Sinusoidal wavelength-scanning interferometric reflectometry

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ABSTRACT

We propose an interferometric reflectometry using a sinusoidal wavelength-scanning tunable laser diode to detect positions and profiles of multiple reflecting surfaces. An objective signal extracted from an interference signal contains the modulation amplitude Z and the phase α which are related to positions and profiles of multiple reflecting surfaces, respectively. By using values of the objective signal at special times, we can produce an image intensity which shows where the reflecting surfaces exist. To obtain exact values of Z or values of α the objective signal is estimated with a conjugate gradient method. Experiments results show that a resolution of two-optical path difference (OPD) in the image intensity is 87 μm, and a final OPD accuracy is 2 μm and 8 μm for the two and three reflecting surfaces, respectively, in the case of the wavelength-scanning width of 7 nm. Profiles of front and rear surfaces of a silica glass plate with thickness of 20 μm are measured with an accuracy of about 10 nm.

Keywords: reflectometry, interferometry, wavelength scanning, thickness measurement, surface profile measurement

1. INTRODUCTION

Reflectometers with a high depth resolution based on interferometry have been developed recently. There are two methods called optical coherence-domain refectometry (OCDR) and optical frequency-domain refelectometry (OFDR). OCDR achieves a high depth resolution by scanning a reference mirror in a low-coherence interferometer.[1-4] In OFDR wavelength scanning of a light source is required to achieve a high depth resolution instead of scanning the reference mirror. The depth resolution is determined mainly by the wavelength-scanning width. In the case of wavelength scanning in space domain[5], a light source with a large spectral width is used and interference intensities for the number of wavelength are separated along one-dimensional direction with a spectrometer. Since use of the spectrometer limits the detection region of the interference signal to a line, one-dimensional scanning of an object is needed in principle. In the case of wavelength scanning in time domain, scanning of an object is not needed in principle. To obtain a large wavelength-scanning width external-cavity tunable laser diodes (TLDs) were widely used.[6, 7] When TLDs are used for a linear wavelength scanning, a deviation from the linearity in the scanning is a problem for achieving a high depth resolution. In Ref.6 the deviation from the linearity was detected with another interferometer to compensate the deviation appearing in the reflectometer.

In this paper we propose OFDR using a sinusoidal wavelength scanning (SWS) in a TLD. A mirror in the external cavity is vibrated rotationally by a galvanometer optical scanner to scan the wavelength sinusoidally. Since the sinusoidal rotation is given more exactly than the linear rotation, an accurate SWS is performed.[8] We describe how to obtain an image intensity that provides rough values of the positions of reflecting surfaces, and how to estimate the interference signal using the rough values of the positions as initial values. The estimated signal provides exact values of the position and the surface profiles.

2. PRINCIPLE

A configuration of the setup is shown in Fig.1. The light source is a sinusoidal wavelength-scanning tunable laser diode (SWS-TLD) whose wavelength $\lambda(t)$ is expressed as $\lambda_0+b\cos(\omega_b t)$. The reference wave is also sinusoidally phase-modulated with a vibrating mirror whose movement is expressed as $a\cos(\omega_c t + \theta)$.[9] An object has two surfaces A and B whose positions are expressed by optical path difference (OPD) L_A and L_B, respectively. There are two object lights which are reflected by surface A and B. A time-varying interference signal is given by

$$S(t)=A_A\cos[Z_c\cos(\omega_c t + \theta)+Z_A\cos(\omega_b t)+\alpha_A] +A_B\cos[Z_c\cos(\omega_c t + \theta)+Z_B\cos(\omega_b t)+\alpha_B] , \quad (1)$$

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

$$Z_A=WL_A, \quad Z_B=WL_B, \quad W=2\pi b/\lambda_0^2 . \tag{2}$$

Through processing the interference signal using the Fourier transformation, we obtain an objective signal

$$S_b(t)=A_A\sin[Z_A\cos(\omega_b t)+\alpha_A] + A_B\sin[Z_B\cos(\omega_b t)+\alpha_B] . \tag{3}$$

For simplicity we explain how to obtain a value of Z_A from an objective signal of $S_b(t)=\sin[Z_A\cos(\omega_b t)+\alpha_A]$. We use the special time t_i which satisfies a equation

$$Z\cos(\omega_b t_i)= -Z + (\pi/2)(i-1), \quad i=1, 2, 3, \cdots, \tag{4}$$

At $Z_A/Z = 1, 3, 5, 7, \cdots$, we have the following equations:

$$S_b(t_1) = S_b(t_5) = \cdots = \sin\gamma ,$$
$$S_b(t_2) = S_b(t_6) = \cdots = \begin{cases} -\cos\gamma & (Z_A/Z = 3, 7, \cdots) \\ \cos\gamma & (Z_A/Z = 1, 5, \cdots) \end{cases} ,$$
$$S_b(t_3) = S_b(t_7) = \cdots = -\sin\gamma ,$$
$$S_b(t_4) = S_b(t_8) = \cdots = \begin{cases} \cos\gamma & (Z_A/Z = 3, 7, \cdots) \\ -\cos\gamma & (Z_A/Z = 1, 5, \cdots) \end{cases} . \tag{5}$$

where $\gamma = -Z + \alpha_A$. At $Z_A/Z = 2$, we have

$$S_b(t_1) = S_b(t_3) = S_b(t_5) = S_b(t_7) = \cdots = \sin\gamma ,$$
$$S_b(t_2) = S_b(t_4) = S_b(t_6) = S_b(t_8) = \cdots = -\sin\gamma . \tag{6}$$

At $Z_A/Z = 4, 6, \cdots$, we have

$$S_b(t_i) = \sin\gamma , \quad i=1, 2, 3, \cdots . \tag{7}$$

When Z_A/Z is not an integer, $S_b(t_i)$ has different values for $i=1, 2, 3, \cdots$. Considering the characteristics of $S_b(t_i)$, we define an image intensity as follows:

$$I(L) = (1/M)|S_b(t_1) - S_b(t_3) + S_b(t_5) - S_b(t_7) + \cdots|^2 + (1/M)|S_b(t_2) - S_b(t_4) + S_b(t_6) - S_b(t_8) + \cdots|^2 , \tag{8}$$

where M is the maximum number of i. The image intensity has a maximum value at $Z_A/Z = 1, 3, 5, \cdots$, and is expected to be almost zero except the region near $Z_A/Z = 1, 3, 5, \cdots$. We can obtain a rough value of Z_A from the peak position of the image intensity. For the objective signal $S_b(t)$ given by Eq.(3), we can also obtain rough values of Z_A and Z_B form the peaks of the image intensity in the condition of $Z_B/3<Z_A<Z_B$.

Next we explain how to obtain exact values of Z_A, Z_B, α_A, and α_B. We estimate a signal

$$\hat{S}_b(t) = \hat{A}_A \sin[\hat{Z}_A \cos(\omega_b t) + \hat{\alpha}_A] + \hat{A}_B \sin[\hat{Z}_B \cos(\omega_b t) + \hat{\alpha}_B] \tag{9}$$

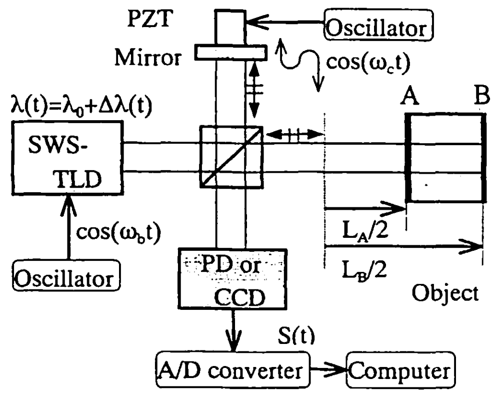

Fig.1 SWS interferometric reflectometer.

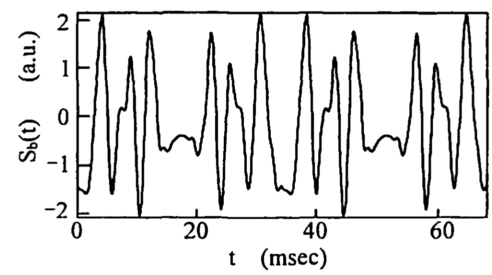

Fig.2 Objective signal $S_b(t)$.

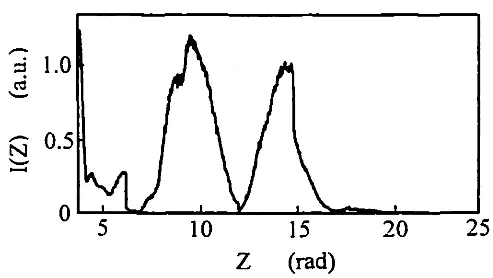

Fig.3 Image intensity I(z).

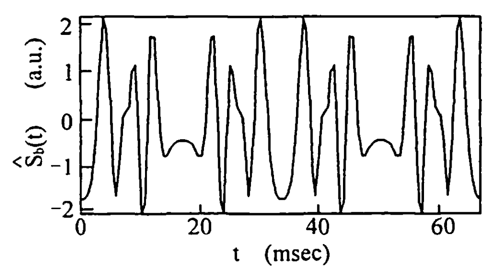

Fig.4 Estimated signal $\hat{S}_b(t)$.

for the signal $S_b(t)$ actually detected by defining an objective function

$$B = \sum_{n=1}^{N} \left| S_b(t_n) - \hat{S}_b(t_n) \right|^2 , \tag{10}$$

where t_n means discrete time for the signals. We search values of the variables in Eq.(6) that minimize B with the conjugate gradient method. The rough values of Z_A and Z_B obtained from the image intensity are used as the initial values for the estimation. The positions of surface A and B are given by $L_A = \hat{Z}_A/W$ and $L_B = \hat{Z}_B/W$ in OPD, respectively. The front surface profile r_A and the rear surface profile r_B are given by

$$r_A = (\lambda_0/4\pi)\alpha_A , \quad r_B = (\lambda_0/4\pi n_R)[(n_R - 1)\alpha_A + \alpha_B] , \tag{11}$$

where the refractive index n_R of the object is constant.

3. EXPERIMENTS

Experiments were carried out in the setup shown in Fig.1. The wavelength of SWS-TLD was scanned by sinusoidally rotating a mirror in the external cavity with an angular frequency ω_b.

First we tried to measure a thickness of a vinyl sheet having two surfaces A and B as shown in Fig.1. We detected an interference signal S(t) for one point of an object with a photodiode. The frequencies of $\omega_b/2\pi$ and $\omega_c/2\pi$ were 30 Hz and 1920 Hz, respectively. Figures 2 and 3 show the objective signal $S_b(t)$ and the image intensity I(z) obtained from the objective signal $S_b(t)$, respectively. It is recognized from the image intensity I(z) that there are two surfaces at $Z_A = 9$ rad and $Z_B = 14$ rad. These rough values became the initial values for estimating the signal $\hat{S}_b(t)$. The estimated signal is shown in Fig.4, which is almost equal to the objective signal $S_b(t)$ of Fig.2. The estimated results were $\hat{Z}_A = 9.21$ rad and $\hat{Z}_B = 14.61$ rad. Now we have to determine a vale of $W=2\pi b/\lambda_0^2$. We measured values of $\hat{Z}$ for the two surfaces A and B every time we gave the object a displacement, which increased L_A and L_B by 10 μm. The measured result is shown in Fig.5, where ΔL is a change in the OPD. It was determined from Fig.5 that W was equal to 3.46×10^{-2} rad/μm. Since $\lambda_0 = 783$ nm, wavelength-scanning width 2b was 6.8 nm. Using the relation of Z=WL, we obtained $L_A = 266$ μm and $L_B = 422$ μm, and a thickness $d=(L_B - L_A)/2n_R = 54.9$ μm, where refractive index n_R of the vinyl sheet was 1.42. By repeating the measurement in time it was made clear that

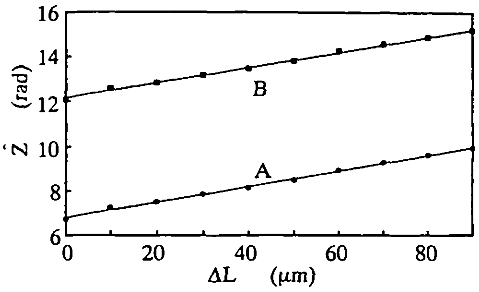

Fig.5 Values of Z versus change ΔL in OPD.

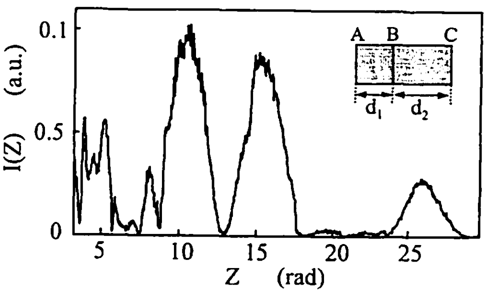

Fig.6 Image intensity I(z).

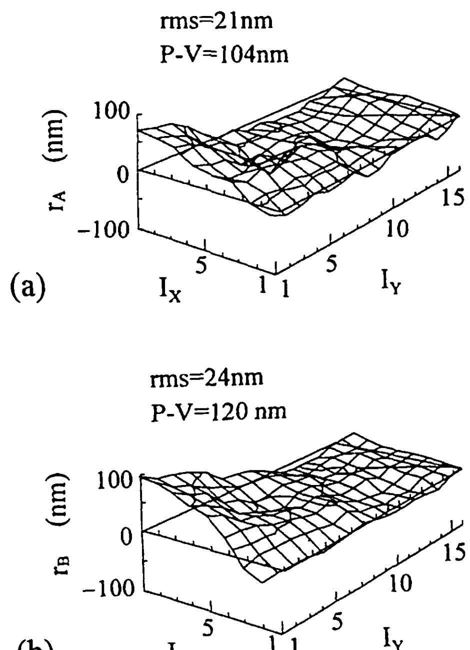

Fig.7 Measured profiles of (a) the front surface and (b) the rear surface of the silica glass plate.

measurement error of Z was 0.07 and the corresponding error of L was 2 μm. It is expected from Fig.3 that two reflecting surfaces are distinguished in the image intensity I(z) if difference in Z between the two surfaces is more than 3 rad. This value corresponds to 87 μm in OPD, which is called a two-OPD resolution. It is considered that the wavelength-scanning produces a synthetic wavelength Λ of $\lambda_0^2/2b$ in the interference signal. In the experiments Λ was 90 μm. We achieved the two-OPD resolution of 87 μm nearly equal to Λ and the OPD accuracy of 2 μm for the measurement of two positions.

Next we measured positions of three surfaces A, B, C of vinyl sheets with thickness d_1 and d_2 as shown in Fig.6. Figure 6 shows the image intensity I(z), and we had the measurement results that L_A= 290 μm, L_B= 460 μm, and L_C = 773 μm, that is, d_1 = 60 μm and d_2 = 110 μm. The measurement error of Z was 0.28 rad and the corresponding error of L was 8 μm.

Finally we tried to measure front and rear surface profiles of a silica glass plate with thickness of 20 μm. We used 8×16 elements of a two-dimensional CCD image sensor to obtain interference signals in a measuring region of 0.68 mm × 1.04 mm. The frequencies of $\omega_b/2\pi$ and $\omega_c/2\pi$ were 26 Hz and 832 Hz, respectively. Figure 7 shows the profiles of the front and rear surfaces calculated from the estimated values of α_A and α_B using Eq.(11), where values of rms and P-V are indicated. We made the same measurement again after ten minutes to examine accuracy in the measurement. Value of rms in the difference between the two measured profiles for the front and rear surfaces were about 10 nm. It is expected from Fig.7 that the estimated values of Z_A and Z_B are constant values, but their values fluctuated at the width of about 1.5 rad in the measuring region. This result indicates that the exact estimation of the modulation amplitude Z is difficult when the objective signal $S_b(t)$ contains a lot of noise. Computer simulations showed that the estimation of phase α was not influenced so much by the noise as that of Z. When the estimated values of Z deviate from the correct values within ±1 rad, the estimation error of phase α is less than 0.1 rad.

4. CONCLUSIONS

We proposed an interferometric reflectometry using a sinusoidal wavelength-scanning tunable laser diode to detect positions and profiles of multiple reflecting surfaces. In position measurements using a photodiode, the two-OPD resolution in the image intensity was 87 μm when the wavelength-scanning width was 6.8 nm. The OPD accuracy was 2 μm in the measurement of two positions, and the thickness of a vinyl sheet of 55 μm was measured with an accuracy of 0.7 μm. The OPD accuracy was 8 μm in the measurement of three positions. In surface profile measurements using a two-dimensional CCD image sensor, the front and rear surfaces of a silica glass plate with thickness of 20 μm were measured with an accuracy of about 10 nm. Although the noises contained in the objective signal influenced the estimation of Z, they did not influence so much the estimation of α.

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