Sinusoidal wavelength-scanning interferometer with double feedback control for real-time measurement of one-dimensional step-profile

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ABSTRACT

An optical path difference (OPD) and the amplitude of sinusoidal wavelength-scanning are controlled with double feedback control system in an interferometer, so that a ruler marking every wavelength and a ruler with scales smaller than a wavelength are generated. These two rulers enable us to measure an OPD longer than a wavelength in real time. A linear CCD image sensor is used to measure one-dimensional step-profiles in real-time. Two different step profiles with a step height of 1 μm and 20 μm, respectively, are measured with the measurement error less than 8 nm. Measuring time for one measuring point is 0.04 s.

Keywords: interferometer, wavelength-scanning, step-profile measurement, feedback control

1. INTRODUCTION

To measure a surface profile with step height larger than half a wavelength, wavelength-scanning interferometers have been used, where external cavity laser diodes[1], a dye laser[2], a Ti:Sapphire laser[3], and broad spectrum sources with Fabry-Perot etalon[4-6] were employed to produce a scanning width more than 10 nm. We have proposed a sinusoidal wavelength-scanning light source using a superluminescent diode (SLD) with gratings and a vibrating slit as an inexpensive light source.[7] Sinusoidal wavelength-scanning (SWS) is unique in that it produces a time-varying interference signal which contains a phase-modulation amplitude Z_b due to the SWS besides the conventional phase α. By detecting the values of Z_b and α exactly and by combing them, an optical path difference (OPD) longer than a wavelength can be measured with a high accuracy of the order of nanometer.[8] Since the interference signals produced by sinusoidal-phase modulation or SWS are continuous with time, operation of the phase lock can be easily carried out with feedback control system.[9] By keeping the two values of Z_b and α at specified values with double feedback control, we generates a ruler marking every wavelength and a ruler with scales smaller than a wavelength in the SWS interferometer. These two rulers enables us to measure an OPD longer than a wavelength in real time.[10]

In this paper we apply the SWS interferometer with double feedback control to measure one-dimensional step-profiles. Step-profile measurements with wavelength-scanning interferometers are generally made using a computer for processing the interference signal. We process the interference signal with electric circuits and feedback controls so that step-profiles are obtained in real time. Although the measurement is limited to one-dimensional step-profiles, the real-time measurement is useful, for an example, to a high-speed test of a step height in industrial products.

The principle of the SWS interferometer with double feedback control is reviewed first. Detection of the interference signal with a linear CCD image sensor is explained, and characteristics of the feedback controls involving the CCD image sensor is analyzed. In experiments a ruler marking every wavelength is obtained, and one-dimensional step-profile measurements are carried out for two different step heights of 1 μm and 20 μm.

2. PRINCIPLE

Figure 1 shows a SWS interferometer using a SLD for real-time 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 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, and it is expressed by

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

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. The intensity of the beam changes with time, and it is denoted by $I_M(t)$.

The reference beam is reflected by reference mirror M_R which is displaced by piezoelectric transducer PZT. Interference intensity on the CCD image sensor is denoted by $I_M(t)S(t)$. Although the CCD image sensor detects integration values of $I_M(t)S(t)$, it is assumed that we obtain the following interference signal by dividing the detected integration values by $I_M(t)$, which is detected with photodiode PD:

$$S(t) = A + B\cos(Z_b\cos\omega_b t + \alpha)\ , \qquad (2)$$

where A and B are constants, and

$$Z_b=(2\pi b/\lambda_0^2)L\ , \qquad (3)$$

$$\alpha=-(2\pi/\lambda_0)L\ , \qquad (4)$$

where L is an OPD.

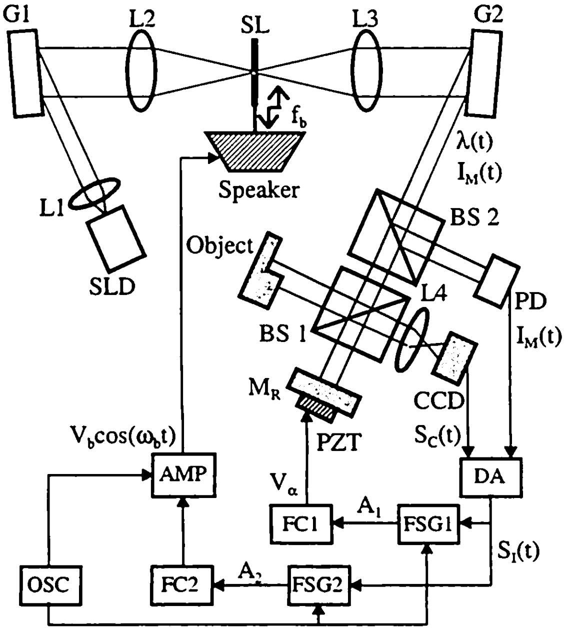

Fig.1 SWS interferometer for real-time step-profile measurement.

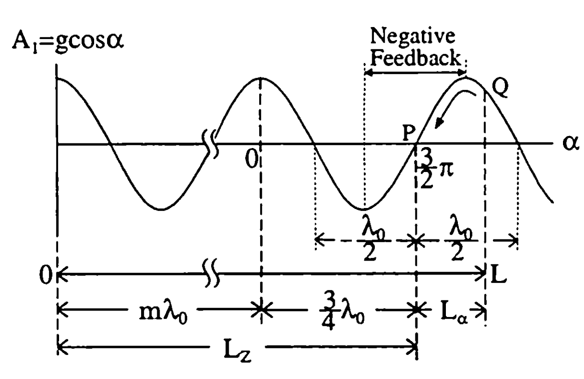

Fig.2 Change in the OPD by feedback, which keeps phase α at 3π/2.

First, we explain how to measure a fractional value of OPD L with a feedback control. By multiplying S(t) by $\cos(2\omega_b t)$ and using a low pass filter feedback signal generator FSG1 produces a feedback signal

$$A_1=BJ_2(Z_b)\cos\alpha=g\cos\alpha\,, \qquad (5)$$

where J_2 is the second-order Bessel function. Feedback controller FC1 produces voltage V_α applied to the PZT. The feedback system controls the position of reference mirror M_R or the OPD so that the feedback signal A_1 becomes zero. A change in the OPD caused by this feedback control is illustrated in Fig.2. First the OPD is L and the position of signal A_1 is at point Q. The position of signal A_1 is moved to a stable point P by the feedback control. Phase α becomes $3\pi/2+2m\pi$, where m is an integer. The OPD at the stable point of the feedback control is given by

$$L_z=L-L_\alpha=3\lambda_0/4+m\lambda_0\,. \qquad (6)$$

L_α is a fractional value of OPD L to be measured. The range of L_α is approximately between $-\lambda_0/2$ and $\lambda_0/2$. If an initial condition is given in which $L_\alpha=0$ at $V_\alpha=0$, L_α can be obtained by measuring the applied voltage V_α and using the relation of $L_\alpha=\beta V_\alpha$, where β is a constant. Its measurement accuracy is of the order of nanometers.

Next, we explain how to measure an integer multiple of the wavelength in the OPD L. Since the phase α is kept at $3\pi/2$ by feedback control, the interference signal is

$$S(t)=A-B\sin(Z_b\cos\omega_b t)\,, \qquad (7)$$

where,

$$Z_b=(2\pi b/\lambda_0^2)L_z\,. \qquad (8)$$

Signal S(t) is sampled with sample holders when $\cos\omega_b t=1$ and $\cos\omega_b t=-1$ so that signals $S_1= A-B\sin Z_b$ and $S_{-1}= A+B\sin Z_b$ are obtained. From these signals a feedback signal

$$A_2= S_{-1}- S_1=2B\sin Z_b \qquad (9)$$

is generated in feedback signal generator FSG2. Feedback controller FC2 produces voltage ΔV_b that is fed to voltage control amplifier VCA and determins the amplitude V_b of the voltage applied to the speaker. The feedback system controls the amplitude V_b or the amplitude b of the wavelength scanning so that the signal A_2 becomes zero. This makes modulation amplitude Z_b equal to π. Then we have:

$$b=\lambda_0^2/2L_z=2\lambda_0/(4m+3)\,. \qquad (10)$$

The values of b are discrete, corresponding to the values of m. Since amplitude b is proportional to amplitude V_b with a form of $b=D_1V_b+D_0$, the values of V_b are also discrete. These discrete values of the amplitude V_b at which Z_b is equal to π are refereed to as stable points of V_b.

The measured value of b is obtained from the measured value of V_b, and a measured value of L_Z is calculated by the relation of $L_Z=\lambda_0^2/2b$. Since L_Z is given by Eq.(6), the following value is calculated by using the measured value of L_Z:

$$m_c = (L_z - 3\lambda_0/4)/\lambda_0\,. \qquad (11)$$

Integer m can be decided by rounding off the value of m_c to an integer if a measurement error of L_z is smaller than $\lambda_0/2$. Finally the OPD is calculated with

$$L= 3\lambda_0/4+m\lambda_0+L_\alpha\,. \qquad (12)$$

Note that once the relation between the integer values of m and the stable points of V_b is given, the OPD can be obtained directly from Eq.(12) without calculation of m_c. This means that the stable points of V_b are regarded as a ruler marking every a wavelength and the voltage V_α is regarded as a ruler with scales smaller than a wavelength. The calibration of the ruler produced by the voltage V_b can be made automatically by double feedback control by changing the OPD at intervals of approximately a wavelength.

3. SIGNAL DETECTION WITH A CCD IMAGE SENSOR

A linear CCD image sensor is used to measure step-surface profiles. The CCD image sensor detects a distribution of interference intensity on a number of cells at intervals of the integration time T_A, as shown in Fig.3. Number of the cells on which intensity is detected is N. Intensity on a specified cell is sampled and held within the integration time T_A. This sample-hold is repeated N_R times, so that an interference signal whose length is $T_m=N_RT_A$ is obtained for one measuring point. This generation of the interference signal is shown in Fig.3, where number of the specified cell is 1. After detection for a specified cell, the point of the sample-hold is moved to the adjacent cell to scan the sampling points.

The integration time T_A is taken to be T_b/p, where $T_b=1/f_b$, and p is an integer. The CCD image sensor integrates $S(t)I_M(t)$ over the period of T_A and outputs the integrated value. At the same time photodiode PD detects $I_M(t)$, and the integrated value is divided by $I_M(t)$. In this case integration values of S(t) can be obtained on the assumption that $I_M(t)$ is almost constant within the period of T_A. Integer p is taken to be 16 or 32 to satisfy this assumption. Then amplitude of frequency component of mf_b contained in the integration values of S(t) is attenuated by coefficient of $[\sin(m/p)\pi]/[(m/p)\pi]$, where m is an integer. Since feedback signal A_1 is generated from frequency component of $2f_b$, the amplitude of A_1 is effected by this attenuation due to the integral detection of the CCD image sensor. Feedback signal A_2 is generated from the two values produced by integrating S(t) over the period of T_A whose central positions satisfy $\cos\omega_b t=1$ and $\cos\omega_b t=-1$, respectively. In this case feedback signal A_2 is given by

$$A_2 = 2B\sum_{n=0}^{\infty}(-1)^n J_{2n+1}(Z_b)\frac{\sin[\{(2n+1)(2\pi/p)\}]}{(2n+1)(2\pi/p)} \quad . \qquad (13)$$

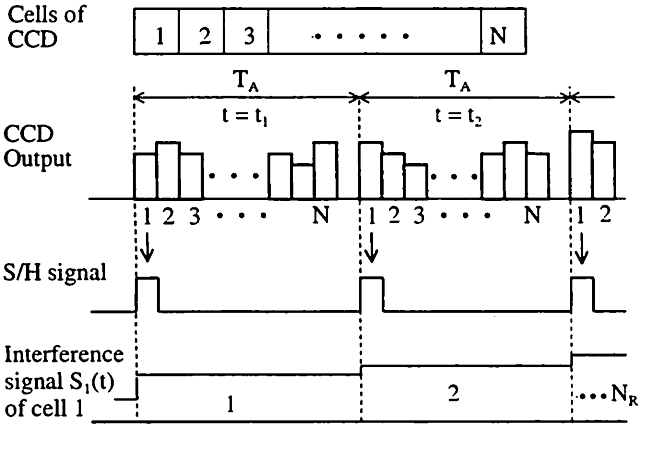

Fig.3 Generation of interference signal for a specified cell of CCD image sensor.

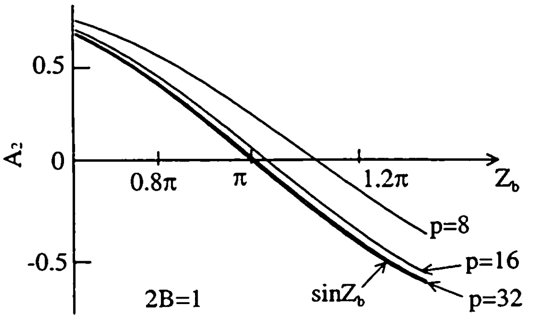

Fig.4 Feedback signal A_2 when the integration time T_A is T_b/p.

When p is infinite, Eq(13) becomes $2B\sin Z_b$ given by Eq.(9). Figure 4 shows the values of Eq.(13) for different values of p, where 2B=1.

4. EXPERIMENTS

4.1. Fundamental Characteristics

An interferometer for real-time 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 focus length of lens L1 and L2 was 25 mm, and the width of slit SL was about 100 μm. The frequency $f_b=\omega_b/2\pi$ was 400 Hz.

We tried to detect the stable points of V_b where a photo diode was used instead of the CCD image sensor. Gauge blocks fixed on a stage was used as an object. We displaced the object with a micrometer to change the OPD. By increasing the OPD at intervals of approximately one wavelength, we could move a stable point of V_b to the next point sequentially. We detected 83 stable points of V_b whose order is denoted by the number N of 0-82, as shown in Table 1.

We need the relation between b and V_b to convert the measured value of V_b into a value of b. We fixed the value of V_b, and detected the interference signal given by Eq.(7), in which the feedback control of V_b did not work. We calculated the value of Z_b from the interference signal with a computer by the method of sinusoidal phase modulating interferometry described in Ref.11. By changing the OPD L, we found the relation of $Z_b = \gamma L$. Since $\gamma = 2\pi b/\lambda_0^2$, we could calculate the value of b. By changing the value of V_b, we obtained a relation of $b=1.59V_b+0.059$.

We tried to decide integer m. We converted stable points of V_b shown in Table 1 into values of b with the relation of $b=1.59V_b+0.059$, and obtained measured values of $L_Z=\lambda_0^2/2b$. The values of m_c were calculated from the measured values of L_Z with Eq.(11). Since the absolute value of the difference was less than 0.5 in the region of N=20-70, we could determine the values of integer m. From this result, the relation of m=46+N was obtained, as shown in Table 1. The measurement range was from 36μm to 101 μm.

Table 1 Stable points of V_b and integer m

N	V_b	m	N	V_b	m	N	V_b	m	N	V_b	m	N	V_b	m
0	4.86	46	17	3.80	63	34	3.05	80	51	2.51	97	68	2.13	114
1	4.78	47	18	3.75	64	35	3.02	81	52	2.48	98	69	2.12	115
2	4.68	48	19	3.70	65	36	2.98	82	53	2.46	99	70	2.10	116
3	4.59	49	20	3.66	66	37	2.94	83	54	2.44	100	71	2.08	117
4	4.53	50	21	3.61	67	38	2.91	84	55	2.41	101	72	2.06	118
5	4.46	51	22	3.57	68	39	2.87	85	56	2.39	102	73	2.05	119
6	4.39	52	23	3.52	69	40	2.84	86	57	2.37	103	74	2.04	120
7	4.33	53	24	3.48	70	41	2.81	87	58	2.34	104	75	2.02	121
8	4.27	54	25	3.43	71	42	2.77	88	59	2.32	105	76	2.01	122
9	4.20	55	26	3.38	72	43	2.74	89	60	2.29	106	77	2.00	123
10	4.14	56	27	3.33	73	44	2.71	90	61	2.27	107	78	1.99	124
11	4.09	57	28	3.29	74	45	2.68	91	62	2.25	108	79	1.98	125
12	4.03	58	29	3.25	75	46	2.65	92	63	2.23	109	80	1.96	126
13	3.98	59	30	3.21	76	47	2.62	93	64	2.21	110	81	1.95	127
14	3.93	60	31	3.17	77	48	2.59	94	65	2.19	111	82	1.93	128
15	3.88	61	32	3.13	78	49	2.56	95	66	2.17	112			
16	3.84	62	33	3.09	79	50	2.53	96	67	2.15	113			

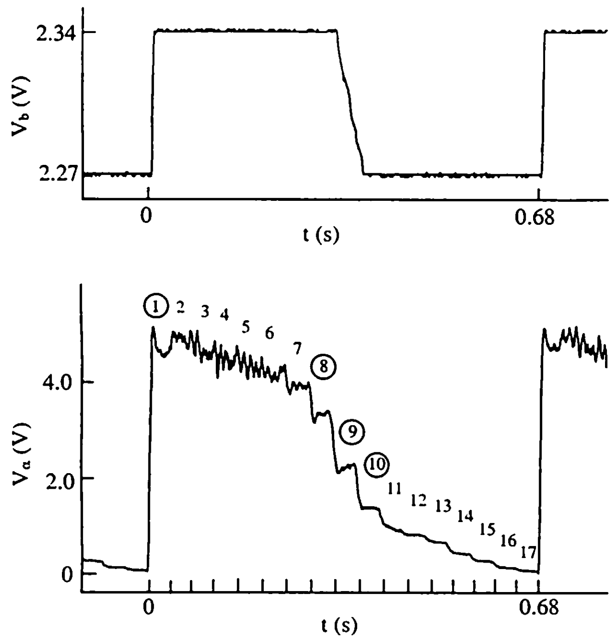

Fig.5 Detected signals of V_b and V_α for step height of 1μm.

Table 2 Measured Values for step height of 1μm.

Cell No.	V_b(V)	V_α(V)	m	L_α (nm)	L (nm)
5	2.34	4.31	104	359	82758
6	2.34	4.13	104	344	82743
7	2.34	3.98	104	332	82731
8	2.34	3.35	104	279	82678
9	2.29	2.28	106	190	84173
10	2.27	1.61	107	134	84910
11	2.27	0.92	107	77	84853
12	2.27	0.78	107	65	84841
13	2.27	0.69	107	50	84826

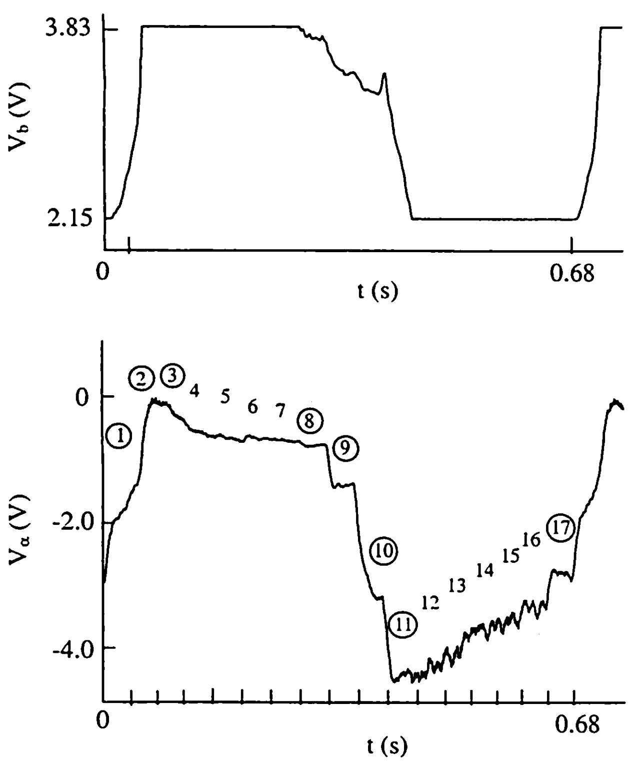

Fig.6 Detected signals of V_b and V_α for step height of 20μm.

Table 3 Measured Values for step height of 20μm.

Cell No.	V_b(V)	V_α(V)	m	L_α (nm)	L (nm)
5	3.38	-0.67	62	-56	49067
6	3.38	-0.69	62	-57	49066
7	3.38	-0.70	62	-58	49065
8	3.66	-0.81	66	-68	52224
9	3.29	-1.37	74	-114	58516
10	3.09	-3.19	79	-266	62326
11	2.65	-4.44	92	-370	72522
12	2.15	-4.30	113	-357	89171
13	2.15	-4.04	113	-337	89192
14	2.15	-3.71	113	-309	89220

4.2. Step-Profile Measurement

We tried to measure a step profile which was made by sticking two gauge blocks of different thickness together. We changed the value of p and made the measurements. When p=8, the feedback control of V_α was unstable because $I_M(t)$ was not regarded to be almost constant within the period of $T_A=T_b/8$. When p=32, the measurement was impossible because the amplitude of the interference signal detected with the CCD image sensor was too small. The most appropriate value of p was 16. Since a low-pass filter with cutoff frequency of $f_b/10$ was used in the feedback control of V_α, measuring time of $T_m=N_R T_A$ for one measuring must be longer than $10T_b$. This means that number of the repetition N_R is must be more than 160 at p=16. When N_R=128, the feedback control of V_α was unstable. When N_R =512, the measurement results were almost the same as N_R=256. Therefore the most suitable condition was that p=16, N_R=256, and T_m= 0.04 s. Number of the measuring points N was 17, and the interval of measuring points was 119 μm on the object surface.

The step height in the two gauge blocks stuck together was 1μm. We detected signals $V_b(t)$ and $V_\alpha(t)$ as shown in Fig.5. Number of the cell that represents the position of the measuring point is indicated above the signal of $V_\alpha(t)$. The number surrounded with a circle represents the measuring point where exact measurement did not made. Table 2 shows the measured values at the cells of 5-13. The values of m were determined with Table 1, and the values of $L_\alpha(t)$ were calculated with relationship $L_\alpha=\beta V_\alpha$, where β=83.37 nm/V. Exact measured values cannot be obtained at the cells of 8-10 around the boundary of the two gauge blocks. When the measuring point returns to the first measuring point (cell 1) from the last one (cell 17), exact measurements also cannot be made at cell 1. The measured height of the step between cells 7 and 11 was 1.061 μm. The feedback control of V_α was sensitive to the amplitude of the interference signal. When the amplitude of signal $A_1$was not suitable to feedback controller FC1, a large fluctuation occured in the signal of V_α between cells 3 and 6, as shown in Fig.5. The measurement error caused by fluctuations of V_α was estimated to be less than 8 nm.

Next we measured a step profile with a step height of 20 μm. The results are shown in Fig.6 and Table 3. Compared with the results shown in Fig.5, a longer time is required to reach the stable vales of V_b and V_α when the measuring point returns to the first measuring point from the last one. Effect of the boundary of the two gauge blocks also becomes stronger. The measured height of the step between cells 7 and 12 was 20.053 μm.

5. CONCLUSION

The SWS light source using the SLD was simple for generating a large scanning width and exact for changing the scanning width. The OPD and the amplitude of the sinusoidal wavelength-scanning were controlled with the double feedback control system, so that a ruler marking every wavelength and a ruler with scales smaller than a wavelength could be generated. These two rulers enabled us to measure an OPD longer than a wavelength in real time. The linear CCD image sensor was used to measure one-dimensional step-profiles in real-time. The most suitable values of p and N_R were made clear. Two different step profiles with a step height of 1 μm and 20 μm, respectively, were measured with the measurement error less than 8 nm. Measuring time for one measuring point was 0.04 s, and the number of the measuring points were 17. The measurement range in the OPD was from 36 μm to 101 μm corresponding to the scanning width from 14 nm to 6 nm.

REFERENCES

1. H.J.Tiziani, B.Franze, and P.Haible, "Wavelength-shift speckle interferometry for absolute profilometry using mode-hope free external cavity diode laser," J. Mod. Opt. 44, 1485-1496 (1994).
2. S.Kuwamura, I.Yamaguchi, "Wavelength scanning profilometry for real-time surface shape measurement," Appl. Opt. 36, 4473-4482 (1997).
3. A.Yamamoto, C.C.Kuo, K.Sunouchi, S.Wada, I.Ymaguchi, and H.Tashiro, "Surface shape measurement by wavelength scanning interferometry using an electronically tuned Ti:sapphire laser," Opt. Rev. 8, 59-63 (2001).
4. K.Tsuji, O.Sasaki, and T.Suzuki, "Sinusoidal phase-modulating superluminescent diode interferometer with

Fabry-Perot etalone for step-profile measurement," Opt. Rev. 6, 62-67 (1999).
5. M.Kinoshita, M.Takeda, H.Yago, Y.Watanabe, and T.Kurokawa, "Optical frequency-domain microprofilometry with a frequency-tunable liquid-crystal Fabry-Perot etalon device," Appl. Opt. 38, 7063-7068 (1999).
6. D.S.Mehta, M.Sugai, H.Hinosugi, S.Saito, M.Takeda, T.Kurokawa, H.Takahashi, M.Ando, M.Shishido, and T.Yoshizawa, "Simultaneous three-dimensional step-height measurement and high-resolution tomographic imaging with a spectral interferometric microscope," Appl. Opt. 41, 3874-3885 (2002).
7. O.Saski, K.Tsuji, S.Sato, T.Kuwahara, and T.Suzuki, "Sinusoidal wavelength-scanning interferometers," SPIE Vol.3478, 37- 44 (1998).
8. O.Sasaki, N.Murata, and T.Suzuki, "Sinusoidal wavelength-scanning interferometer with a superluminescent diode for step-profile measurement," Appl. Opt. 39, 4589-4592 (2000).
9. T.Suzuki, O.Sasaki, T.Maruyama, "Phase-locked laser diode interferometry for surface profile measurement," Appl. Opt. 28, 4407-4410 (1989).
10. O.Sasaki, K.Akiyama, and T.Suzuki, "Sinusoidal-wavelength-scanning interferometer with double feedback control for real-time distance measurement," Appl. Opt. 41, 3906-3910 (2002).
11. O.Sasaki and H.Okazaki, "Sinusoidal phase modulating interferometry for surface profile measurement," Appl. Opt. 25, 3137-3140 (1986).