Exact measurements of surface profiles of a glass plate by a superluminescent diode interferometer

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Abstract. A superluminescent diode interferometer that uses sinusoidal phase-modulating interferometry and the shifting method is applied to measure the front and rear surface profiles of a glass plate with an accuracy of a few nanometers. Since the roughness of the reference surface is large, a glass plate is put behind the object as another reference surface, which is estimated by the shifting method with an accuracy of a few nanometers.
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1 Introduction

Low coherence interferometers with a superluminescent diode (SLD) are widely used for reflectometry[1-3] and optical coherence tomography[4] in which the positions of multiple reflecting surfaces are measured by detecting amplitudes of the interference signals. If a low coherence interferometer is applied for measurement of front and rear surface profiles of a glass plate, phase distributions of the interference signals must be detected. It has been reported that front and rear surface profiles and distribution of refractive index of a glass plate were measured by a wavelength-scanning interferometer.[5] In this case, phase-shifting interferometry was employed to detect the phase of the interference signal, and the root mean square (rms) error in the measurement of surface profiles was less than 15 nm.

In this paper, sinusoidal phase-modulating (SPM) interferometry[6,7] is employed for the phase detection in a low coherence interferometer with an SLD. It is assumed that distribution of refractive index of a glass plate is homogenous and known beforehand. Then the SLD interferometer can measure front and rear surface profiles of a glass plate, and SPM interferometry provides us measurement accuracy of a few nanometers. The sinusoidal phase modulation is generated by sinusoidally vibrating reference glass plate GP1 with a piezoelectric transducer (PZT). The attachment of the PZT to a rear surface of GP1 causes a large roughness in the reference surface of the interferometer. To eliminate the effects of the reference surface profile on the measurement of surface profiles of an object, glass plate GP2 is put behind the object. The front surface of GP2 can be considered to be another reference surface of the interferometer. However, the surface roughness of GP2 is larger than a few nanometers, which requires that the front surface profile of GP2 is known beforehand. For this requirement the method proposed in Ref. 8 is applied to estimate the front surface profile of GP2. Since the surface roughness of GP2 is smaller than that of GP1 and the object, it is a good way to estimate the front surface profile of GP2. This paper describes how to measure front and rear surface profiles of a glass plate with an accuracy of a few nanometers through exact estimation of the surface profile of GP2.

2 SLD Interferometer Using Sinusoidal Phase Modulation

Figure 1 shows a configuration of an interferometer for an exact measurement of front and rear surface profilers of a glass plate. A central wavelength λ_0 of a SLD is 840 nm, and the half width of the spectrum is about 20 nm, which leads to the characteristic that the coherence length of the SLD is shorter than about 20 μm. A reference light of the interferometer is a light reflected by a front surface of glass plate GP1. A PZT is attached to the rear surface of GP1 to vibrate GP1 with a waveform of $a\cos(\omega_c t + \theta)$. The reference light is phase-modulated sinusoidally with amplitude of $z = (4\pi/\lambda_0)a$. Lights reflected by front and rear surfaces of an object, and a front surface of glass plate GP2 become an object light of the interferometer. When an optical path difference (OPD) L is less than the coherence length of the SLD, we detect an interference signal

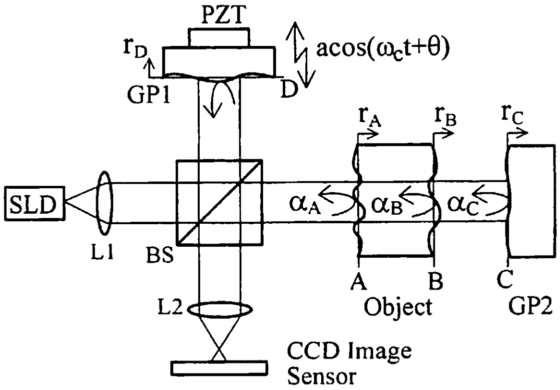

Fig. 1 SLD interferometer using sinusoidal phase modulation for measurement of surface profiles of a glass plate.

$$S(t)=S_0\cos[z\cos(\omega_c t+\theta)+\alpha], \tag{1}$$

where phase α is $(2\pi/\lambda_0)L$. We can detect an interference signal expressed by Eq. (1) for each reflecting surface separately by displacing glass plate GP1 so that the OPD becomes almost zero for the respective surface. From the detected interference signal a phase α is calculated with the method of SPM interferometry.

3 Principle of Exact Measurement

The object is a glass plate whose front and rear surface profilers are represented by r_A and r_B, which are deviations from reference planes A and B, respectively, as shown in Fig. 1. Attachment of the PZT to GP1 with glue causes a large roughness in the surface profile of GP1. The front surface profile of glass plate GP1 is represented by r_D, and its reference plane is D. To eliminate effects of surface profile r_D on the measured surface profiles r_A and r_B, glass plate GP2 is put behind the object. The surface profile of GP2 is represented by r_C, and its reference plane is C. By displacing glass plate GP1, three different interference signals can be detected that are produced from three different lights reflected by the front and rear surfaces of the object, and the front surface of GP2, respectively. Phases of the three interference signals are given by

$$\alpha_A=(4\pi/\lambda_0)(r_A-r_D), \tag{2}$$

$$\alpha_B=\alpha_A+(4\pi/\lambda_0)n(r_B-r_A), \tag{3}$$

$$\alpha_C=\alpha_B+(4\pi/\lambda_0)(r_C-r_B), \tag{4}$$

where n is the refractive index of the object glass plate. From Eqs. (2)–(4) we have

$$r_A=(\lambda_0/4\pi)\{(1/n)\alpha_A+[1-(1/n)]\alpha_B-\alpha_C\}+r_C, \tag{5}$$

$$r_B=(\lambda_0/4\pi)(\alpha_B-\alpha_C)+r_C. \tag{6}$$

Equations (5) and (6) indicate that surface profiles r_A and r_B can be measured from the three phases of the three interference signals without being influenced by surface profile r_D if surface profile r_C is a perfect plane. Since surface profile r_C is not a perfect plane in a practical situation, measurement of the surface profile r_C is required. For this measurement we adopt the method proposed in Ref. 8, which is referred to here as the shifting method.

We consider 2-D phase distribution $\alpha_C(x,y)$ to explain how to measure surface profile r_C by the shifting method. After detecting phase distribution $\alpha_C(x,y)$, glass plate GP2 is shifted by an interval d_x of measuring points in the direction of x-axis to detect phase distribution $\alpha_C(x+d_x,y)$. In a similar way, phase distribution $\alpha_C(x,y+d_y)$ is detected by shifting GP2 in the direction of y-axis. From these phase distributions, we obtain difference values of $r_C(x,y)$ with respect to the x-axis and the y-axis as follows:

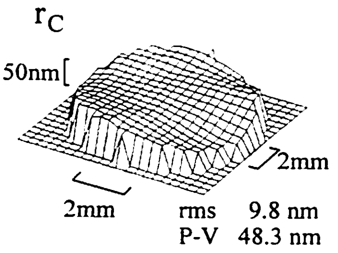

Fig. 2 Estimated surface profile of r_C.

$$\begin{aligned} h(x,y)&=(\lambda_0/4\pi)[\alpha_C(x+d_x,y)-\alpha_C(x,y)]\\ &=r_C(x+d_x,y)-r_C(x,y), \end{aligned} \tag{7}$$

$$\begin{aligned} v(x,y)&=(\lambda_0/4\pi)[\alpha_C(x,y+d_y)-\alpha_C(x,y)]\\ &=r_C(x,y+d_y)-r_C(x,y). \end{aligned} \tag{8}$$

By solving the difference equations we can estimate the surface profile of $r_C(x,y)$. However, the shifts of GP2 involve inclinations of the surface, which requires us to subtract mathematical reference planes from the detected raw phase distributions. Since the phase distributions $\alpha_C(x,y)$, $\alpha_C(x+d_x,y)$, and $\alpha_C(x,y+d_y)$ are a little different from each other, the three mathematical reference planes are also a little different from each other. Then two different planes inclining from the x-y plane by very small angles are added to the right sides of Eqs. (7) and (8), respectively, which causes a small error in estimation of the surface profile of $r_C(x,y)$. Root mean square (rms) and peak-to-valley (P-V) values of the error are proportional to those values of the surface profile of GP2. Since rms and P-V values of the surface profile r_C are much smaller than those of surface profiles r_A and r_B, the exact surface profiles r_A and r_B can be obtained through the measurement of the surface profile r_C.

4 Experimental Results and Discussions

The thickness of the object glass plate was 1 mm. The rear surface of the glass plate GP1 was not parallel to its front surface, so that only the light reflected by the front surface of the glass plate GP1 became the reference light. We used 20×20 elements of a 2-D CCD image sensor to detect interference signals in a measuring region of 7.6 ×11.4 mm. Intervals of the measuring points are 0.4 and 0.6 mm along the x and y-axes, respectively. The output signal of the CCD was sampled with an analog-to-digital converter. The phase modulation frequency $\omega_c/2\pi$ was 100 Hz, and the sampling frequency of the interference signal for one measuring point was 800 Hz. We detected the three different interference signals, that is, phase distributions $\alpha_A(x,y)$, $\alpha_B(x,y)$, and $\alpha_C(x,y)$ by giving displacements to GP1. After detecting $\alpha_C(x,y)$, we detected $\alpha_C(x+d_x,y)$ and $\alpha_C(x,y+d_y)$ by giving shifts of d_x and d_y to GP2, respectively. The values of d_x and d_y were 0.4 and 0.6 mm, respectively. Calculations to obtain the phase distributions and surface profiles were done on a personal computer.

Figure 2 shows estimated surface profile of r_C. Figure 3 shows surface profiles of r_A and r_B calculated with Eqs. (5)

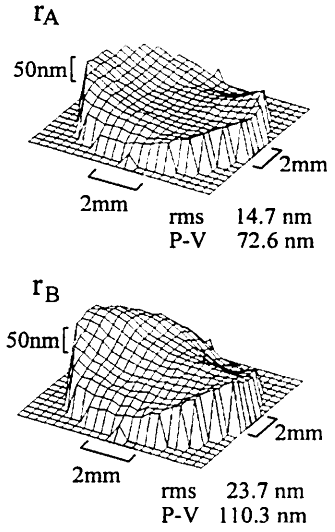

Fig. 3 Measured surface profiles of r_A and r_B.

and (6), where $n=1.5$. When we assumed that GP2 was a perfect plane, that is, $r_C=0$, we obtained surface profiles r_A-r_C and r_B-r_C as measured surface profiles of r_A and r_B, respectively, as shown in Fig. 4. Values of rms and P-V are indicated for the results of the surface profiles.

Measurement accuracy strongly depends on how exactly the surface profile r_C is estimated. We examined the accuracy in estimating the surface profile r_C by again estimating the surface profile r_C shown in Fig. 2 on a computer by the shifting method. We gathered data for $h(x,y)$ and $v(x,y)$ in the region of 19×19 measuring points from the surface profile of r_C shown in Fig. 2. We compared a surface profile estimated by this computer simulation with the surface profile of r_C shown in Fig. 2. Values of rms and P-V of the difference between the two surface profiles were about 1 and 2 nm, respectively. This result assures us that the error caused by the difference among the three reference planes for $\alpha_C(x,y)$, $\alpha_C(x+d_x,y)$ and $\alpha_C(x,y+d_y)$ is smaller than the error in detection of the phases of the interference signals. The phase detection error was a few nanometers.

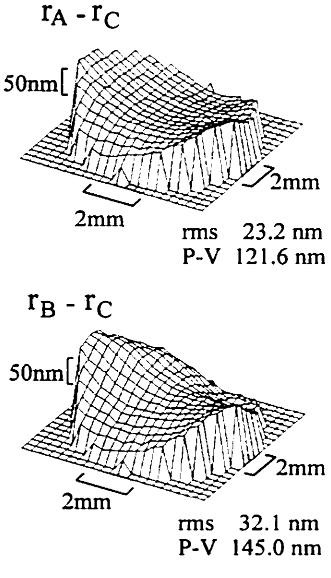

Fig. 4 Surface profiles r_A-r_C and r_B-r_C obtained as two measured surface profiles of the object when it was assumed that $r_C=0$.

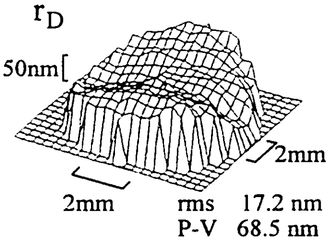

Fig. 5 Measured surface profile of r_D.

Figure 5 shows the surface profile r_D calculated from the detected phase of α_A and the measured surface profile of r_A with Eq. (2). This result indicates that attachment of the PZT to GP1 with glue caused a large roughness in surface profile r_D. If we estimate the surface profile r_D with the shifting method, GP2 is not required to measure the surface profiles of r_A and r_B. However, this measurement is not recommended because of a large roughness in surface profile r_D.

5 Conclusions

We have proposed a SLD interferometer that uses SPM interferometry and the shifting method for an exact measurement of the front and rear surface profiles of a glass plate. The roughness of the reference surface was about 17 nm in rms value, and it was as large as the roughness of the object surfaces. To measure the object surfaces without being influenced by the roughness of the reference surface, we used glass plate GP2, whose surface roughness was about 10 nm. The shifting method estimated the surface profile of GP2 with an accuracy higher than that in detection of the phases of the interference signals. Therefore we could measure the front and rear surface profiles of the glass plate with an accuracy of a few nanometers.

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