Superluminescent diode interferometer using sinusoidal phase modulation for step-profile measurement

Osami Sasaki, Yoshihiro Ikeada, and Takamasa Suzuki

We propose an interferometer in which the relationship between the degree of coherence (DCH) and the optical path difference (OPD) is utilized for determining an OPD longer than a wavelength. A superluminescent diode is employed as the source of the interferometer, and sinusoidal phase-modulating interferometry is used to detect the DCH and the phase of the interference signal. The combination of the OPD determined from the DCH and the phase of an interference signal enables us to measure an OPD longer than a wavelength with a high accuracy of a few nanometers. Experimental results show clearly the usefulness of the interferometer for a step-profile measurement.

© 1998 Optical Society of America

OCIS codes: 120.3180, 120.6650, 120.3890.

1. Introduction

Single-wavelength interferometers are limited to measurements of smooth and continuous surfaces on which the change in the optical path difference (OPD) between two measuring points is smaller than a half-wavelength. A method for overcoming this limitation is to use many phases of an interference signal for a number of wavelengths that determine an OPD longer than a wavelength. This method leads to two-wavelength interferometers,[1–5] wavelength-scanning interferometers,[6–9] and dispersive white-light interferometers[10–12] or white-light channeled spectrum interferometers. In two-wavelength interferometers the two wavelengths offer a synthetic wavelength longer than each of the two wavelengths. The combination between an OPD measured with the synthetic wavelength and an OPD measured with a single wavelength requires that the two wavelengths be highly stable. Wavelength-scanning interferometers detect how the phase of an interference signal changes in the time domain when the wavelength of a source is scanned with time. The measurement accuracy of an OPD becomes higher as the scanning width of the wavelength becomes larger. Dispersive white-light interferometers observe a phase distribution of an interferogram for a wavelength in the space domain with the help of a diffraction grating. Another method for determining an OPD longer than a wavelength is to use the property that the visibility of an inteferogram generated by white light is maximum when the OPD is zero. White-light interferometers[13–15] look for positions where OPD = 0 on the object surface by mechanically displacing the reference surface.

In this paper the visibility of the interference signal or the degree of coherence (DCH) is used to determine an OPD that is longer than a wavelength. A superluminescent diode (SLD) is employed as the source of the interferometer, and the relationship between the DCH and the OPD is known beforehand. Since the accuracy in determining the OPD from the DCH is higher than a half-wavelength, the OPD determined from the DCH can be combined with a measured value of the phase of the interference signal. This combination enables us to measure the OPD longer than a wavelength with a high accuracy of a few nanometers. To detect the DCH and the phase of the interference signal, we adopt sinusoidal phase-modulating interferometry[16] where phase modulation is carried out simply and exactly. We reported that this interferometer has been applied to measuring a step height of displacement larger than a half-wavelength.[17] Here we measure a step profile with a linear CCD image sensor, and the characteristics of the interferometer are made clear through experiments.

The authors are with the Faculty of Engineering, Niigata University, Niigata-shi 950-21, Japan.

Received 20 November 1997; revised manuscript received 16 March 1998.
0003-6935/98/225126-06$15.00/0

© 1998 Optical Society of America

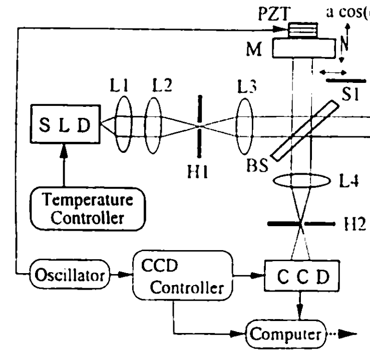

Fig. 1. SLD interferometer using sinusoidal phase modulation for surface-profile measurement.

2. Principle of the Superluminescent Diode Interferometer

A. Interference Signal

Figure 1 shows a SLD interferometer using sinusoidal phase modulation for step-profile measurement. The output beam from a SLD is collimated with lens L1, and an exact collimated beam is formed with lenses L2 and L3 and pinhole H1. The beam is divided into an object wave and a reference wave by a beam splitter, BS. The reference beam is normally reflected by mirror M vibrating with a sinusoidal wave of $a \cos(\omega_c t + \theta)$. Lens L4 makes an image of an object surface on a linear CCD image sensor. Pinhole H2 on the focus of lens L4 eliminates undesirable light for the image formation. Interference between the object and the reference waves generates a fringe pattern whose visibility depends on the OPD L between the two waves. Let $R(L)$ be the DCH between the two waves. The interference signal on the detecting point of the CCD is given by

$$S(t) = I_o + I_r + 2[I_o I_r R(L_t)]^{1/2} \times \cos[z \cos(\omega_c t + \theta) + \alpha], \quad (1)$$

where I_o and I_r are the intensities of the object and the reference waves, respectively, $z = 4\pi a/\lambda_c$, $\alpha = 2\pi L/\lambda_c$, and λ_c is the central wavelength of the SLD. Since the OPD varies as $L_t = L + 2a \cos(\omega_c t + \theta)$ according to the vibration of mirror M, $R(L_t)$ has a component that changes periodically with amplitude R_a. Since the amplitude a of mirror M is much smaller than L in L_t, the amplitude R_a is so small that it can be neglected in $R(L_t)$. Then we rewrite Eq. (1) as

$$S(t) = A + B \cos[z \cos(\omega_c t + \theta) + \alpha], \quad (2)$$

where

$$A = I_o + I_r, \quad B = 2[I_o I_r R(L)]^{1/2}. \quad (3)$$

Taking the Fourier transform $F(\omega)$ of Eq. (2), we have

$$\begin{aligned} F(\omega_c) &= -B \sin \alpha J_1(z) \exp(j\theta), \\ F(2\omega_c) &= -B \cos \alpha J_2(z) \exp(j2\theta), \\ F(3\omega_c) &= B \sin \alpha J_3(z) \exp(j3\theta), \end{aligned} \quad (4)$$

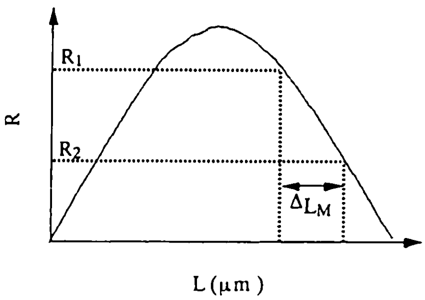

Fig. 2. Determination of a rough value ΔL_M in OPD L from the detected values of R_1 and R_2.

where $J_n(z)$ is the nth-order Bessel function. Phase-modulation amplitude z has a relationship of

$$r_{31} = |F(3\omega_c)/F(\omega_c)| = |J_3(z)/J_1(z)|. \quad (5)$$

Since the value of z is smaller than 3.5 in this modulation, the value r_{31} calculated from $F(\omega_c)$ and $F(3\omega_c)$ provides the value of z through the relationship between r_{31} and z. Phase θ is obtained from the argument of $F(\omega_c)$. Phase α is calculated from $F(\omega_c)$ and $F(2\omega_c)$ after the values of z and θ are known.[14]

B. Determination of the Optical Path Difference

From the values of z, $F(\omega_c)$, $F(2\omega_c)$, and $F(3\omega_c)$, the value of B is calculated as

$$2B^2 = [|F(\omega_c)|/J_1(z)]^2 + 2[|F(2\omega_c)|/J_2(z)]^2 + [|F(3\omega_c)|/J_3(z)]^2. \quad (6)$$

In addition, we detect the intensities I_o and I_r to finally obtain

$$R(L) = B/2(I_o I_r)^{1/2}. \quad (7)$$

We consider a relative OPD ΔL between two measuring points, P1 and P2, on the object surface. We detect phase α_1 of the interference signal and DCH R_1 for point P1, and we also detect phase α_2 and R_2 for point P2. Since the detected values of phases α_1 and α_2 are from $-\pi$ to π, we have

$$\alpha_R = 2\pi \Delta L/\lambda_c = 2m\pi + \alpha_D, \quad (8)$$

where

$$\alpha_D = \alpha_2 - \alpha_1, \quad -2\pi < \alpha_D < 2\pi. \quad (9)$$

By using a relationship between DCH R and OPD L, we can obtain a rough value ΔL_M of ΔL from the detected values of R_1 and R_2, as shown in Fig. 2. The phase corresponding to ΔL_M is $\alpha_M = 2\pi \Delta L_M/\lambda_c$. It is required that the value of α_M satisfy the condition

$$(2m - 1)\pi + \alpha_D < \alpha_M < (2m + 1)\pi + \alpha_D. \quad (10)$$

The condition of Eq. (10) means that α_M determines the integer value m exactly if the measurement error of α_M is within π. Thus we can finally obtain an exact value of ΔL larger than a wavelength λ_c from Eq. (8) with a high accuracy in the measurement of α_D.

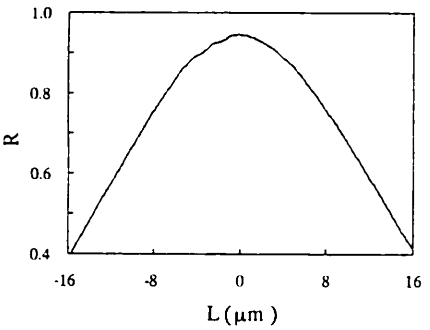

Fig. 3. DCH curve R as a function of OPD L detected in the SLD interferometer.

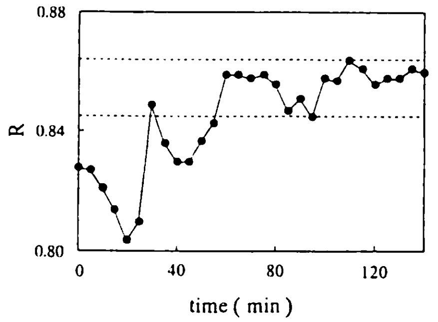

Fig. 4. Stability of the DCH with time after the temperature of the SLD is controlled.

3. Fundamental Experimental Results

A. Interferometer

The interferometer shown in Fig. 1 was used. The central wavelength λ_c of the SLD was 838 nm, and its half-width of the spectrum was 21 nm. The output power of the SLD was 7 mW, and its temperature was controlled to 25°. Lens L1 was a 10× objective lens, and the focus length of lens L2 and L4 was 70 mm. The diameters of pinholes H1 and H2 were 100 and 700 μm, respectively. Mirror M was vibrated sinusoidally with a piezoelectric transducer. The vibration frequency $\omega_c/2\pi$ was 50 Hz, and its amplitude a was 0.18 μm. We used 40 elements of the photodiodes of a linear CCD image sensor whose output signal was sampled with an analog-to-digital converter. The size of one element of the photodiodes was 14 μm × 14 μm. We detected interference signal $S(t)$ and intensities I_o and I_r with the CCD image sensor. When we detected intensities I_o and I_r, we blocked the reference and the objective waves by shutters S1 and S2, respectively. The interference signal for one measuring point was sampled with a frequency of 50×16 Hz, and the number of sampling points was 512.

B. Characteristics of the Degree of Coherences

First, we measured a relationship between the DCH and the OPD in the interferometer in Fig. 1. We used a flat mirror as an object. We inclined the mirror to the optical axis of the interferometer so that the OPD changed within the measuring region by $\sim$2 μm. Moreover we displaced the mirror, making it parallel to the optical axis so that the OPD changed by 1 μm. We measured the distribution of the DCH over the measuring region with a linear CCD image sensor every time we displaced the mirror. We corrected the error in the amount of displacement by comparing the two distributions of DCH measured on two adjacent positions of the mirror. In this way we obtained a DCH curve $R(L)$ for the OPD L as shown in Fig. 3.

Next we measured the stability of the DCH with time. One hour after we started controlling the temperature of the SLD at 25°, the maximum variation in the DCH was reduced to 0.02 as shown in Fig. 4. When the temperature was not controlled, the variation in the DCH was $\sim$0.04. The stability of the DCH demands a condition in which the change in the OPD is smaller than π in phase when the DCH changes by 0.02. Inversely this condition indicates that the DCH must change by more than 0.02 when the OPD changes by $\pm\pi$ in phase. By using Fig. 3, we calculated the change ΔR in the DCH when the OPD changes by $\pm\pi$ in phase for each value of R, as shown in Fig. 5. This figure indicates that we can use a DCH curve in the R region of less than $\sim$0.8. In our experiments we used part of the DCH curve for a positive value of L from $R = 0.8$ to 0.4.

Because we used a liner CCD image sensor, the detection size of a measuring point was a dimension of a photodiode of the CCD. We assume that the detection size is a line on which the phase of a fringe pattern changes linearly by $\Delta\alpha$ between both ends. In this case the value of B in Eq. (3) or the value of the DCH in Eq. (7) is reduced by a coefficient of $[\sin(\Delta\alpha/2)/(\Delta\alpha/2)]$. For example, when we measured the DCH curve of Fig. 3, the value of $\Delta\alpha$ caused by the inclination of the mirror was $\sim$0.5 rad and the reduction coefficient of $[\sin(\Delta\alpha/2)/(\Delta\alpha/2)]$ was 0.99. This value does not affect the determination of the integer m, because the allowable measurement error in the DCH is within 0.02 as described above. We estimate the maximum allowable value in $\Delta\alpha$ to be $\sim$0.8 rad.

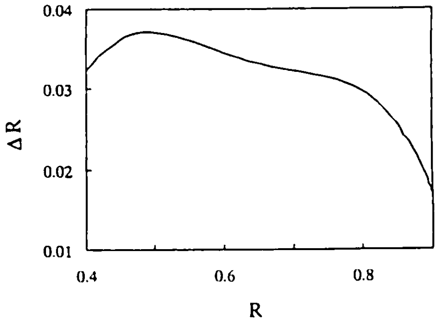

Fig. 5. Change ΔR of the DCH obtained from Fig. 3 when the OPD changes by $\pm\pi$ in phase for each value of R.

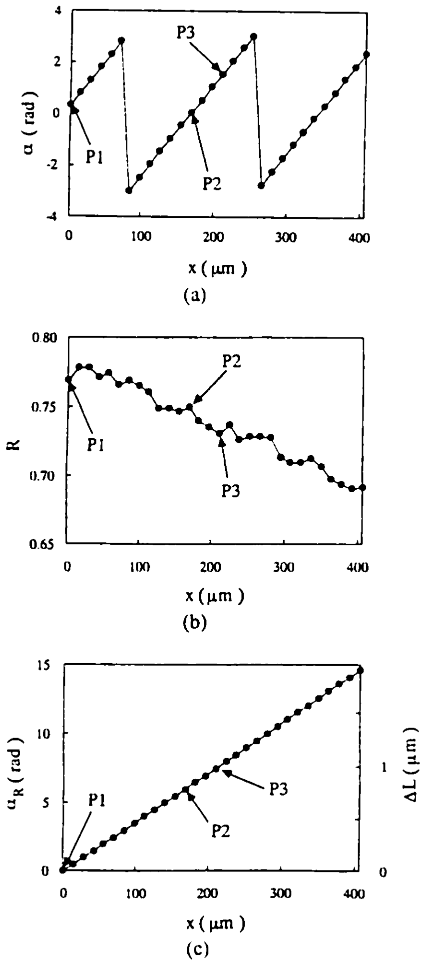

Fig. 6. Measurements of OPD relative to one measuring point P1 on a flat mirror inclined to the optical axis: (a) phase α, (b) DCH R, and (c) phase α_R or relative OPD ΔL.

C. Measurement of the Optical Path Difference

We measured the OPD relative to one measuring point by using a flat mirror inclined to the optical axis as an object. Experimental results about phase α, DCH R, and phase α_R are shown in Figs. 6(a), 6(b), and 6(c), respectively, in which the horizontal axis x represents positions on the object. We consider three measuring points, P1, P2, and P3, as shown in Fig. 6. Although the measured distribution of α provides values of α_R, we tried to determine values of α_R from the measured DCH with the method described in Section 2. Results from points P1, P2, and P3 are shown in Table 1. The value of ΔL_M between P1 and P2 obtained when we use the measured DCH curves of Fig. 3 and related values are written in the P2 row. For P1 and P2 Eq. (10) becomes $(2m - 1)\pi - 0.28 < 3.34 < (2m + 1)\pi + 0.28$, and we decided on $m = 1$. For P1 and P3 we have the inequality of $(2m - 1)\pi + 1.22 < 7.29 < (2m + 1)\pi + 1.22$, and we decide on $m = 1$. For the other measuring points we calculated values of α_R or ΔL relative to measuring point P1 as shown in Fig. 6(c). These results show that the proposed method can exactly measure an OPD longer than a wavelength with an accuracy in the measurement of phase α.

Table 1. Experimental Results from Determination of Integer m and phase α_R for Measuring Points P1, P2, and P3

Points	α (rad)	R	ΔL_M (μm)	α_M (rad)	α_D (rad)	m	α_R (rad)
P1	0.33	0.769					
P2	0.05	0.750	0.459	3.44	−0.28	1	6.00
P3	1.55	0.731	0.975	7.29	1.22	1	7.50

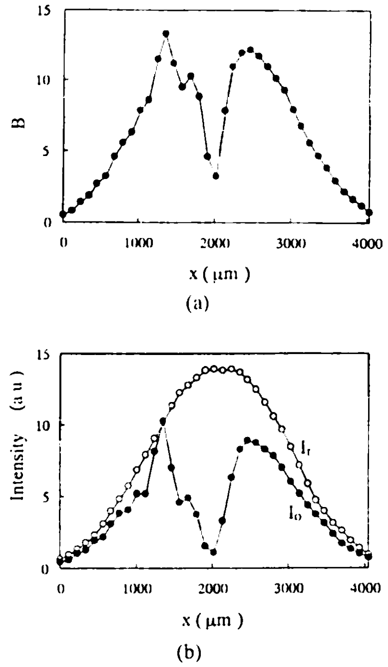

Fig. 7. Measurement of a step profile whose height was 1 μm: (a) value of B and (b) intensities I_o and I_r.

4. Step-Profile Measurement

We measured a step profile that was made by sticking together two gauge blocks of different thickness. The step height was 1 μm. Figures 7(a) and 7(b) show the values of B and intensities I_o and I_r, respectively. We see that the intensity I_o of the object wave is weak around the boundary of the two gauge blocks at $x = 2000$ μm. From these measured values we calculated the DCH as shown in Fig. 8(a) in which phase α of the interference signal is also shown. The measurement accuracy in phase α was higher than 2 nm in OPD. Using the DOH curve of Fig. 3, we finally obtained values of α_R or ΔL where α_R and ΔL were taken to be zero at one side of the measuring region or $x = 0$ μm, as shown in Fig. 8(b). Exact measured values cannot be obtained at a few measuring points around the boundary, because light is strongly diffracted on the boundary. Exact measured values also cannot be obtained on both sides of the object because of the weak intensity of light. The gauge block was scratched, which was detected at $x = 1444$ μm as

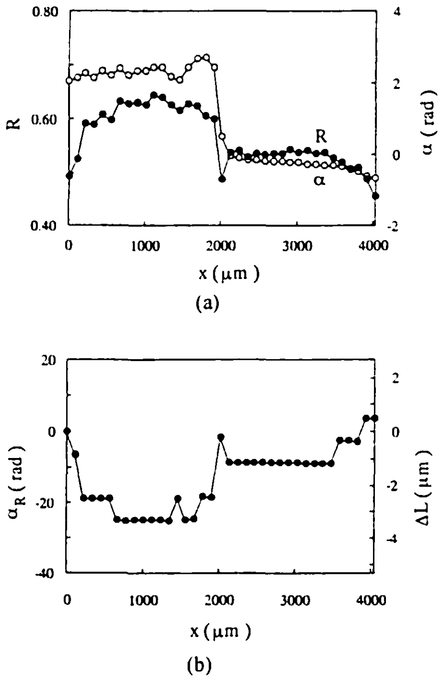

Fig. 8. Measurement of a step profile whose height was 1 μm: (a) DCH R and phase α; (b) phase α_R or relative OPD ΔL.

shown in Fig. 8(b). The measured height of the step between some two measuring points was 1.086 μm. Next we measured another step profile whose height was 3 μm. The measured results in a measuring region of 2555 μm are shown in Figs. 9(a) and 9(b). The boundary is at $x \cong 1000$ μm, and we can see from measured values of α that one gauge block was greatly inclined. The measured step height between some two measuring points was 2.948 μm.

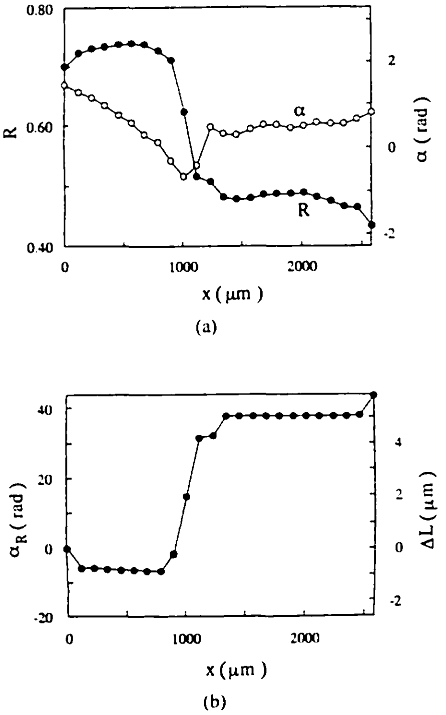

Fig. 9. Measurement of a step profile whose height was 3 μm: (a) DCH R and phase α; (b) phase α_R or relative OPD ΔL.

5. Conclusions

We have proposed a SLD interferometer that uses sinusoidal phase-modulating interferometry for step-profile measurement. We detected the DCH from the sinusoidal phase-modulated interference signal and the intensities of the object and the reference waves with an error of less than 0.02. From the detected DCH we could determine an OPD longer than a wavelength with an accuracy higher than a half-wavelength. We combined the OPD determined from the DCH with the phase of the interference signal to obtain an exact OPD with an accuracy of 2 nm. When an object has many steps with a width of a few hundred micrometers, the effect of diffraction on imaging disturbs the distribution of DCH on the image of the object, and the measurement becomes impossible. The interferometer proposed here is most suitable for measuring a one-step profile as shown in the experiments.

References

1. C. Polhemus, "Two-wavelength interferometer," Appl. Opt. **12**, 2071–2074 (1973).
2. K. Creath, "Step height measurement using two-wavelength phase-shifting interferometry," Appl. Opt. **26**, 2810–2816 (1987).
3. P. de Groot and S. Kishner, "Synthetic wavelength stabilization for two-color laser-diode interferometry," Appl. Opt. **30**, 4026–4033 (1991).
4. O. Sasaki, H. Sasazaki, and T. Suzuki, "Two-wavelength sinusoidal phase/modulating laser-diode interferometer insensitive to external disturbances," Appl. Opt. **30**, 4040–4045 (1991).
5. R. Onodera and Y. Ishii, "Two-wavelength laser-diode interferometer with fractional fringe techniques," Appl. Opt. **34**, 4740–4746 (1995).
6. H. Kikuta, K. Iwata, and R. Nagata, "Distance measurement by the wavelength shift of laser diode light," Appl. Opt. **25**, 2976–2980 (1986).
7. O. Sasaki, T. Yoshida, and T. Suzuki, "Double sinusoidal phase-modulating laser diode interferometer for distance measurement," Appl. Opt. **30**, 3617–3621 (1991).
8. S. Kuwamura and I. Yamaguchi, "Wavelength scanning profilometry for real-time surface shape measurement," Appl. Opt. **36**, 4473–4482 (1997).
9. F. Lexer, C. K. Hitzenberger, A. F. Fercher, and M. Kulhavy, "Wavelength-tuning interferometry of intraocular distances," Appl. Opt. **36**, 6548–6553 (1997).
10. J. Schwider and L. Zhou, "Dispersive interferometric profilometer," Opt. Lett. **19**, 995–997 (1994).
11. U. Schnell, E. Zimmermann, and R. Dandliker, "Absolute distance measurement with synchronously sampled white-light channeled spectrum interferometry," Pure Appl. Opt. **4**, 643–651 (1995).
12. L. Rovati, U. Minoni, and F. Docchio, "Dispersive white-light combined with a frequency-modulated continuous-wave interferometer for high-resolution absolute measurements of distance," Opt. Lett. **22**, 850–852 (1997).
13. B. S. Lee and T. C. Strand, "Profilometry with a coherence scanning microscope," Appl. Opt. **29**, 3784–3788 (1990).

14. P. J. Caber, "Interferometric profiler for rough surface," Appl. Opt. **32,** 3438–3441 (1993).
15. L. Deck and P. de Groot, "High-speed noncontact profiler based on scanning white-light interferometry," Appl. Opt. **33,** 7334–7338 (1994).
16. O. Sasaki and H. Okazaki, "Sinusoidal phase modulating interferometry for surface profile measurement," Appl. Opt. **25,** 3137–3140 (1986).
17. O. Sasaki, Y. Ikeda, and T. Suzuki, "Superluminescent diode interferometer using sinusoidal phase-modulation for step profile measurement," in *Meeting Digest of Frontiers in Information Optics* (International Commission for Optics, Kyoto, 1994), p. 146.