Sinusoidal wavelength-scanning interferometers using a superluminescent diode

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ABSTRACT

Two different sinusoidal wavelength-scanning (SWS) interferometers with a SWS light source using a superluminescent laser diode are proposed for step-profile measurement and real-time distance measurement, respectively. An optical path difference (OPD) longer than a wavelength is measured from detection of sinusoidal phase-modulation amplitude Z_b of the interference signal that is proportional to the OPD and the scanning width 2b. In step-profile measurement, if measurement error in the OPD obtained from Z_b is smaller than a half wavelength, this measured value of the OPD is combined with a fractional value of the OPD obtained from the conventional phase of the interference signal. This combination enables us to measure the OPD longer than a wavelength with a high accuracy of a few nm. In real-time distance measurement, the amplitude Z_b is kept at a specified constant value for changes of OPD by controlling the scanning width 2b of the wavelength with a feedback system. The amplitude Z_b is detected by processing the interference signal with electric circuits in real-time. The value of b is easily controlled in the SWS light source, and an OPD longer than a wavelength is measured from the value of b with an accuracy of about a wavelength.

1. INTRODUCTION

Interferometers using a single wavelength are limited to measurements of a change of the optical path difference (OPD) smaller than a wavelength. If a number of wavelengths are used, it is possible to measure an OPD longer than a wavelength. Two wavelengths have been used in an interferometer as a simple method, but it is difficult to obtain measurement accuracy as high as a wavelength. Interferometers using a large number of wavelengths at the same time are called white-light interferometer or low-coherence interferometer. In these interferometers a reference surface must be scanned mechanically to find positions of OPD=0. Interferometers using a large number of wavelengths separately are called dispersive white-light interferometers[1-6] and wavelength-scanning interferometers[7-11]. In dispersive white-light interferometers a large number of wavelengths are separated in space domain with help of a diffraction grating. In wavelength-scanning interferometers wavelength of a light source is scanned with time, and the interference signal corresponding to each wavelength is detected with time. Measurement accuracy in these interferometers is proportional to the width of the employed wavelengths. External-cavity tunable laser diodes are generally used for wavelength-scanning interferometers.

In this paper wavelength of a light source is scanned sinusoidally with time. Sinusoidal wavelength-scanning (SWS) light source using a superluminescent laser diode (SLD)[10] is used. A large scanning width of wavelength is easily obtained by filtering an optical spectrum distribution of a SLD by a sinusoidally moving slit. In SWS interferometers using the SWS light source an OPD longer than a wavelength is measured from detection of sinusoidal phase-modulation amplitude Z_b of the interference signal that is proportional to the OPD and the scanning width 2b. Two different SWS interferometers for step-profile measurement and real-time distance measurement, respectively, are proposed.

In step-profile measurement, double sinusoidal phase-modulating interferometry[12] is employed to detect exactly the amplitude Z_b. Conventional phase α of the interference signal is also detected to obtain a fractional value of the OPD longer than a wavelength with a high accuracy of a few nm. If the measurement error in OPD obtained from Z_b is smaller than a half wavelength, the two measured values of the OPD obtained from Z_b and α can be combined. This combination enables us to measure the OPD longer than a wavelength with a high accuracy of a few nm. The interference signals are detected with a linear CCD image sensor and processed in a personal computer to obtain step-surface profiles.

In real-time distance measurement, the amplitude Z_b is kept at a specified constant value for changes of OPD by controlling the scanning width 2b of the wavelength with a feedback system. In order to detect the amplitude Z_b by processing the interference signal with electric circuits in real-time, a triangular phase-modulation is added to the interference signal as a carrier signal for the sinusoidal phase-modulation due to the SWS. The value of b is exactly controlled in the SWS light source, and an OPD longer than a wavelength is measured from the value of b with an accuracy of about a wavelength.

2. SWS LIGHT SOURCE

Figure 1 shows a SWS interferometer using a SLD for step-profile measurement. 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 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

$$\lambda(t) = \lambda_0 + \Delta\lambda(t) = \lambda_0 + b\cos(\omega_b t)\,. \tag{1}$$

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 a SWS light source for an interferometer.

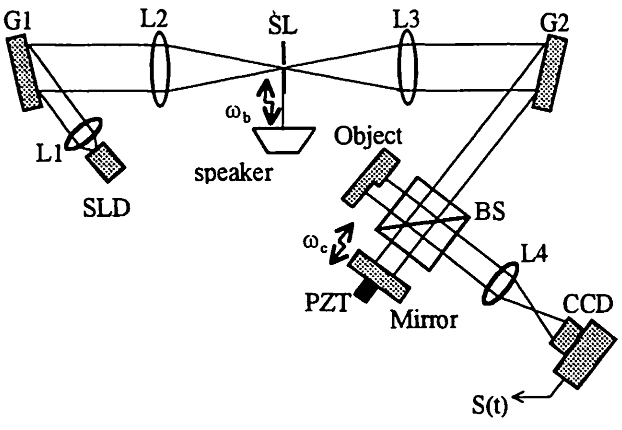

Fig.1 SWS interferometer using a SLD for step-profile measurement.

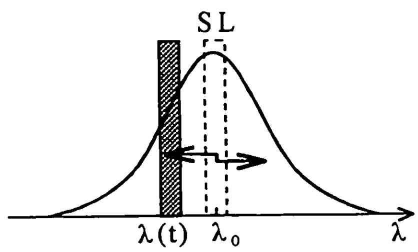

Fig.2 Continuous spectrum of a SLD and its filtering.

3. SWS-SLD INTERFROMETER FOR STEP-PROFILE MEASUREMENT

3.1. PRINCIPLE

A SWS-SLD interferometer for step-profile measurement is shown in Fig.1. A collimated output beam from a SWS light source is divided into two beams. One of them is reflected by an object. The other one is reflected by mirror M which is sinusoidally vibrated by a peizoelectric transducer (PZT) with angular frequency ω_c to adapt double sinusoidal phase-modulating interferometry[12]. Denoting an OPD by L, a phase of an interference signal is approximated as

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

in the condition of $b<<\lambda_0$. Considering the sinusoidal phase modulation by mirror M, and intensity change $I_M(t)$ of the output beam from a SWS light source, an interference signal detected with a photo diode is given by

$$S(t) = I_M(t)\ [\ A+ B \cos(\ Z_c os\omega_c t + Z_b \cos\omega_b t + \alpha)], \qquad (3)$$

where A and B are constant values, $Z_c=4\pi a/\lambda_0$, and

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

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

By processing signal S(t) using Fourier-transform as described in Ref.12, we obtain

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

The carrier signal of $Z_c \cos\omega_c t$ plays an important role in calculating an 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 consatant $2\pi b/\lambda_0^2$ is determined by measuring Z_b for different values of OPD. After that, measurement of Z_b provides a value of OPD which is denoted by L_z. We also obtain a fractional value of OPD from the value of α which is denoted by L_α. Since a value of α is expressed 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 nm. OPD L that represents the absolute distance is given by

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

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

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

This value of ε_{LZ} 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 determination of m. In 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 microns with a high accuracy of a few nm.

3. 2. EXPERIMENTAL RESULTS

A SWS-SLD interferometer for step-profile measurement shown in Fig.1 was constructed. Central wavelength λ_0 and spectral bandwidth of the SLD were 788.7 nm 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 about 60 degrees. The focus length of lens L1 and L2 was 150 mm, and the width of the slit SL was about 1 mm. The angular frequencies of $\omega_b/2\pi$ and $\omega_c/2\pi=16(\omega_b/2\pi)$ were 70 Hz and 1120 Hz, respectively. The interference signals were detected with a linear CCD image sensor in the same way as described in Ref.13. 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 cell or one measuring point was sampled with a frequency of 8×1120 Hz, and the number of measuring points was 16. The sampled interference signals were processed in a personal computer.

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 1.0 μm. Figure 3 shows values of Z_b measured for different values of change ΔL in OPD. From these results we obtain a relationship between Z_b and L, which is $Z_b=(1/D)L=(1/14.8)L(\mu m)$. It was made clear by repeating the measurement of D that the measurement error ε_D in D was about 0.1. The proportional constant D of 14.8 leads to width 2b of the wavelength-scanning of 13.4 nm. Figure 4 shows variation of Z_b with time in which the measurement of Z_b was repeated five times at intervals of 1 minute. The horizontal axis is the cell number of the CCD which represents the measuring points at intervals of 0.14 mm on the object surface. It is concluded from these results that OPD can be measured from Z_b with an error ε_L of 0.104 μm. Since this error is smaller than half of wavelength λ_0, the combination of L_Z and L_α is possible.

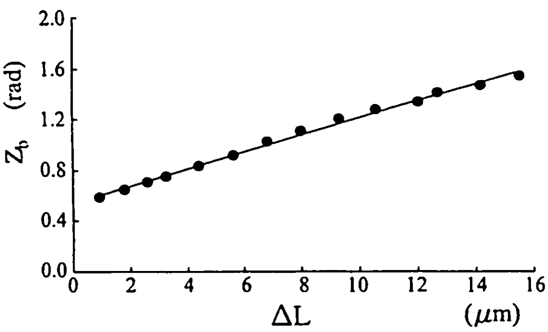

Fig.3 Values of Z_b measured for different values of change ΔL in OPD.

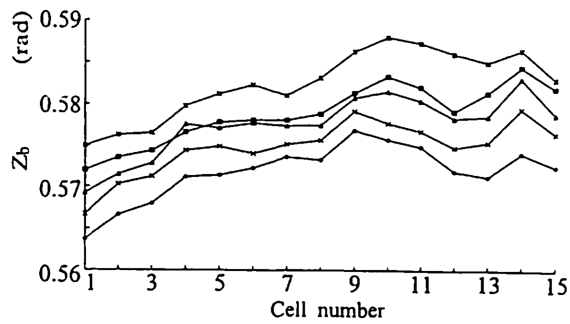

Fig.4 Variation of Z_b with time.

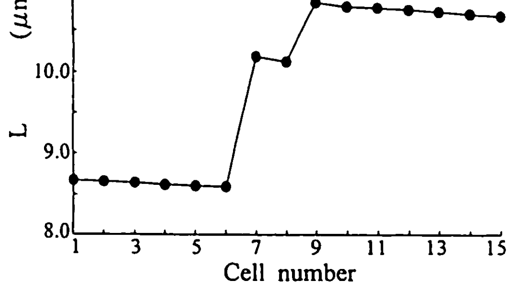

Fig.5 Measured result of step-surface profile.

Table 1 Measured Values.

Cell no.	Z_b(rad)	Lz(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

We measured a step profile which was made by sticking two gauge blocks of different thickness together. The difference between the two heights of the gauge blocks was 1μm. The measured step-profiler is shown in Fig.5, and Table 1 shows the measured values for some cells. Exact measured values cannot be obtained at cell 7, 8, and 9 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 about 2 nm. The measured height of the step between cell 6 and 10 was 1.113 μm.

4. SWS-SLD INTERFROMETER FOR REAL-TIME DISTANCE MEASUREMENT

4.1. PRINCIPLE

A SWS-SLD interferometer for real-time distance measurement is shown Fig.6. A collimated output beam from a SWS light source is divided into two beams by beam splitter 1 (BS1). One of them is reflected by mirror 1 (M1) as an object. The other one is reflected by mirror 2 (M2) which is vibrated by a peizoelectric transducer (PZT) with a triangular waveform a(t). In the same manner as Eq.(3) an interference signal detected with photodiode 1 (PD1) is given by

$$S_D(t) = I_M(t)\,[\,A + B\cos(Z_b\cos\omega_b t + \gamma(t) + \alpha)], \qquad (9)$$

where $\gamma(t) = (4\pi/\lambda_0)a(t)$. Intensity change $I_M(t)$ of the output beam of the SWS light source is detected with photodiode 2 (PD2). The interference signal is processed in a feedback signal generator (FSG) shown in Fig.7. Signal S(t) is written as

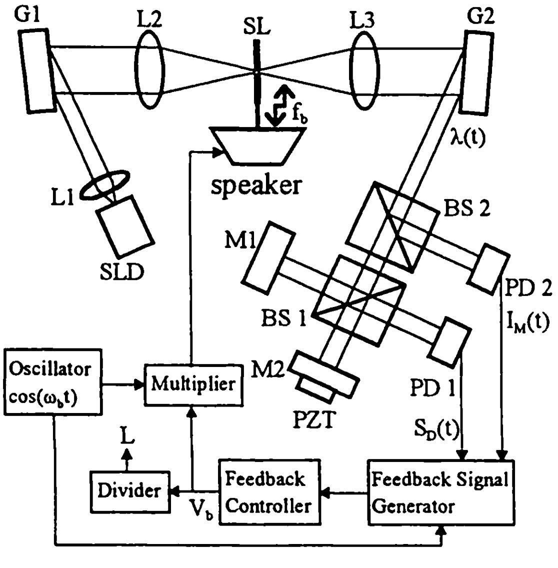

Fig.6 Configuration of SWS-SLD interferometer for real-time distance measurement.

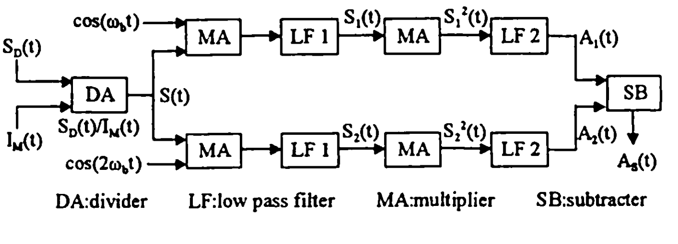

Fig.7 Block diagram of feedback signal generator.

$$S(t) = S_D(t)/I_M(t)$$
$$= A + B\cos\Phi(t)[J_0(Z_b) - 2J_2(Z_b)\cos 2\omega_b t + \cdots]$$
$$-B\sin\Phi(t)[2J_1(Z_b)\cos\omega_b t + 2J_3(Z_b)\cos 3\omega_b t + \cdots] . \quad (10)$$

where $\Phi(t)=\gamma(t)+\alpha$. Amplitude and frequency of the triangular waveform a(t) are adjusted so that the following conditions are satisfied:

$$\Im\{\cos\Phi(t)\}=0, \quad \Im\{\sin\Phi(t)\}=0 \qquad |\omega|>\omega_b/2 . \quad (11)$$

where $\Im$ means Fourier transformation between t and ω variables. Frequency components in the range of $0<\omega<\omega_b/2$ are extracted from signals $S(t)\times\cos\omega_b t$ and $S(t)\times\cos 2\omega_b t$ with low-pass filter 1 (LF1) of cutoff frequency $f_{c1}=f_b/10=(\omega_b/2\pi)/10$ to produce the following signals, respectively:

$$S_1(t)=gJ_1(Z_b)\sin\Phi(t), \quad S_2(t)=gJ_2(Z_b)\cos\Phi(t) . \quad (12)$$

where g is a constant determined the electric circuits. Signals $\sin\Phi(t)$ and $\cos\Phi(t)$ contain sinusoidal waves of frequency f_a caused by vibration a(t) of mirror M2. By feeding signals $S_1^2(t)$ and $S_2^2(t)$ to low-pass filter 2 (LF2) of cutoff frequency $f_{c2}=f_a/10$, we obtain signals $A_1(t)=g^2J_1^2(Z_b)$ and $A_2(t)=g^2J_2^2(Z_b)$, respectively. Finally we make the following feedback signal with a subtracter (SB):

$$A_S(t)=g^2[\{J_1(Z_b)\}^2-\{J_2(Z_b)\}^2] . \quad (13)$$

When $A_S = 0$, that is, at $Z_b=2.63$, from Eq.(4) we have the relation

$$L=2.63\lambda_0^2/2\pi b=K/b . \quad (14)$$

We detect signal A_S for a given value of L, and change the value of b with a feedback control so that A_S becomes zero. The value of L is obtained from the value of b at $A_S=0$ using Eq.(14).

4.2. EXPERIMENTS

We constructed an interferometer shown in Fig.6. The frequency f_b was 400 Hz, and the frequency f_a of 14 Hz was generated from vibration a(t) of 4 Hz. Feedback controller (FC) performed proportional and integral control. A signal applied to the speaker was $V_b\cos\omega_b t$, and the amplitude V_b was a sum of the output of FC and a dc voltage. Figure 8 shows waveforms of $S_1(t)$ and $S_2(t)$ obtained from the interference signal in the circuits of FSG. The length of a continuous part of the sinusoidal waves in the signals was two periods. Figure 9 shows a waveform of $S_1^2(t)$ and the output $A_1(t)$ of LF2 where there is a little fluctuation in amplitude with the period of 250 msec. This fluctuation was caused by the discontinuous movement of vibration a(t). Figure 10 shows signal $V_b(t)$ obtained when the feedback control worked to keep A_S at zero. A measured value of V_b was obtained by averaging $V_b(t)$ over time.

To determine the value of OPD it is required that the measured value of V_b is converted into the value of b. We tried to obtain a relationship between V_b and b from experiments. We detected an interference signal

$$S(t)=A+B\cos[Z_b\cos\omega_b t+\alpha] , \quad (15)$$

by not giving the vibration to mirror M2, and processed the signal in a personal computer to obtain the value of Z_b with the method of sinusoidal phase-modulating interferometry described in Ref.13. For a fixed value of V_b, we measured values of Z_b for different values of change of ΔL in OPD. The measured result at V_b = 4.0 V is shown in Fig.11. The measurement was repeated five times at a value of ΔL intervals of a few tens of seconds. From Fig.11 a

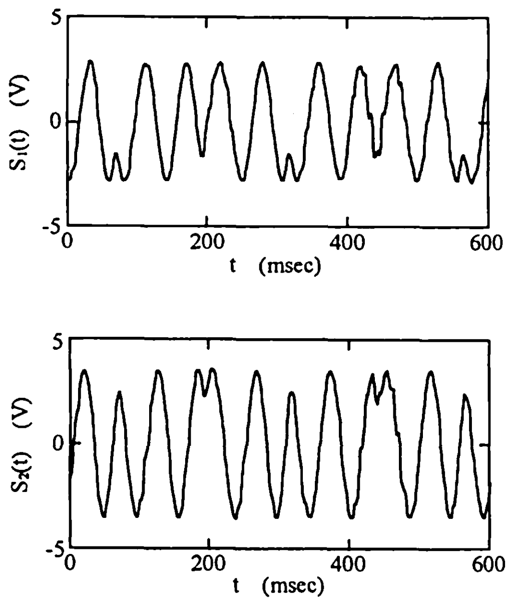

Fig.8 Waveforms of $S_1(t)$ and $S_2(t)$.

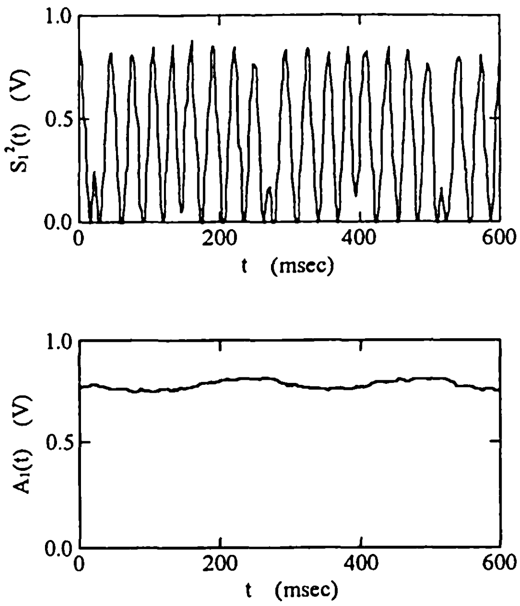

Fig.9 Waveforms of $S_1{}^2(t)$ and$A_1(t)$.

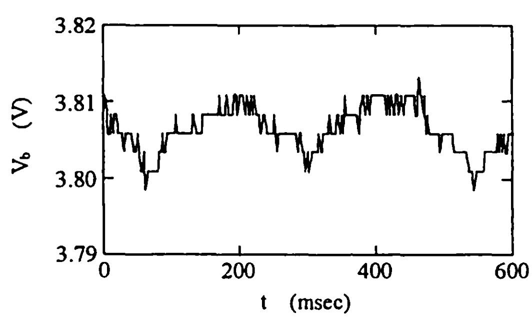

Fig.10 Waveforms of $V_b(t)$.

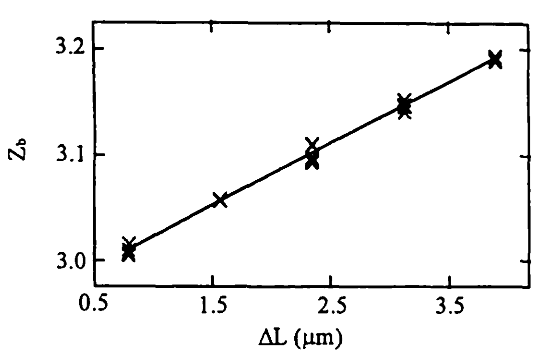

Fig.11 ΔL vereus Z_b at V_b=4.0 V.

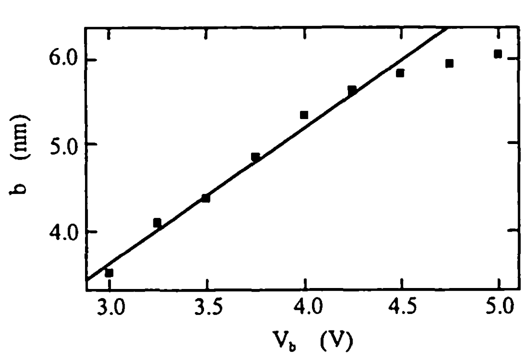

Fig.12 Relationship between V_b and b.

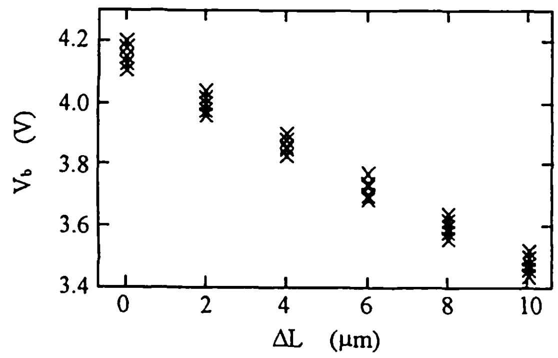

Fig. 13. Change ΔL of OPD versus V_b.

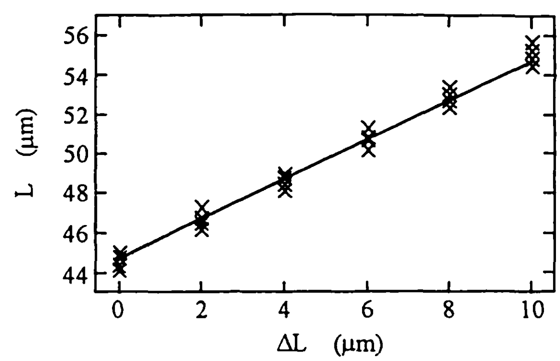

Fig. 14. Measured vales of OPD for ΔL

linear relationship between Z_b and L was obtained and the value of b was determined. This determination was repeated different values of V_b, as shown in Fig.12. In the region of V_b<4.5V, a linear relation

$$b=1.58V_b-1.01 \tag{16}$$

was obtained.

We tried to measure changes of OPD due to displacements of mirror M1. At the first position of ΔL=0, V_b was about 4.15 V when signal A_S was kept at zero by the feedback control. We increased OPD intervals of 2 μm and measured values of V_b. The result is shown in Fig.13 where five measured values are plotted for a value of ΔL. Values of L were obtained from the values of V_b shown in Fig.13 according to Eqs.(16) and (14), as shown in Fig.14. Deviations of the measured values of L from the linear line leads to measurement error of about 0.5 μm except at ΔL= 10 μm. Measurement range is about ±4 μm from L= 49 μm.

5. CONCLUSIONS

The SWS light source using a SLD was simple for getting a large scanning width and exact for changing the scanning width. In the step-profile measurements the measurement error in L_z obtained from the sinusoidal phase-modulation amplitude Z_b was 104 nm at the scanning width 2b of 13 nm. The fractional value L_α of the OPD was also obtained from the conventional phase α of the interference signal. 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 nm were measured exactly. In the real-time distance measurements, the electric circuits extracted the amplitude Z_b from the interference signal to which the triangular phase-modulation was added. The amplitude Z_b was kept at 2.63 for changes of OPD by controlling the scanning width 2b with the feedback system. An OPD longer than a wavelength was measured from the value of b with an accuracy of about 0.5μm in the region from 45 μm to 54 μm. The value of b changed from 4nm to 6 nm in the range of OPD.

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