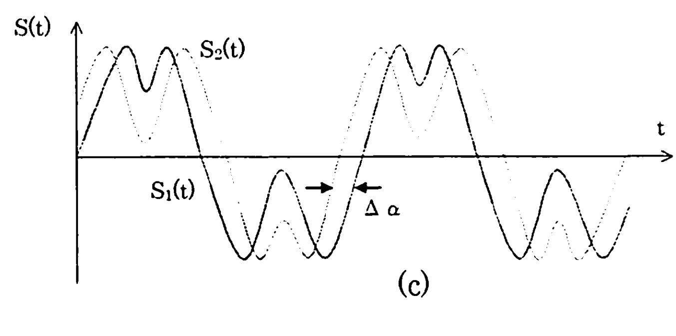


Fig. 1 Schematic of quasi-TWI: (a) optical setup, (b) injection currents, and (c) obtained interference signals.

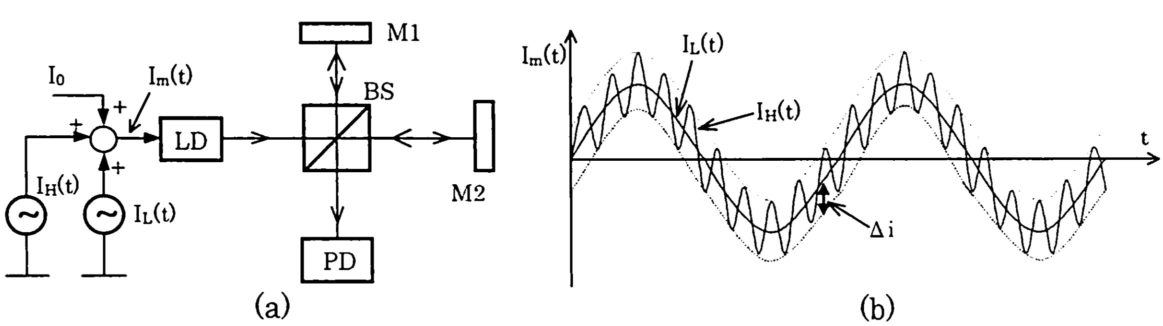


Fig. 2 Schematic of DSPM interferometer: (a) optical setup and (b) injection currents.

$$\alpha_1 = \frac{2\pi L}{\lambda_0 - \Delta\lambda}, \tag{4}$$

and

$$\alpha_2 = \frac{2\pi L}{\lambda_0 + \Delta\lambda}, \tag{5}$$

where L represents the optical path difference (OPD). If we can detect α_1 and α_2 independently, the OPD is given by[1, 4]

$$L = \frac{\Lambda}{2\pi}\Delta\alpha = \frac{\lambda_0^2}{4\pi\Delta\lambda}\Delta\alpha, \tag{6}$$

where $\Delta\alpha=\alpha_1-\alpha_2$ and

$$\Lambda = \frac{\lambda_0^2}{2\Delta\lambda} \tag{7}$$

is the equivalent wavelength. This is well known formula in TWI.

In these procedures, however, we have to change the dc current's level discretely. It is a complicated process and actually the wavelength cannot follow the sudden current-change due to the restricted response of the LD. To overcome these problems, we inject another sinusoidal signal $I_H(t)$, whose amplitude is Δi, instead of the dc offset current as shown in Fig. 2(a). That is, DSPM interferometer is constructed. $I_H(t)$ is synchronous with $I_L(t)$. Frequency of $I_H(t)$ is higher than that of $I_L(t)$. The injection currents are shown in Fig. 2(b). Although the injection current we used actually consists of $I_L(t)$, $I_H(t)$, and control current $I_C(t)$, $I_C(t)$ is omitted in Fig. 2(b). Maxima and minima of I_H (t) give the offset to the injection current. When we sample the interference signal at peaks and valleys of $I_H(t)$, respectively, we can detect two interference signals whose phase difference is $\Delta\alpha$. Thus, the OPD is calculated with Eq. (6).

2.2 FEEDBACK CONTROL

Figure 3 schematically shows the feedback control in the interferometer. If the OPD's deviation is d(t), the SPM interference signal on the wavelength λ_0 is given by

$$S(t)=a+b\cos[z\cos\omega_c t+\alpha_0+\delta(t)], \tag{8}$$

where $\alpha_0=2\pi L/\lambda_0$ and $\delta(t)=2\pi d(t)/\lambda_0$. The feedback signal generator (FBSG) generates the feedback signal that contains external disturbance $\delta(t)$ as follows[5]:

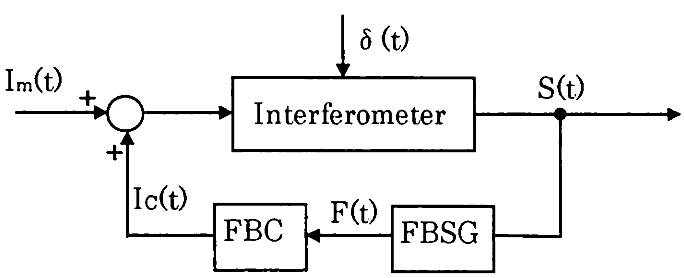


Fig. 3 Feedback control in the interferometer.

$$F(t)=K\sin[\alpha+\delta(t)]. \quad (9)$$

This feedback signal is fed to the feedback controller (FBC) and control current $I_C(t)$ is generated. $I_C(t)$ is mixed with the modulating signal and fed into the LD. If the FBC controls so as to compensate F(t)=0, we have

$$\frac{2\pi}{\lambda_0+\lambda_c}[L+d(t)]=\alpha_L, \quad (10)$$

where λ_c is the compensating wavelength introduced by the feedback control and α_L is the constant phase controlled. When the feedback control works sufficiently, α_L becomes $2n\pi$, irrespective of L. In this case, although the disturbance is eliminated, OPD's information is lost by the feedback control. It means that distance measurement cannot be implemented with only one phase under the feedback control. The idea we propose in this paper overcomes this problem, because we use phase difference $\Delta\alpha$ to measure the OPD. If we introduce offset in wavelength by injecting the offset current $-\Delta i$ or $+\Delta i$, the phases corresponding to the wavelength-offset $\pm\Delta\lambda$ are given by

$$\begin{aligned}\alpha_1 &= \frac{2\pi[L+d(t)]}{(\lambda_0+\lambda_c)-\Delta\lambda} \\ &= \frac{2\pi}{\lambda_0+\lambda_c}[L+d(t)]\left(1+\frac{\Delta\lambda}{\lambda_0+\lambda_c}\right),\end{aligned} \quad (11)$$

and

$$\begin{aligned}\alpha_2 &= \frac{2\pi[L+d(t)]}{(\lambda_0+\lambda_c)+\Delta\lambda} \\ &= \frac{2\pi}{\lambda_0+\lambda_c}[L+d(t)]\left(1-\frac{\Delta\lambda}{\lambda_0+\lambda_c}\right).\end{aligned} \quad (12)$$

As the coefficients contained in Eqs. (11) and (12) are equal to α_L, respectively, we can measure α_1 and α_2 without the external disturbance. Calculating the phase difference, we have

$$\Delta\alpha=\frac{4\pi\Delta\lambda}{(\lambda_0+\Delta\lambda)^2}L+\frac{4\pi\Delta\lambda}{(\lambda_0+\Delta\lambda)^2}d(t). \quad (13)$$

The second term in Eq. (13) is nearly equal to zero. From the condition of $\lambda_c \ll \lambda_0$, the OPD L can be calculated by using Eq. (6). Thus, we can measure the OPD under the feedback control.

3. EXPERIMENT

3.1 EXPERIMENTAL SETUP

Figure 4 shows the experimental setup. Laser beam radiated from the LD is fed into the Twyman-Green interferometer. Wavelength and the modulation efficiency of the LD are 683 nm and 1.23×10^{-3} nm/mA, respectively. The distance is indicated by ΔL. An analyzer (A) and quarter-wave-plates (QWPs) form an optical isolator. The interference signal detected by the photodiode (PD) is sampled at the specific timing and converted to the digital signal to save it into the computer. The signal-processing unit (SPU) supplies the modulating signal $I_m(t)$ and sampling pulse SP.

Block diagram of the SPU is shown in Fig. 5. The sampling pulse generator (SPG) generates the sampling pulse at peaks and valleys of $I_H(t)$ that is supplied by oscillator 1 (OSC1). The frequency of $I_H(t)$ is 128 kHz. $I_H(t)$ is converted to 1 kHz-rectangular signal with a 1/128 divider. This converted signal is fed into the SYNC input terminal of oscillator 2 (OSC2) to generates the 1 kHz-sinusoidal signal $I_L(t)$ that is synchronous to $I_H(t)$. The FBSG generates the feedback signal F(t). The feedback controller (FBC) supplies the feedback signal $I_C(t)$ to compensate the phase deviation caused by the external disturbance. $I_H(t)$, $I_L(t)$, and $I_C(t)$ are mixed and injected into the LD as $I_m(t)$.

Schematic of the FBSG is shown in Fig. 6. A zero-cross circuit (ZCC) generates the sampling pulse at the zero-level of $I_H(t)$. When S(t) is sampled and held at the aero-cross timing of $I_H(t)$, we can obtain the signal $S_h(t)$. In this case, we obtain the interference signal that is modulated only by $I_L(t)$. Multiplying $S_h(t)$ with $I_L(t)$ and passes it to the low-pass-filter (LPF), we have the feedback signal F(t) that is given by Eq. (9).

3.2 EXPERIMENTAL RESULTS

We first observed the modulating signal and interference signal. Amplitude of $I_L(t)$ and $I_H(t)$ were 1.4 mA and 0.3 mA, respectively. The results are shown in Fig. 7. Figure 7(a) shows the observed modulating signal. Higher frequency signal $I_H(t)$ is superimposed onto the lower frequency one $I_L(t)$. Interference signal modulated with the signal shown in Fig. 7(a) is traced in Fig. 7(b). As two interference signals are overlapped, the waveform is not so clear. While they are clearly separated as shown in Fig. 7(c), when the detected interference signals sampled at peaks and valleys of $I_H(t)$ are plotted alternately. They are traced with a solid line and a dashed line, respectively.

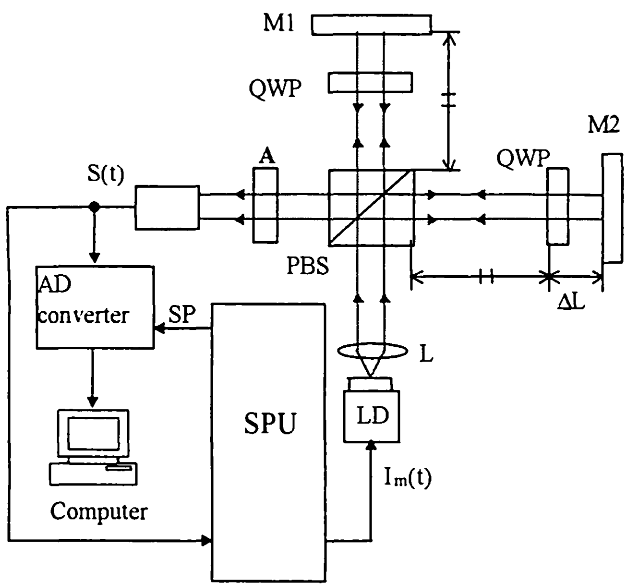


Fig. 4 Experimental setup.

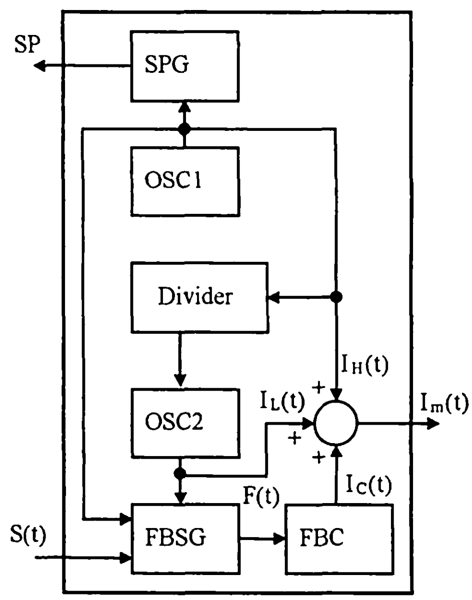


Fig. 5 Block diagram of the SPU. SPG; sampling pulse generator, OSC; oscillator, FBSG; feedback signal generator, FBC; feedback controller.

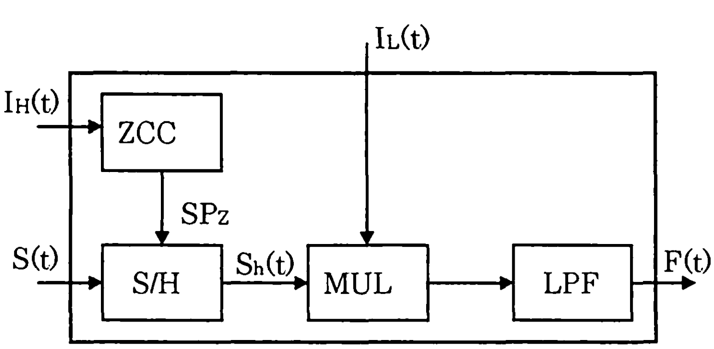


Fig. 6 Block diagram of the FBSG. ZCC; zero-cross circuit, S/H; sample and hold circuit, MUL; multiplier, LPF; low-pass filter.

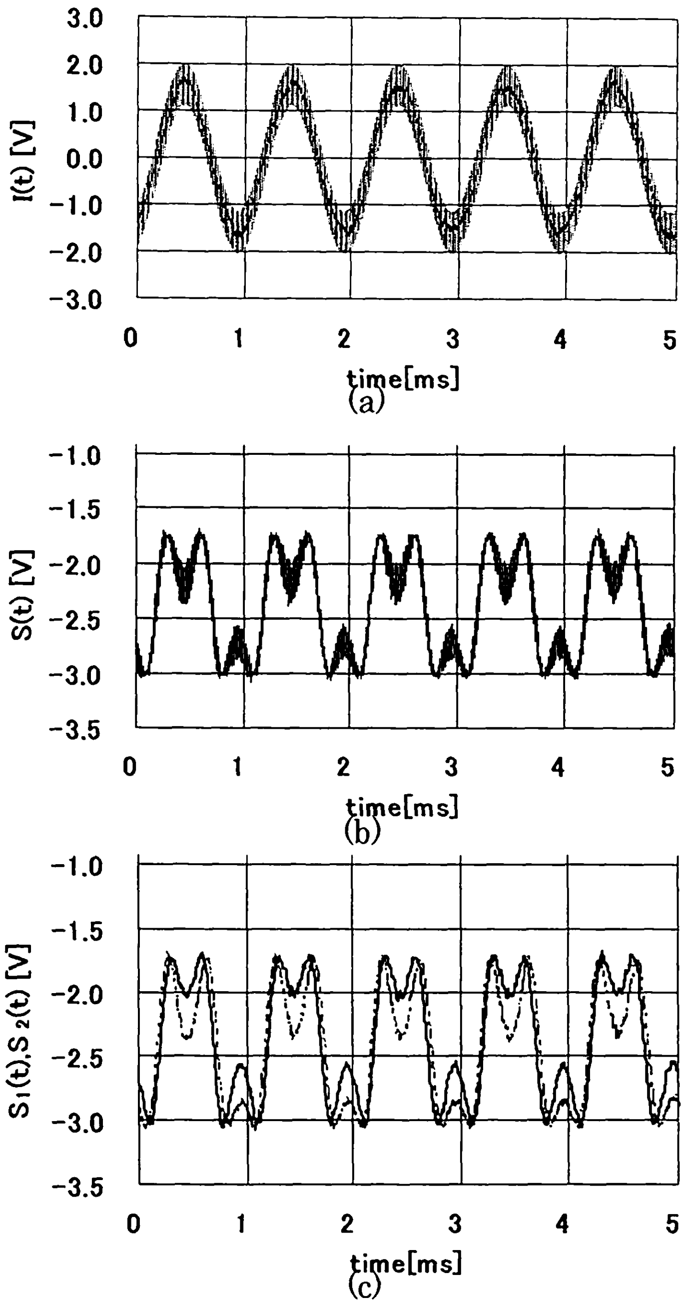


Fig. 7 Observed signals: (a) modulating signal, (b) mixed interference signal, and (c) separated interference signals.

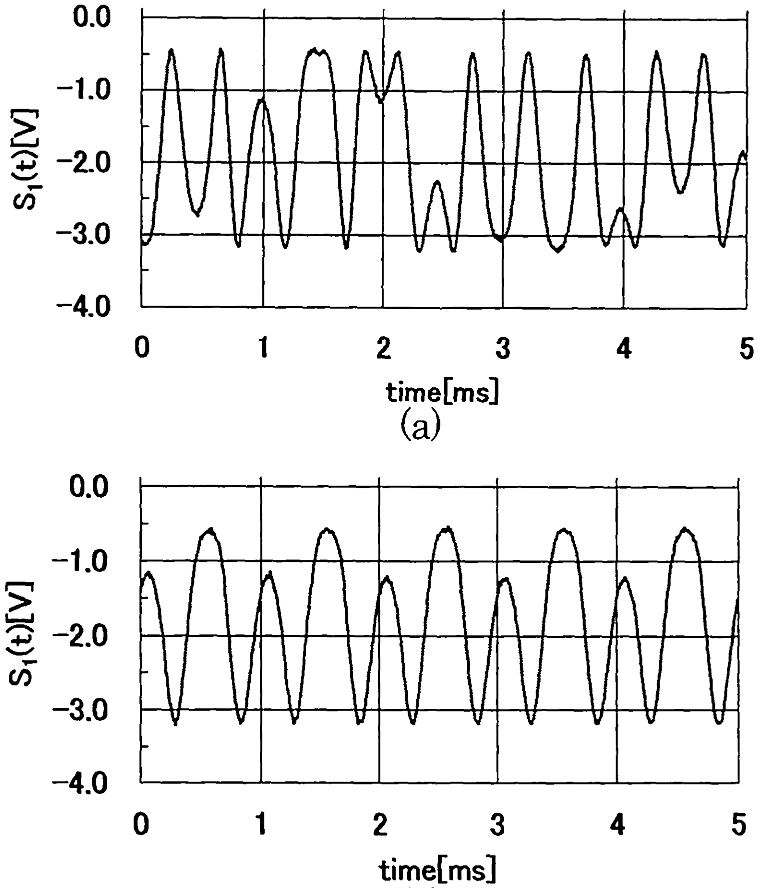


Fig. 8 Interference signals under (a) feedback control OFF and (b) feedback control ON.

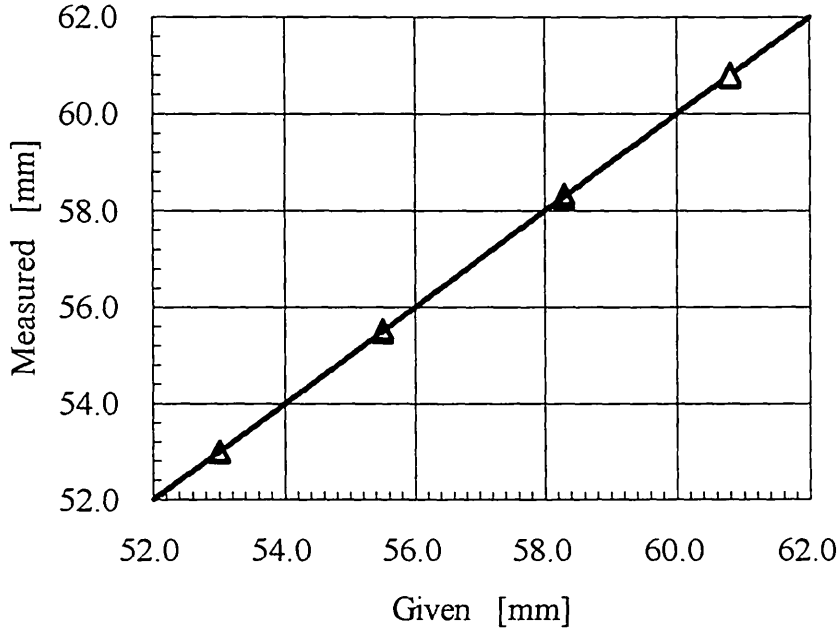


Fig. 9 Results of the distance measurement.

Next, we confirmed the effect of the feedback control. The LD was modulated only with $I_L(t)$. Observed interference signal is shown in Fig. 8. When the feedback control was OFF, interference signal was affected by the external disturbance very much as shown in Fig. 8(a). While the disturbance was eliminated clearly when the feedback control was ON as shown in Fig. 8(b).

Finally, we measured the distance by varying the OPD. Amplitude of $I_L(t)$ and $I_H(t)$ were 1.4 mA and 1.15 mA, respectively. Wavelength difference $\Delta\lambda$ and the equivalent wavelength Λ calculated from Eqs. (1) and (7) were 2.8×10^{-3} nm and 166.6 mm, respectively. We moved M2 to four different positions with an x-axis stage. We measured ΔL four times at the same position and calculated mean value. Four mean values are plotted in Fig. 9. Measurement error is estimated as 34 μm rms from these measurements.

4. CONCLUSIONS

We have proposed a sampling type of double sinusoidal phase-modulating laser diode interferometer that measures absolute distance. Wavelength tunability of the DSPM LD interferometry allowed us to realize the two-wavelength type of interferometer with a single LD. We have shown that the distance-variation can be detected even if the phase change is compensated by the feedback control that eliminates external disturbance. Absolute distances of 500 mm to 600mm were accurately measured with the accuracy of 34 μm.rms in our system.

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