Displacement measurement with a dual-colored sinusoidal phase-modulating interferometer

Takamasa Suzuki*, Toshihiko Sato, and Osami Sasaki
Niigata University, 8050 Ikarashi 2, Niigata, Japan

ABSTRACT

Interferometric displacement sensor based on a two-wavelength interferometry is proposed and demonstrated. A combination of time-shared two-wavelength laser diode and sinusoidal phase-modulating interferometry enables us to realize accurate and wide-range displacement measurement with a simple optical setup.

Keywords: displacement measurement, laser diode, interferometry, sinusoidal phase-modulation

1. INTRODUCTION

The measurement range of a laser diode (LD) interferometer working on a single wavelength is limited to within a half wavelength. It makes difficult to conduct the measurement in sub-millimeter range. One of the solutions for such a wide-range measurement is the use of multiple wavelengths. Two wavelength interferometers (TWIs), for instance, have been proposed to expand the measurement range[1]. While the combination of two LDs enables us to compose TWI easily, the optical setup becomes complicated and sensitive to the mechanical disturbance because two optical paths exist independently. A single LD is also applicable to a two-wavelength light source, in which two different bias currents are alternately injected[2]. In this case, small wavelength-difference gives us the large synthetic wavelength. For example, wavelengths of 670 nm and 670.01 nm gives us the synthetic wavelength of 45 mm. It results in the measurement range between several hundred of μm and tens of mm. The measurement resolution is degraded. Therefore, the measurement in the range between a few μm and a few hundreds μm was difficult.

Recently, we reported the dual-color operating technique on the LD, in which two wavelengths were obtained on a time-sharing basis[3]. Because the wavelength difference in this technique is ~0.5 nm, we can accurately measure the above region by using the synthetic wavelength of ~800 μm. We constructed and demonstrated the sinusoidal phase-modulating (SPM) TWI that uses the dual-color operation.

2. PRINCIPLE

The dual-colored operation is realized around the mode-hop region in a LD. Typical relationship between operating current and wavelength of the LD is shown in Fig. 1. The wavelength is gradually lengthened accompanied by the mode-hop as the operating current increases[4].

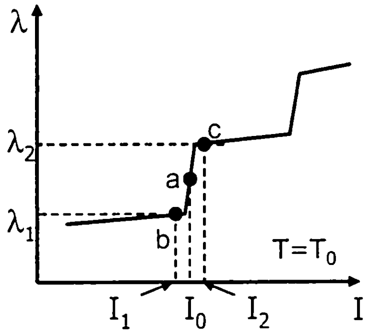

Figure 1. Relationship between operating current and wavelength of the LD.

---

*Telephone and fax: +81-25-262-7215, e-mail address: takamasa@eng.niigata-u.ac.jp

ICO20: Optical Devices and Instruments, edited by James C. Wyant, X. J. Zhang, Proc. of SPIE
Vol. 6024, 60240F, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.666819

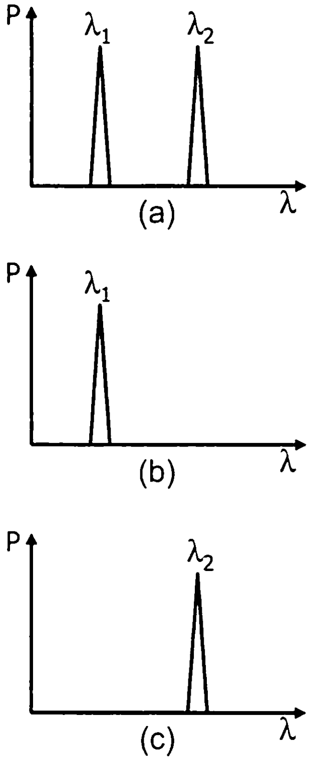

Figure 2. Schematic of the spectra observed at (a) the mode-hop point, (b) $I = I_1$, and (c) $I = I_2$ in Fig. 1.

When the temperature of the LD is controlled to $T = T_0$ at the operating current of $I = I_0$, the mode-hop occurs at the operating point 'a' in Fig. 1. In this case, two major spectra are observed as shown in Fig. 2(a). We use these spectra on time-sharing basis by changing the operating current. When the operating current is set to $I = I_1$ as shown in Fig. 1, LD oscillates with $\lambda = \lambda_1$ at the operating point 'b'. Similarly, LD oscillates with $\lambda = \lambda_2$ at the operating point 'c' when the operating current I is set to I_2. The spectral intensities observed at I_1 and I_2 are schematically shown in Fig. 2(b) and 2(c), respectively.

When we use an interferometer whose optical path difference (OPD) is 2L, phases measured with two wavelengths are represented by

$$\alpha_1 + 2m\pi = 4\pi L/\lambda_1, \qquad (1)$$

and

$$\alpha_2 + 2n\pi = 4\pi L/\lambda_2, \qquad (2)$$

where m and n are integers. A half of OPD is then calculated by

$$L = k\Lambda/2 + D, \qquad (3)$$

where $k = m - n$, $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$ is the synthetic wavelength, $D = (\Lambda/4\pi)\Delta\alpha$, and $\Delta\alpha = \alpha_1 - \alpha_2$. If the displacement ΔD is smaller than $\Lambda/2$, it is given by

$$\Delta D = (\Lambda/4\pi)(\Delta\alpha_M - \Delta\alpha_S), \qquad (4)$$

where $\Delta\alpha_M$ and $\Delta\alpha_S$ are the phase differences before and after the displacement.

We used the SPM interferometry[5] to detect phases α_1 and α_2. The dc level of the modulating current is alternately changed as shown in Fig. 3 to use different two wavelengths on a time-sharing basis. Dc levels I_1 and I_2 of the injection current determine the central wavelength and the sinusoidal current modulates the phase of the interference signal.

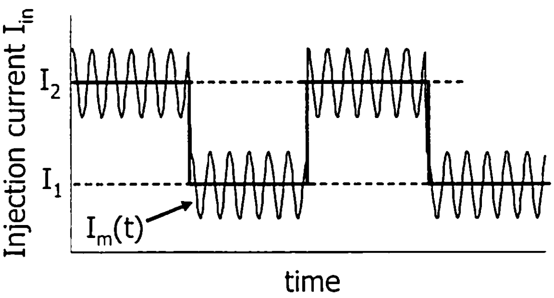

Figure 3. Injection current that is composed of dc bias currents I_1, I_2, and modulating current $I_m(t)$.

3. EXPERIMENTAL SETUP

The prototype system we proposed is shown in Fig. 4. Laser beam radiated from the LD is fed into a Fizeau interferometer, which consists of BS2 and M, through BS1. The M is moved by the micrometer and the displacement is monitored with the dedicated sensor whose resolution is 0.1 µm. The wavelength of the light reflected by BS1 is monitored with the optical spectrum analyzer (OSA). Sinusoidal modulating current $I_m(t)$ is superimposed onto the dc bias current supplied by the bias current controller and injected into the LD. The current and temperature are controlled within 0.01 mA and 0.01 °C, respectively. We select one of the wavelengths and capture the corresponding interference signal with the photodiode (PD).

Block diagram of the bias current controller is illustrated in Fig. 5. The first 1/16 divider (1/16 DIV) supplies the sampling pulse (SP) for the analog-to-digital (A/D) converter by dividing the signal from the standard 16MHz-oscillator (OSC). The second 1/16 DIV generates the signal (SYNC) that synchronizes the external oscillator with the bias current. Therefore, the frequency of the modulating current is 62.5 kHz. The 1/128 DIV supplies the rectangular bias current. The sum of this bias current and the modulating current $I_m(t)$ forms the required injection current that is shown in Fig. 3.

4. RESULTS

When we controlled the LD's temperature and the injection current to 27.4 °C and 70.0 mA, respectively, the LD was worked at the mode-hop point. In this case, two spectra were observed at λ_1 =684.299 nm and λ_2 = 684.864 nm with the OSA as shown in Fig. 6(a). When the operating current was changed by ±1.4 mA at the same temperature, the LD oscillated at λ_1 =684.299 nm (I_1 = 68.6 mA) and λ_2 = 684.864 nm (I_2 = 71.4 mA), respectively, as shown in Fig. 6(b) and 6(c). Figure 6 corresponds to Fig. 2. The wavelength-difference of 0.565 nm gives us the synthetic wavelength of ~829.5 µm. One example of the observed injection current and the SPM interference signal are

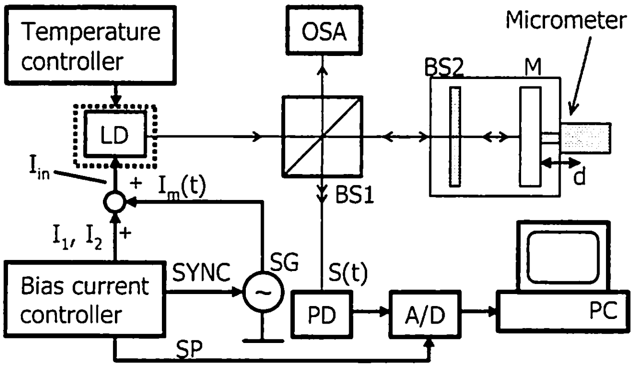

Figure 4. Experimental setup: LD, laser diode; OSA, optical spectrum analyzer; BS, beam splitters; M, mirror; d, displacement; PD, photodiode; A/D, analog-to-digital converter; S(t), interference signal; SYNC, synchronizing signal; SG, sinusoidal signal generator.

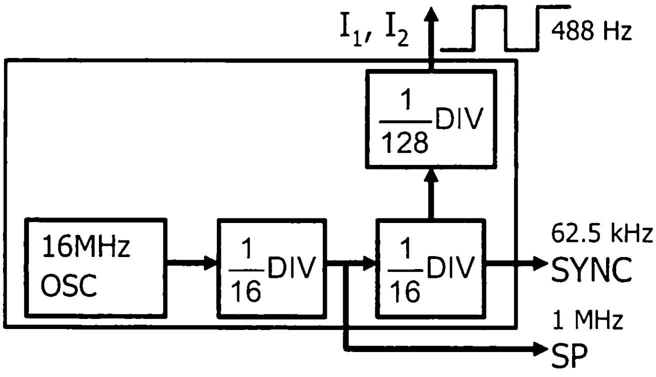

Figure 5. Block diagram of the bias current controller. OSC, oscillator; DIV, divider; I_1, I_2, bias currents; SYNC, synchronizing signal for the external oscillator; SP, sampling pulse for the A/D converter.

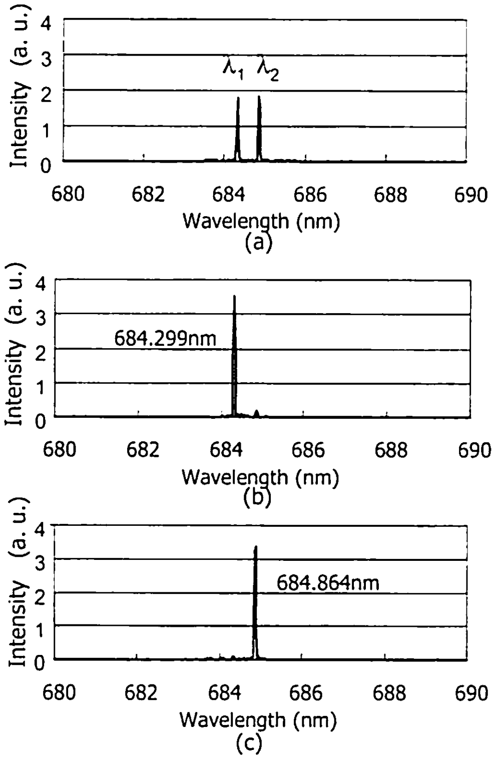

Figure 6. Spectra observed at (a) the mode-hop point of I_0 = 70.0 mA, (b) I_1 = 68.6 mA, and (c) I_2 = 71.4 mA with the temperature of 27.4 °C.

shown in Fig. 7. Although the modulating frequency actually used for the displacement measurement was 62.5 kHz as mentioned above, in this observation, the frequency of $I_m(t)$ was set to 25 kHz so as to observe $I_m(t)$ apparently with the bias current. Figure 7(a) is corresponding to Fig. 3. We can find that the phase of S(t) immediately changes according to the wavelength-change as indicated by $S_1(t)$ and $S_2(t)$. In this experiment, the transitional time for the wavelength-change was confirmed as 0.4 msec. Figure 8 shows $S_1(t)$ and $S_2(t)$ that are obtained under the modulating frequency of 62.5 kHz. The phase of $S_1(t)$ differs from that of $S_2(t)$ because the wavelength is different. We demonstrated several displacement measurements to confirm the accuracy. Figure 9 shows the measurements for the wide range of displacement. We moved the M along the optical axis a total of 300 μm in discrete 30 μm increments. Phases α_1 and α_2 were measured for each displacement and ΔD was calculated from Eq. (4). The measurement was implemented twice. The second measurement was conducted after putting M back in its original position. The deviations from the theoretical line were 2.92 μm and 2.86 μm in rms, respectively, for the first and the second measurement. The measurements for the narrow range of displacement were indicated in Fig. 10. The mirror was moved a total of 10 μm in discrete 1 μm increments. The other procedure was the same with the wide range of measurement. The errors in the first and the second measurement were 0.33 μm and 0.48 μm in rms, respectively. These experiments indicate that our technique is applicable to the displacement measurement in the range between a few μm and a few hundreds μm with a sub-micrometer resolution.

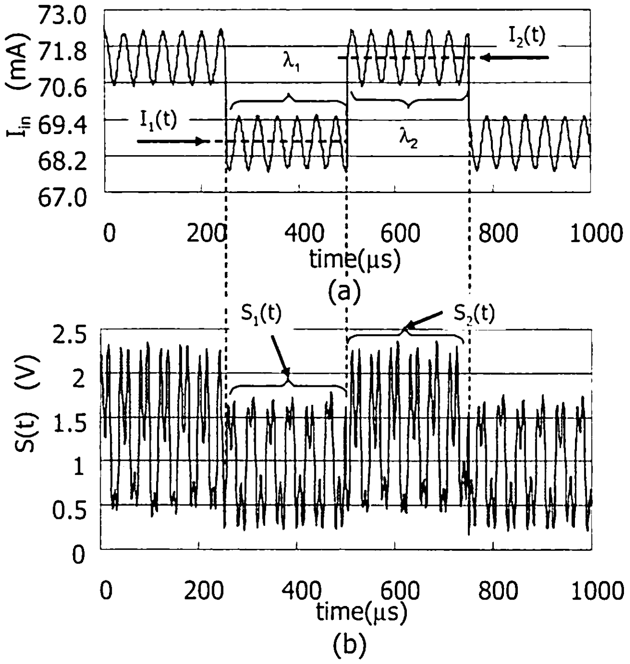

Figure 7. Observations of (a) time-shared sinusoidal modulating signal and (b) sinusoidal phase-modulating interference signal.

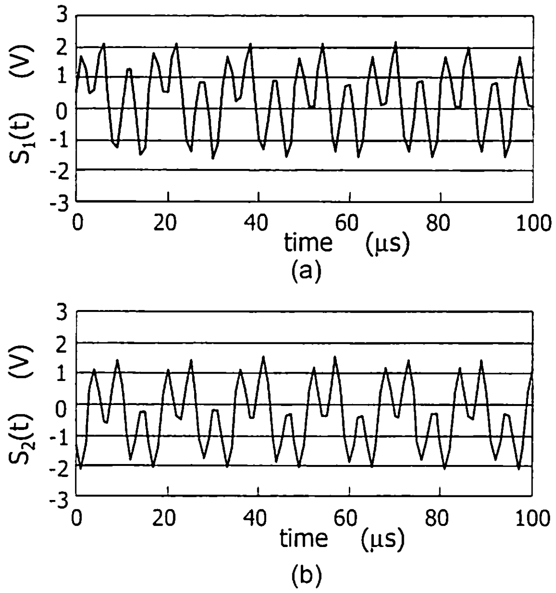

Figure 8. Interference signals (a) $S_1(t)$ and (b) $S_2(t)$ observed with the wavelength of λ_1 =684.299 nm and λ_2 = 684.864 nm, respectively.

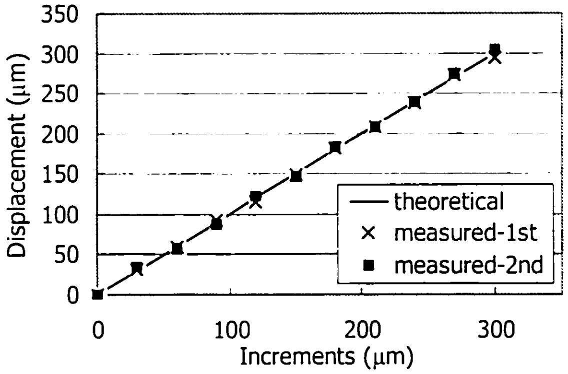

Figure 9. Measurement for the wide range of displacement. The mirror was moved a total of 300 μm in discrete 30 μm increments. The deviation from the theoretical line was ~3 μm in rms.

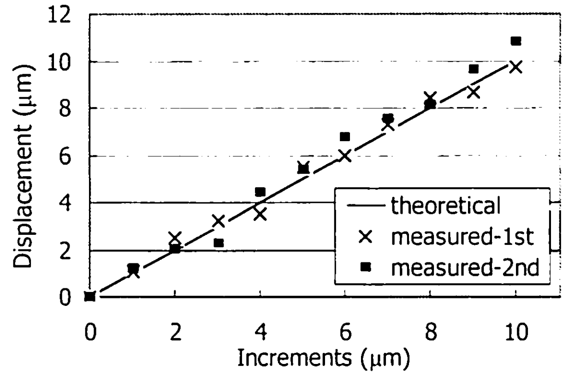

Figure 10. Measurement for the narrow range of displacement. The mirror was moved a total of 10 μm in discrete 1 μm increments. The deviation from the theoretical line was ~0.5 μm in rms.

5. CONCLUSIONS

We proposed and demonstrated a novel interferometric displacement sensor that uses dual-color operation of a LD. A time-shared two-wavelength laser diode enables us to realize a wide-range measurement with a simple optical setup. Measurement error of the demonstration was estimated to be ~3 μm in rms at a measurement range of 300 μm in our prototype. The resolution was confirmed as 0.5 μm from the short range of displacement measurement.

REFERENCES

1. A. J. den Boef, "Two-wavelength scanning spot interferometer using single-frequency diode lasers," Appl. Opt. 27, 306-311 (1988).
2. T. Suzuki, O. Sasaki, and T. Maruyama, "Absolute distance measurement using wavelength-multiplexed phase-locked laser diode interferometry," Opt. Eng. 35, 492-497 (1996).
3. T. Suzuki, N. Hido, X. Zhao, and O. Sasaki, "Dual-color operation of a laser diode under current and temperature control," Appl. Opt. 42, 6640-6644 (2003).
4. K. Tatsuno and Y. Tsunoda, "Diode laser direct modulation heterodyne interferometer," Appl. Opt. 26, 37-40 (1987).
5. O. Sasaki and H. Okazaki, "Sinusoidal phase modulating interferometry for surface profile measurement," Appl. Opt. 25, 3137-3140 (1986).