Sinusoidal wavelength-scanning interferometer with a superluminescent diode for step-profile measurement

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In sinusoidal phase-modulating interferometry an optical path length (OPD) larger than a wavelength is measured by detection of sinusoidal phase-modulation amplitude Z_b of the interference signal that is produced by sinusoidal scanning of the wavelength of a light source. A light source with a large scanning width of wavelength is created by use of a superluminescent laser diode for the error in the measured value obtained by Z_b to be smaller than half of the central wavelength. In this situation the measured value can be combined with a fractional value of the OPD obtained from the conventional phase of the interference signal. A sinusoidal wavelength-scanning interferometer with the light source measures an OPD over a few tens of micrometers with a high accuracy of a few nanometers. © 2000 Optical Society of America

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1. Introduction

Single-wavelength interferometers are limited to measurements of smooth and continuous surfaces on which a change of the optical path difference (OPD) between two measuring points is smaller than a wavelength. An idea to overcome this limitation is to use a number of wavelengths whose phases of an interference signal determine an OPD longer than a wavelength. This idea leads to two-wavelength interferometers,[1,2] wavelength-scanning interferometers,[3–9] and dispersive white-light interferometers[9–13] or white-light channeled spectrum interferometers. In two-wavelength interferometers the two wavelengths offer a synthetic wavelength longer than each of the two wavelengths. Combination between an OPD measured with the synthetic wavelength and an OPD measured with a single wavelength requests a high stability of the two wavelengths, so that it is not easy to get a high measurement accuracy of a few nanometers. Wavelength-scanning interferometers detect how a phase of interference signal changes in time domain when the wavelength of a source is scanned with time. Dispersive white-light interferometers observe a phase distribution of an interferogram for wavelengths in the space domain with the help of a diffraction grating. Since the use of the diffraction grating demands one-dimensional detecting points for one measuring point, wavelength-scanning interferometers are handled more easily than dispersive white-light interferometers. Since measurement accuracy in OPD is higher as the scanning width of wavelength is larger in wavelength-scanning interferometers, a light source with a large scanning width of wavelength is desirable. Sasaki *et al.*[14] and Tsuji *et al.*[15] proposed two different light sources with a superluminescent laser diode (SLD) in which a wavelength is scanned sinusoidally with a large width.

In this paper we employ the sinusoidal wavelength-scanning (SWS) light source with a SLD as had been proposed previously.[14] An optical spectrum distribution of a SLD obtained with a diffraction grating is filtered by a sinusoidally moving slit to generate a large scanning width. Since a sinusoidal movement of the slit is easily made compared with other movements, SWS can be exactly achieved. An interferometer with this light source is called a SWS–SLD interferometer. A SWS light source produces a sinusoidally phase-modulated interference signal, and its phase-modulation amplitude Z_b is propor-

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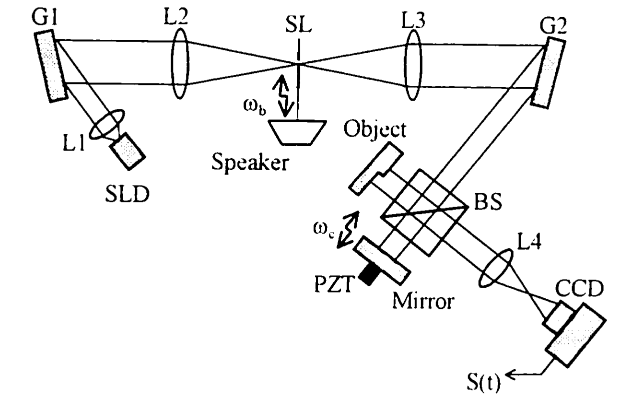

Fig. 1. SWS–SLD interferometer for step-profile measurement.

tional to OPD and to the scanning width of wavelength. An OPD longer than a wavelength is measured from detection of the phase-modulation amplitude. At the same time, a fractional value of the OPD is measured with a high accuracy of a few nanometers from detection of the conventional phase α of the interference signal. If the measurement accuracy by the phase-modulation amplitude is higher than a half wavelength, these two measured values can be combined. This combination enables us to measure an OPD longer than a wavelength with a high accuracy of a few nanometers. For a time-varying phase change of the interference signal due to the SWS to be detected accurately, double sinusoidal phase-modulating interferometry[4] is used. Characteristics of the SWS–SLD interferometer are made clearly, and step-profile measurements are carried out.

2. Sinusoidal Wavelength-Scanning–Superluminescent Laser Diode Interferometer

A. Sinusoidal Wavelength-Scanning Light Source

Figure 1 shows a SWS–SLD interferometer for step-profile measurement. The output beam from the SLD is collimated with lens L1 and incident on diffraction grating G1. The first-order reflection from the grating is Fourier transformed with lens L2 to perform a grating spectroscope. A continuous spectrum of the SLD, as shown in Fig. 2, appears on the focal plane of lens L2 and L3. A central wavelength of the spectrum is λ_0. Slit SL, put on the focal plane, transmits a portion of the spectrum. The slit is connected with a magnetic coil of a speaker and vibrated sinusoidally with an angular frequency of ω_b. The central wavelength of the light passing through the slit is sinusoidally scanned as shown in Fig. 2, and it is expressed by

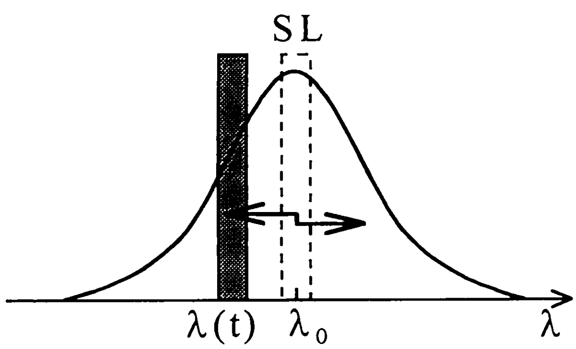

Fig. 2. Continuous spectrum of a SLD and its filtering.

$$\lambda(t) = \lambda_0 + \Delta\lambda(t) = \lambda_0 + b\cos(\omega_b t). \quad (1)$$

The light coming out of the slit is Fourier transformed with lens L3 and incident on grating G2 so that the first-order reflection from the grating produces a collimated beam whose propagating direction is constant for all of wavelengths contained in the spectrum of the SLD. The collimated beam becomes an output of a SWS light source for an interferometer.

B. Measurement Method

The output beam from the SWS light source is divided into two beams. One of them is reflected by an object. The other is reflected by a reference mirror that is vibrated by piezoelectric transducer PZT with a waveform of $a \cos \omega_c t$ to adapt double sinusoidal phase-modulating interferometry. Denoting an OPD by L, we approximate a phase of an interference signal as

$$\Psi(t) = 2\pi L/\lambda(t) = -2\pi[\Delta\lambda(t)/\lambda_0^2]L + (2\pi/\lambda_0)L, \quad (2)$$

in the condition of $b \ll \lambda_0$. Consideration of the sinusoidal phase modulation by the reference mirror, intensity change $M(t)$ of the output beam from a SWS light source, and visibility V, yields an interference signal

$$S(t) = M(t) + M(t)V\cos(Z_c \cos \omega_c t + Z_b \cos \omega_b t + \alpha), \quad (3)$$

where

$$Z_c = 4\pi a/\lambda_0,$$

$$Z_b = (2\pi b/\lambda_0^2)L, \quad (4)$$

$$\alpha = -(2\pi/\lambda_0)L. \quad (5)$$

By processing signal $S(t)$ with the Fourier transform as has been described previously,[1,4] we obtain

$$\phi(t) = Z_b \cos \omega_b t + \alpha. \quad (6)$$

The carrier signal of $Z_c \cos \omega_c t$ plays an important role in calculating a value of $\phi(t)$ with a high accuracy. Fourier transform of $\phi(t)$ provides us values of Z_b and α.

The value of proportional constant $2\pi b/\lambda_0^2$ in Eq. (4) is determined by measurement of Z_b for different values of OPD. After that, measurement of Z_b provides a value of OPD that is denoted by L_z. We also obtain a fractional value of OPD from the value of α that is denoted by L_α. Since a value of α is expressed

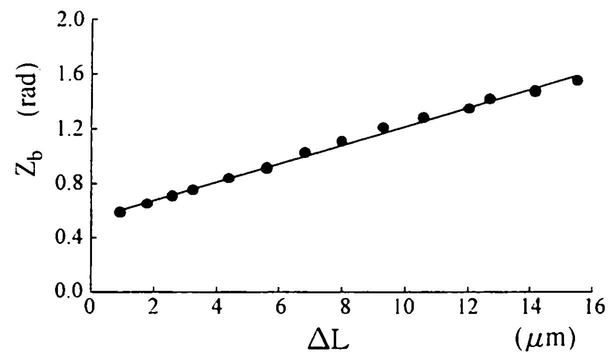

Fig. 3. Values of Z_b measured for different values of change ΔL in OPD.

in the range from $-\pi$ to π, a value of L_α is in the range from $-\lambda_0/2$ to $\lambda_0/2$, and its measurement accuracy is a few nanometers. OPD L that represents the absolute distance is given by

$$L = m\lambda_0 + L_\alpha, \quad (7)$$

and one can obtain integer m by rounding off the following number to an integer if measurement error ϵ_{LZ} in L_z is smaller than $\lambda_0/2$:

$$m_c = (L_z - L_\alpha)/\lambda_0. \quad (8)$$

The condition of $\epsilon_{LZ} < \lambda_0/2$ is achieved for a large value of b. When there are random errors in detection of Z_b, averaging a lot of measured values of m_c is effective for accurate determination of m. In a SWS interferometer the combination of two measured values of L_z and L_α results in an exact OPD measurement over a few tens of micronmeters with a high accuracy of a few nanometers.

3. Experiments

A. Experimental Setup

A SWS–SLD interferometer for step-profile measurement, as shown in Fig. 1, was constructed. Central wavelength λ_0 and spectral bandwidth of the SLD were 788.7 and 20 nm, respectively. An 1200-line/mm holographic grating was used for G1 and G2. The incident angle of the beam to grating G1 was approximately 60°. The focal length of lens L2 and L3 was 150 mm, and their optical axis was coincident with the propagation direction of the central wavelength λ_0 in the first-order reflection. The width of the slit SL was approximately 1 mm, which transmitted the spectrum of 5.6-nm width. The angular frequencies of $\omega_b/2\pi$ and $\omega_c/2\pi = 16(\omega_b/2\pi)$ were 70 and 1120 Hz, respectively. The interference signals were detected with a linear CCD image sensor in the same way as had been described previously.[16] Lens 4 made an image of the object surface on the CCD image sensor, and each cell of the photodiodes of the CCD formed the measuring interval of 0.14 mm on the object surface. The interference signal for one measuring point was sampled with a frequency of 8×1120 Hz,

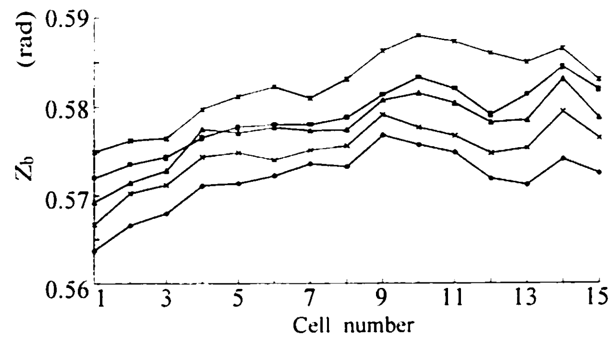

Fig. 4. Variations of Z_b with time.

and the number of measuring points was 15. The sampled interference signals were processed in a personal computer.

B. Fundamental Characteristic

A mirror fixed on a stage was used as an object surface. We gave a displacement to the object by means of a micrometer to change the OPD by approximately 1 μm. Figure 3 shows values of Z_b measured for different values of change ΔL in OPD. The values of ΔL were calculated from a change in phase α, which was caused by the object's displacement of approximately 1 μm. For these measured results a linear line was fitted as shown in Fig. 3, and we obtained a relation of $Z_b = (1/D)L$ where $D = 14.8$ μm/rad. It was made clear by repetition of the measurement of D that the measurement error ϵ_D in D was approximately 0.1 μm/rad. The proportional constant D of 14.8 μm/rad leads to wavelength-scanning width $2b$ of 13.4 nm. Figure 4 shows variations of Z_b with time in which the measurement of Z_b was repeated five times at intervals of 1 min. The horizontal axis is the cell number of the CCD that represents the measuring points at intervals of 0.14 mm on the object surface. This result indicates that the measurement error ϵ_Z in Z_b is approximately 0.01 rad.

The measurement error ϵ_{LZ} in L_Z is given by

$$\epsilon_{LZ} = D\epsilon_Z + Z_b\epsilon_D, \quad (9)$$

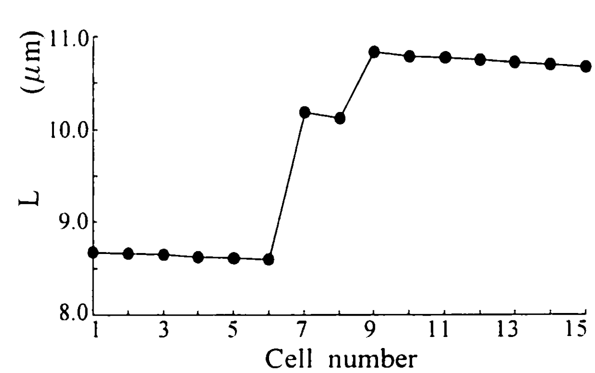

Fig. 5. Measured result of step profile.

Table 1. Measured Values

Cell Number	Z_b (rad)	L_Z (μm)	α (rad)	L_α (μm)	m_c	L (μm)
3	0.584	8.632	−0.26	−0.033	10.9	8.643
5	0.578	8.555	−0.52	−0.065	10.9	8.610
7	0.666	9.857	−0.51	−0.064	12.6	10.189
9	0.725	10.717	−1.70	−0.213	13.9	10.828
11	0.743	10.993	−2.19	−0.275	14.2	10.767
13	0.713	10.552	−2.59	−0.325	13.8	10.717

where a term of $\epsilon_Z \epsilon_D$ is ignored because of its small value. The measurement region of OPD is limited by the condition of $\epsilon_{LZ} < \lambda_0/2$. In these experiments the relation of $\epsilon_{LZ} = 0.15 + 0.1 \times (1/14.8)L$ leads to the measurement region of $L < 35$ μm in which the combination of L_Z and L_α is possible.

C. Step-Profile Measurement

We measured a step profile that was made by sticking two gauge blocks of different thickness together. The difference between the two heights of the gauge blocks was 1 μm in nominal value. The measured step profile is shown in Fig. 5, and Table 1 shows the measured values for some cells. Exact measured values cannot be obtained at cells 7, 8, and 9 (See Fig. 5) around the boundary of the two gauge blocks, because light is strongly diffracted on the boundary. At the other cells, differences between the value of m_c and an integer of its round number are within 0.2. An exact OPD can be obtained with the measurement error in L_α of approximately 2 nm. The measured height of the step between cells 6 and 10 (See Fig. 5) was 1.113 μm.

4. Conclusions

We employed the SWS light source with the SLD in which a large scanning width of 13 nm was easily obtained. We described how to measure an OPD larger than a wavelength with the SWS–SLD interferometer. The fundamental experiments showed clearly that the combination of L_Z and L_α was possible in the measurement region of $L < 35$ μm. The combination of the two measured values of L_Z and L_α enabled us to measure the OPD longer than a wavelength with a high accuracy of 2 nm. Step profiles with a step height of a few nanometers were measured exactly.

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