Coaxial type of self-mixing interferometer equipped with a wavelength stabilizing system

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ABSTRACT

Because the wavelength of a laser diode (LD) has the temperature-sensitivity, in conventional LD interferometers, a temperature control is required to stabilize the wavelength in long-term measurements. We propose a self-mixing laser diode interferometer that has two coaxial measurement arms. Two interference signals are used for the measurement of displacement and wavelength stabilization in our system. As the wavelength is not stabilized thermostatically, but by adjusting current feedback, compensation is simple and response-time minimal. The feedback controls for displacement measurement and wavelength stabilization were implemented on a time-sharing basis. The devise we propose enables us to conduct long-term measurements of microscopic levels of displacement.

Keywords: self-mixing interferometer, laser diode, wavelength stabilization, feedback control

1. INTRODUCTION

In a cutting machine for fabricating precision parts, cutting force or temperature change causes spindle displacement. They will eventually affect machining accuracy. In-process monitoring allows us to control the relative positions of the cutter and the object, maintaining the long-term stability of the measuring system itself.

Bearing in mind the temperature-sensitivity of the LD's operative wavelength, even if the injection current is steady, conventional LD interferometers that implement long-term measurements require sensitive temperature sensors and insulators, as well as a Peltier element and its driver to stabilize the wavelength.

In this paper, we propose a self-mixing laser diode LD interferometer equipped with two coaxial measurement arms. It is capable of conducting long-term measurements of microscopic levels of displacement. Since self-mixing interferometers[1] require no beam splitter, reference mirror, or external photodetector (PD), their optical systems' construction is simpler than that of conventional types. Displacement measurements are realized by detecting phase of the SMI signal[2]. We have proposed a phase-locked laser diode (PLLD) self-mixing interferometer and demonstrated measurements of microscopic displacement[3]. The phase-locked technique enables us to fix the phase of the SMI signal at a specific value. The system we propose employs a phase-locked loop for each measurement arm. One is used for displacement-measurement; the other, to stabilize the LD's wavelength. Because our system requires only a simple adjustment of current feedback, as opposed to thermostatic wavelength stabilization, compensation is simple and response-time minimal. We implemented the feedback controls for displacement measurement and wavelength stabilization on a time-sharing basis.

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2. PRINCIPLE

2.1 Self-mixing interferometers

Schematics for a conventional self-mixing interferometer and the one we propose are shown in Figs. 1(a) and (b), respectively. Conventional units consist of only three optical parts; an LD package with a built-in PD, a lens and an external mirror. A model of the external-cavity laser diode[4] shown in Fig. 2 explains the SMI effect. Reflectivities on both edges of both the LD and external mirror are given by r_1, r_2, and r_3, respectively, as shown in Fig. 2(a). When the distance between the LD and the external mirror is d_0, the equivalent system is represented by Fig. 2(b), in which an effective reflectivity on the facet of the LD is given by

$$r_{23} = \frac{r_2 - r_3 \exp(i\alpha_0)}{1 - r_2 r_3 \exp(i\alpha_0)}, \tag{1}$$

where

$$\alpha_0 = \frac{4\pi}{\lambda_0} d_0, \tag{2}$$

is the phase that depends on d_0 and the optical wavelength λ_0. The threshold current I_{th} of the LD is represented by[5]

$$I_{th} = \eta\left[\gamma_i + \frac{1}{2L}\ln\left(\frac{1}{r_1 r_{23}}\right)\right], \tag{3}$$

where η is the constant determined by the gain medium in the LD and its size, γ_i being an internal loss-coefficient, and L representing the LD's cavity-length. When d_0 varies with the displacement of the mirror, and/or when λ_0 varies with the LD injection current, threshold current I_{th} changes according to Eq. (3). The output power $P_o(t)$ of the LD varies with injection current $I(t)$. It is given by[6]

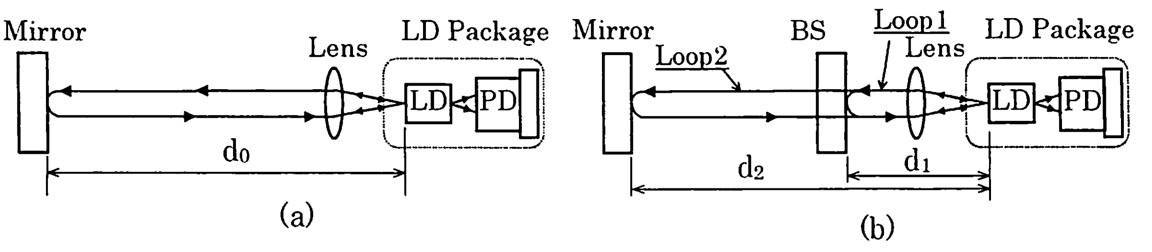

Fig. 1 Schematic of (a) a conventional self-mixing interferometer and (b) the proposed one.

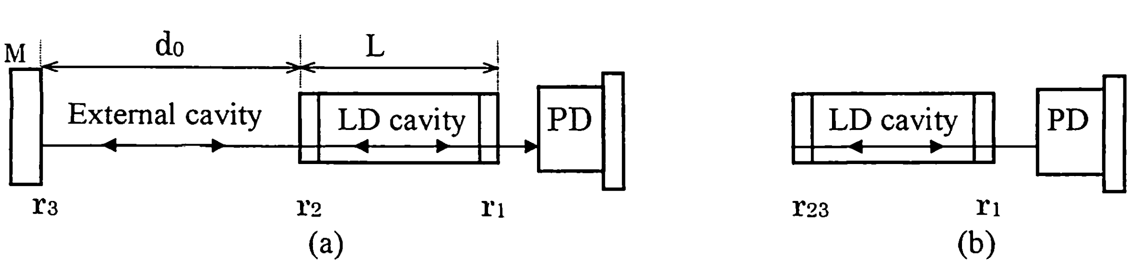

Fig. 2 Schematic of (a) external-cavity laser diode and (b) an equivalent system.

$$P_o(t) = \kappa\left[\frac{I(t)}{I_{th}} - 1\right], \qquad (4)$$

where κ is an easily determined constant. The mirror's displacement is demonstrated in the variation of the optical output $P_o(t)$, which we detect as an interference signal.

When the LD is modulated by a triangular injection current

$$I_m(t)=\pm at, \qquad (5)$$

its wavelength changes by $\pm\beta at$, where a represents current-slope, and β is a modulation efficiency of the LD. Then the phase of the SMI signal is given by

$$\alpha(t) = \frac{4\pi}{\lambda_0 - \beta at} d_0 \approx 2\pi f_0 t + \alpha_0 \qquad (6)$$

on the negative slope, where

$$f_0 = \frac{2a\beta}{\lambda_0^2} d_0 \qquad (7)$$

is a beat-frequency.

Our self-mixing interferometer (Fig. 1(b)) has two external reflectors placed at d_1 and d_2 from the face of the LD. These reflectors comprising optical feedback loops Loop1 and Loop2 correspond to d_1 and d_2. Although each measurement arm independently generates the SMI signal, the PD detects these signals simultaneously. Since the lengths of the measurement arms differ, each SMI signal varies according to different beat-frequencies. The SMI signals are separated by use of the difference in the beat-frequencies, which are shown in the first term of Eq. (6).

Although the mechanism of optical-intensity change in the self-mixing interferometer is different from that operating in conventional interferometers, $P_0(t)$ can be controlled by adjusting α_0. We use the second term in Eq. (6) to apply PLLD interferometry[7]. Loops1 and 2 (Fig. 1(b)) eliminate wavelength fluctuation and measure displacement, respectively.

2.2 Elimination of wavelength fluctuation

In Loop1, we assume a constant value for distance d_1 during measurement. If the wavelength varies by $\Delta\lambda_1$ due to environmental factors such as temperature, the second term in Eq. (6) is given by

$$\alpha_0 + \Delta\alpha_1 = \frac{4\pi}{\lambda_0 + \Delta\lambda_1} d_1 \ . \qquad (8)$$

In PLLD interferometry, we change the LD's wavelength by $-\Delta\lambda_1$ to compensate for the phase deviation $\Delta\alpha_1$. This compensation is achieved by controlling electrical feedback on the LD's injection current, satisfying condition

$$\frac{4\pi}{(\lambda_0 - \Delta\lambda_1) + \Delta\lambda_1} d_1 = \frac{4\pi}{\lambda_0} d_1 \, . \qquad (9)$$

The wavelength fluctuation is then given by

$$\Delta\lambda_1=\beta\Delta i_1. \qquad (10)$$

As $\Delta\lambda_1$ is proportional to the control current, we are able to monitor fluctuations in wavelength by observing Δi_1. If d_1 varies by Δd_1, according to temperature, the wavelength changes by

$$\delta\lambda_1 = \rho\Delta\theta\lambda_0 \ , \qquad (11)$$

where ρ is a coefficient of thermal expansion and $\Delta\theta$ represents temperature fluctuation. This is a major error in our wavelength stabilization system; one that will have to be dealt with, in a future study.

2.3 Displacement measurement

In Loop2, when the mirror (M) moves by Δd, along the optical axis, the phase change is represented by

$$\alpha_0 + \Delta\alpha_2 = \frac{4\pi}{\lambda_0}[d_2 + \Delta d]. \quad (12)$$

We compensate $\Delta\alpha_2$ by varying the wavelength. From relationship

$$\frac{4\pi}{\lambda_0 + \Delta\lambda_2}[d_2 + \Delta d] = \frac{4\pi}{\lambda_0} d_2 , \quad (13)$$

the displacement of the mirror is given by

$$\Delta d = \frac{d_2}{\lambda_0}\Delta\lambda_2 , \quad (14)$$

where

$$\Delta\lambda_2 = \beta\Delta i_2. \quad (15)$$

We can measure displacement by observing control current Δi_2. As displacement is not observed by phase, but rather by indirectly controlling injection current in PLLD interferometry, phase detection is unnecessary and signal processing is simplified.

2.4 Time-shared PLLD interferometry

When the wavelength changes by $\Delta\lambda_1$ and M moves by Δd, the phase is represented by

$$\alpha_0 + \Delta\alpha_1 + \Delta\alpha_2 = \frac{4\pi}{\lambda_0 + \Delta\lambda_1}[d_2 + \Delta d]. \quad (16)$$

If wavelength fluctuation is minimized and displacement-measurement is implemented on a time-sharing basis, condition

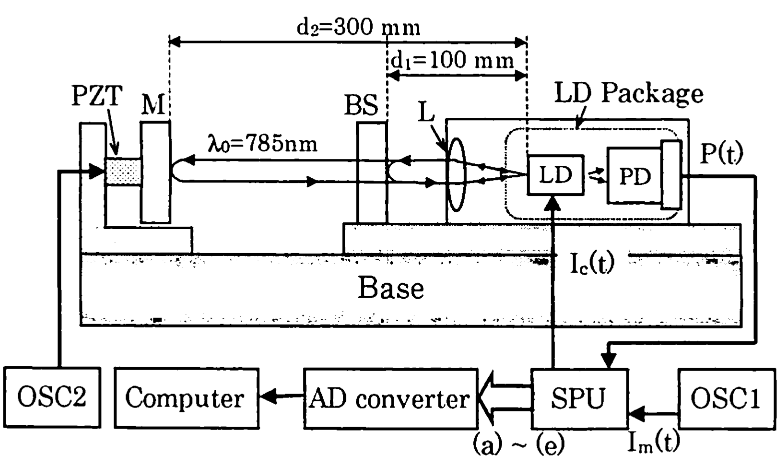

Fig. 3 Experimental setup: OSC1 and OSC2, oscillators; SPU, signal processing unit.

$$\frac{4\pi}{(\lambda_0 - \Delta\lambda_1) + \Delta\lambda_1 + \Delta\lambda_2}[d_2 + \Delta d] = \frac{4\pi}{\lambda_0} d_2 \quad (17)$$

is held in Loop2, where $-\Delta\lambda_1$ is introduced as a result of the phase-lock in Loop1. This signal is indicated in Fig. 4 as Δi_1. Since Eq. (17) is equal to Eq. (13), the displacement is given by Eq. (14).

3. EXPERIMENTS

3.1 Experimental setup

Figure 3 shows the optical system consisting of the LD, a lens (L), a beam splitter (BS), and a mirror (M) mounted on a piezoelectric transducer (PZT). The optical parts are securely mounted on an iron base. The central wavelength and the maximum power of the LD are 785 nm and 50 mW, respectively. The modulation efficiency β is estimated as 2×10^{-3} nm/mA. Distances d_1 and d_2 are 100 mm and 300 mm, respectively. Light radiated from the LD is reflected by the BS and the M, respectively. These two beams are fed back into the LD. The SMI signals generated by Loop1 and Loop2 are detected by the PD. The overlapping SMI signal P(t) is processed by a signal processing unit (SPU). The SPU generates control signals that compensate wavelength fluctuation and phase deviation caused by the mirror's displacement. SPU's outputs (a)-(e) are digitally processed. A block diagram of the SPU is shown in Fig. 4. The mixed SMI signal P(t) is fed to band-pass filters BPF1 and BPF2, and separated into independent SMI signals $S_1(t)$ and $S_2(t)$, respectively. These signals have frequencies corresponding to the optical path distances. Each SMI signal is sampled according to the specific timing provided by sampling pulses SP_1 and SP_2, by means of sample-and-hold circuits S/H1 and S/H2. These sampling pulses are generated synchronously, using the modulating signal $I_m(t)$, as shown in Fig. 5. The sampled and held signal $S_h(t)$ is step-shaped. Low-pass filters LPF1 and LPF2 eliminate the useless higher components from $S_{h1}(t)$ and $S_{h2}(t)$, respectively, to generate feedback signals FB1 and FB2. Proportional-integral controllers PI1 and PI2, respectively, generate the control signals that compensate for wavelength fluctuation, as well as the phase change introduced by the mirror's displacement. The switch (SW) selects and passes one of the control signals according to the signal provided by the timing controller (CNT). The selected control signal mixed with dc bias current I_0 and modulating signal $I_m(t)$ is injected into the LD. The feedback controls for Loop1 and Loop2 are implemented on a time-sharing basis, as shown in Fig. 6.

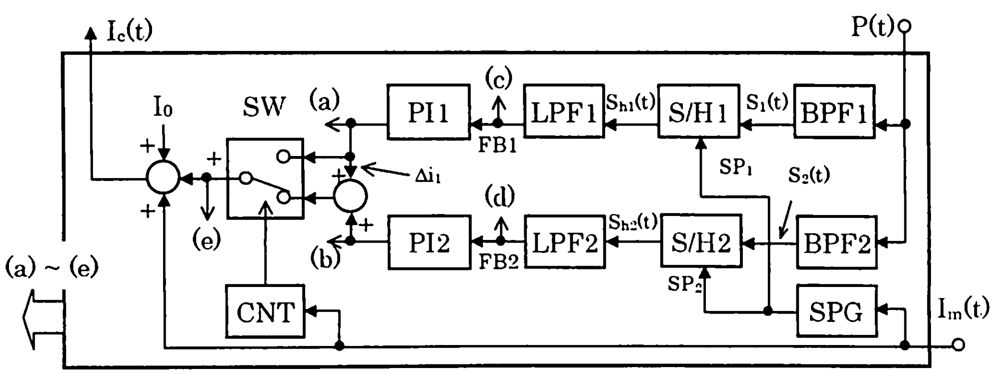

Fig. 4 Block diagram of the SPU: BPF1 and BPF2, band-pass filters, S/H1 and S/H2, sample-and-hold circuits; SPG, sampling pulse generator; LPF1 and LPF2, low-pass filters, PI1 and PI2, proportional-integral controllers; CNT, timing controller; SW, switch.

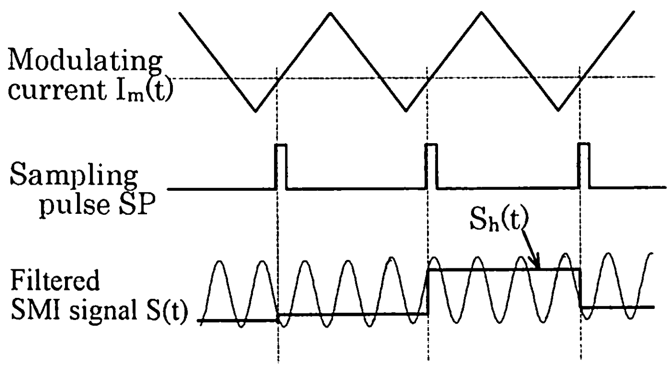

Fig. 5 Generation of the feedback signal for PLLD interferometry: $S_h(t)$, generated feedback signal.

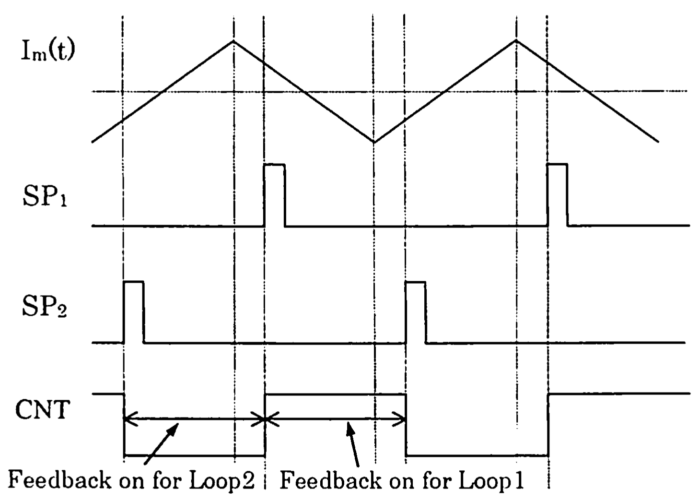

Fig. 6 Timing chart of the time-shared feedback control.

3.2 Results

We implemented simultaneously, the wavelength stabilization and the measurement of the mirror's vibration, over the short-term (Fig. 7). The upper trace gives the PZT's driving signal. The mirror was vibrated sinusoidally by the PZT, at 50 Hz. The lower trace represents the time-shared control signal, which is indicated by (e), in Fig. 4. The SW passes control signals (a) and (b), alternately. The upper and lower parts of the signal (e) represent wavelength fluctuation and the mirror's vibration. Although no wavelength fluctuation was seen, during this short observation, sinusoidal vibration was detected by the phase-locked technique.

Figure 8 illustrates control signals (a) and (b), and feedback signals (c) and (d), where (a) through (d) correspond to those in Fig. 4. Because the control signal (a) compensates the wavelength fluctuation in loop1, no phase change is observed on feedback signal (c) other than small noises. At the same time, phase-lock was implemented on loop2. We conducted long-term wavelength-stabilization tests. Control signal (a) changes a lot to compensate the wavelength fluctuation. Control signal (b), however, increased slightly, even though the wavelength was stabilized using control Loop1. We believe that the

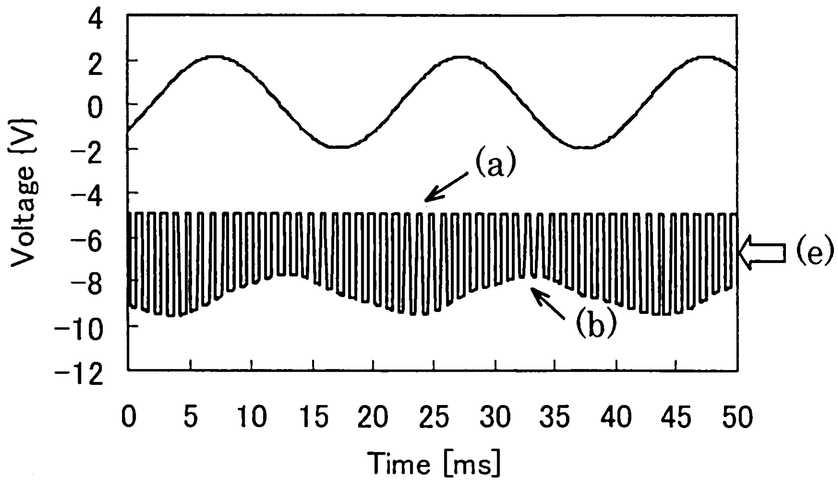

Fig. 7 Short-term observations. Upper trace is the PZT's driving signal, lower trace (e) is the time-shared control signal ; (a) and (b) are control signals Loop1 and Loop2, respectively.

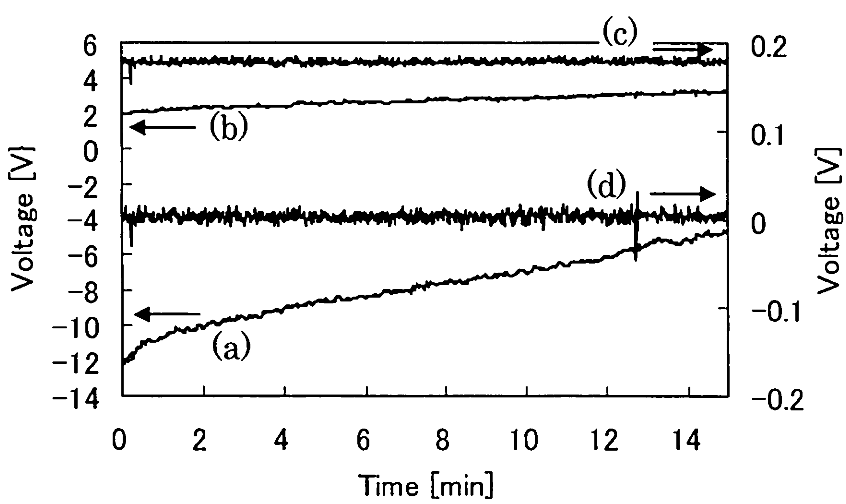

Fig. 8 Long-term observations of (a) control signal for wavelength stabilization, (b) control signal for displacement measurement, (c) feedback signal for wavelength stabilization, and (d) feedback signal for displacement measurement.

device's iron base underwent expansion, resulting from changes in temperature. Feedback signal (d), however, is compensated by the phase-locked control.

4. CONCLUSIONS

We have proposed and demonstrated a coaxial type of self-mixing interferometer that measures wavelength fluctuation and displacement of the object on a time-sharing basis. We have shown how to separate the SMI signal and apply the phase-locked technique to a self-mixing interferometer equipped with two measurement arms. As we do not stabilize wavelength fluctuation thermostatically, but rather by using an electric feedback control, our system requires neither temperature sensors/controllers, nor insulators. This simple devise enables us to conduct long-term measurements of microscopic displacement.

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