Multiple-wavelength interferometers using backpropagation of optical fields for profile measurement of thin glass sheets

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ABSTRACT

Multiple-wavelength optical fields at a detecting plane of an interferometer are generated by a computer from the detected interference signals of a thin glass sheet. The generated optical fields are backpropagated towards the glass sheet along the optical axis. An optical field along the optical axis is reconstructed by summing the backpropagated fields over the multiple wavelengths. The amplitude and phase distributions of the reconstructed optical field provide the positions of the two surfaces of the glass sheet where peak values of the amplitude and zero or π values of the phase appear. The accuracy of the position measurement is several nanometers.

Keywords: multiple wavelengths, interferometer, shape measurement, backpropagation of optical field

1. INTRODUCTION

It is important to measure positions of the surfaces of thin glass sheets in three dimensions with a high accuracy of a few nanometers. For this measurement, white light interferometers have been used in which the positions of the reflecting surfaces are determined by finding peak positions of the envelope of the interference signal through a mechanical scanning of the optical path difference. To eliminate this mechanical scanning, linear wavelength-scanning interferometers are used in which positions of the reflecting surfaces are determined by the peaks of the frequency spectrum of the interference signal. Recently frequency-comb light interferometers have been developed in which the frequency spacing is swept to find positions where the amplitude envelope of the interference signal has a peak [1]. But measurement accuracy of these interferometers is not so high because only the amplitude distribution of the interference signal is utilized while ignoring its phase distribution.

In this paper both of the amplitude and phase of the interference signal are utilized for the analysis of the signal. Multiple-wavelength optical fields on the detecting plane of an interferometer are generated by a computer from the interference signals detected for the thin glass sheet surfaces. There is no dispersion influence in the detected interference signal because the refractive index of the glass sheet can be regarded as a constant for the multiple wavelengths. The generated optical fields are backpropagated toward the thin sheet surfaces along the optical axis. The optical field along the optical axis is reconstructed by summing the backpropagated fields over the multiple wavelengths. The reconstructed optical field has peak values in the amplitude distribution and zero or π values in the phase distribution at the positions of the sheet surfaces. The zero or π values of the phase provide exact positions of the sheet surfaces with a high accuracy of several nanometers even

Interferometry XV: Techniques and Analysis, edited by Catherine E. Towers, Joanna Schmit, Katherine Creath,
Proc. of SPIE Vol. 7790, 77900U · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.861534

when the peak values of the amplitude provide the positions with an error of a few hundred nanometers. This method is called backpropagation method, and it was applied to the step profile measurement with the multiple wavelength interferometer [2] and with the multiperiod fringe projection interferometer [3].

2. PRINCIPLE

A sinusoidal phase-modulating interferometer using multiple wavelengths for profile measurement is shown in Fig. 1. It is assumed that the object has two reflecting surfaces, F and R, whose positions are expressed by optical path difference (OPD) L_F and L_R, respectively. An image of the object is made by the lens on the CCD image sensor. The reference mirror is vibrating sinusoidally with amplitude a and angular frequency ω_c by the piezoelectric transducer (PZT). The wavelength of the light source is scanned as

$$\lambda_m=\lambda_0+m\Delta\lambda \qquad m=0, 1, \cdots, M . \qquad (1)$$

with the scanning width of $B_\lambda=M\Delta\lambda$. An image of the object is made of the beams reflected by the surfaces. For single wavelength the interference signal detected by the CCD image sensor is given by

$$\begin{aligned} S(t, m) &= A_m+ B_{mF}\cos(Z\cos\omega_c t+\alpha_{mF})+B_{mR}\cos(Z\cos\omega_c t+\alpha_{mR}) \\ &= A_m+ B_m \cos(Z\cos\omega_c t+\Phi_m) , \qquad (2) \end{aligned}$$

where A_m and B_m are constant with time, $\alpha_{mF}=(2\pi/\lambda_m)L_F$, and $\alpha_{mR}=(2\pi/\lambda_m)L_R$. The phase modulation amplitude of $Z=4\pi a/\lambda_m$ is regarded as a constant value of $4\pi a/\lambda_0$ for the multiple wavelengths because B_λ is much smaller than λ_0. And the following relation holds:

$$B_m\cos\Phi_m=B_{mF}\cos(\alpha_{mF}) + B_{mR}\cos(\alpha_{mR}) . \qquad (3)$$

By extracting B_m and Φ_m from S(t, m) with sinusoidal phase-modulating interferometry [4], the following detected optical field is generated:

$$D(m)=B_m\exp(j\Phi_m) \quad m=0, 1, \cdots, M . \qquad (4)$$

The optical field D(m) is back-propagated to a position specified by OPD L to obtain an optical field

$$U_m(L)=D(m)\exp[-j(2\pi/\lambda_m)L] . \qquad (5)$$

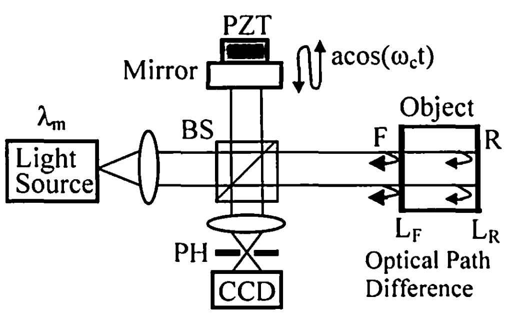

Fig. 1 Sinusoidal phase-modulating interferometer for shape measurement.

Finally the optical field reconstructed using the multiple wavelengths is given by

$$U_R(L)=\sum_{m=0}^{M}U_m(L)=A_R\exp(j\Phi_R)\,. \qquad (6)$$

When only one reflecting surface exists at $L=L_o$, it can be considered that $B_m=1$. By substituting $D(m)=\exp[j(2\pi/\lambda_m)L_o]$ into Eq. (6) and letting $L_D=L-L_o$, Eq. (6) is reduced to

$$U_R(L_D)=\sin[\pi(B_\lambda/\lambda_0^2)L_D]/\sin[\pi(\Delta\lambda/\lambda_0^2)L_D]\,, \qquad (7)$$

$$\Phi_R(L_D)=-(2\pi/\lambda_C)L_D\,, \qquad (8)$$

where

$$\lambda_C=\lambda_0+(M\Delta\lambda/2)\,. \qquad (9)$$

Equations (7) and (8) show that the amplitude A_R has a maximum value and the phase Φ_R is zero at $L=L_o$. The amplitude has a distribution with a spread width W_l of $2\lambda_0^2/B_\lambda$ as shown in Fig.2. The phase has a linear distribution whose period is the central wavelength λ_C given by Eq. (9). These characteristics enable us to measure the position of L_o with a measurement error of less than a few microns. The condition that a phase change in α_m caused by the wavelength change $\Delta\lambda$ must be less than 2π leads to the measurement range of the position

$$L_{max}=\lambda_0^2/\Delta\lambda\,, \qquad (10)$$

and the distribution of $U_R(L)$ is repeated with a period of L_{max} over all of values of L.

When the object has two reflecting surfaces, F and R, as shown in Fig.1, the amplitude and phase distributions are illustrated in Fig.2. The phase is π at the rear surface position of L_R where the reflected light propagates in the glass. In this case it is important to reduce the width of the side lobes in the amplitude distribution because the small values of the side lobe caused by a reflecting surface changes the phase distribution caused by the other reflecting surface. In order to reduce the side lobe given by a Sinc function, a reconstructed optical field is calculated by weighting the back-propagated optical wave with a Gaussian function whose maximum value is at λ_C.

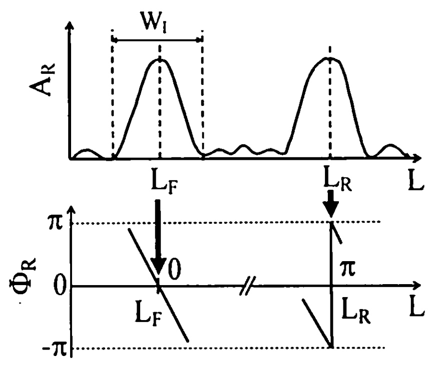

Fig. 2 Amplitude and phase distributions of the optical field reconstructed by the backpropagation of the detected optical fields of multiple wavelengths.

3. PROFILE MEASUREMENT OF A GLASS SHEET

The interferometer shown in Fig. 1 was constructed where a tunable laser diode with an external cavity was used as the wavelength-scanning light source. The wavelength was scanned from λ_0=767 nm to 782 nm at intervals of $\Delta\lambda$=0.5 nm. The interference signal was sampled at intervals of $T_c/8$ over the length of $8T_c$, where $T_c=2\pi/\omega_c$, and the sinusoidal phase modulating frequency of $\omega_c/2\pi$ was 392 Hz. The interval and number of the measurement points on x -y plane were 30 μm×30 μm and 40×40, respectively.

The object was a silica glass sheet with thickness of 170 μm. Its refractive index was regarded as a constant vale of 1.45 because the difference in the refractive index is about 0.002 between 767 nm and 782 nm. Figure 3 shows the amplitude distribution of the reconstructed optical field at one measurement point. There are two peaks of the amplitude corresponding to the two surfaces of F and R, respectively. The amplitude and phase distributions around the two peaks are shown in Fig.4 (a) and (b), respectively. It was verified that the peak position of A_R is greatly affected by measurement error in phase α_{mF} or α_{mR}, but the phase distribution Φ_R is scarcely affected by it [2]. Because of this characteristic the measured values of L_F and L_R are provided by the

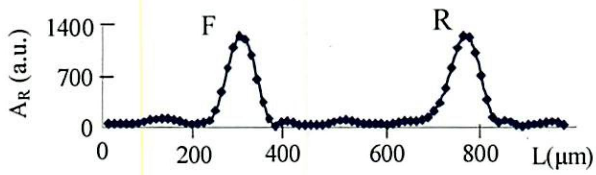

Fig.3 Amplitude distribution of the reconstructed optical field at one measurement point.

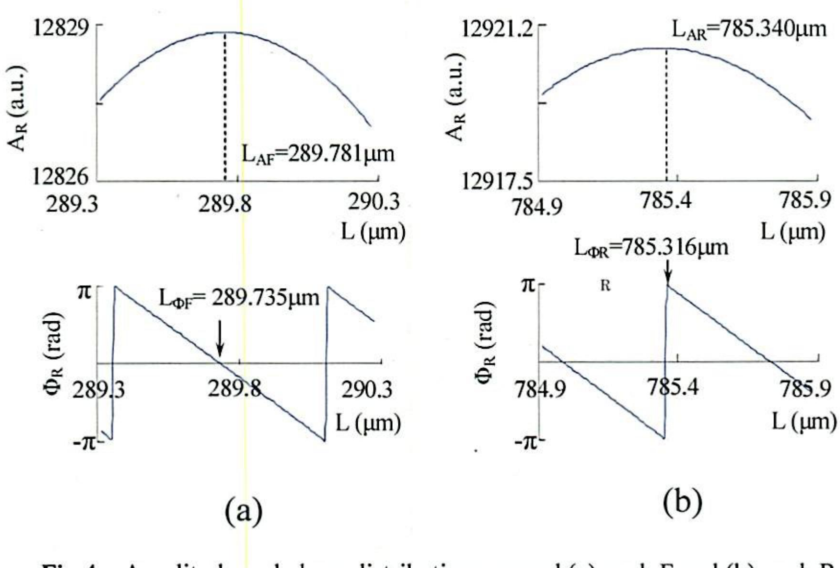

Fig.4 Amplitude and phase distributions around (a) peak F and (b) peak R in Fig.3.

positions where the values of the phase are zero and π, respectively. The zero phase position of $L_{\Phi F}$ corresponding to the front surface F is determined to be a zero phase position that is the closest to the peak position of L_{AF} in the amplitude distribution. This means that $|L_{\Phi F} - L_{AF}|$ is less than $\lambda_C/2$. The determination of the π phase position of $L_{\Phi R}$ from the peak position of L_{AR} is the same. Although the peak position in the

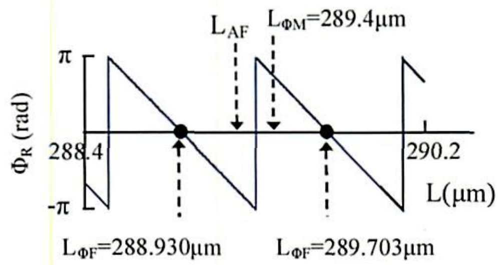

Fig.6 Determination of an exact position of $L_{\Phi F}$ by using the mean value $L_{\Phi M}$ of the positions measured by using of L_{AF}.

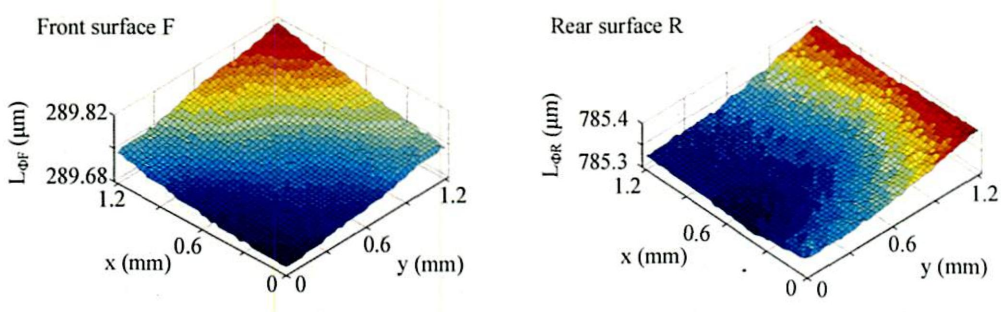

Fig.7 Measured profiles of front and rear surfaces represented by $L_{\Phi F}$ and $L_{\Phi R}$, respectively.

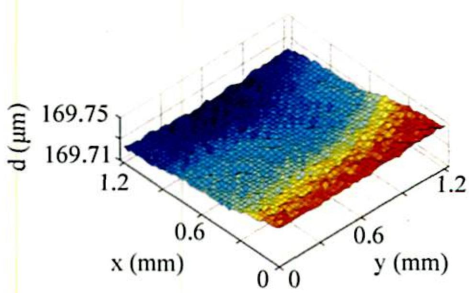

Fig.8 Thickness distributions obtained from Fig.7.

amplitude distribution has a measurement error, the exact position of the surface can be determined from the phase distribution if the measurement error in the amplitude distribution is less than $\lambda_C/2$. The result shown in Fig.4 is a good case where the peak positions are almost equal to the zero and π phase position, respectively.

The difference in the measured positions of $L_{\Phi F}$ or $L_{\Phi R}$ between the two measurement points was more than a wavelength of λ_C at some measurement points. It was known beforehand that the peak-valley value of the surface was less than λ_C. For an example, the measured position determined by using the peak position L_{AF} was $L_{\Phi F}$=288.930 μm, as shown in Fig.6. To obtain an exact position of $L_{\Phi F}$ the mean value of the measured positions over the surface F was calculated to be $L_{\Phi M}$=289.4 μm. The phase zero position that is closest to the mean value of $L_{\Phi M}$ was regarded to be the exact measured position, as shown in Fig.6. The exact measured position was $L_{\Phi F}$=289.703μm. When the measurement error in the peak position is larger than $\lambda_C/2$, this compensation process leads to the exact measured position. Figure 7 shows the measured profiles of front and rear surfaces represented by $L_{\Phi F}$ and $L_{\Phi R}$, respectively. The measurement repeatability of the surface positions was estimated to be about 8 nm. Figure 8 shows the thickness distribution obtained from Fig.7.

5. CONCLUSIONS

Positions of the front and rear surfaces of a glass sheet with thickness of 170 μm were measured by backpropagating the multiple-wavelength optical fields detected on the CCD image sensor plane with sinusoidal phase-modulating interferometry. The optical field along the optical axis was reconstructed by summing the backpropagated fields over the multiple wavelengths. In the reconstructed optical field the zero or π phase positions closest to the peak position in the amplitude distribution were the measured positions of the two surfaces of the glass sheet. The zero or π phase positions were not affected by the error in the detected optical field although the peak position in the amplitude distribution was affected greatly by it. Because of this characteristic, the zero or π phase positions closest to the mean value of the measured surface positions was regarded to be the correct position of the surface. By using this compensation process the measurement repeatability of 8 nm was obtained.

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