Vibration-insensitive measurement of thickness variation of glass panels using double-slit interferometry

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Abstract: A technique which can measure thickness variation of a moving glass plate in real-time with nanometric resolution is proposed. The technique is based on the double-slit interference of light. Owing to the nature of differential measurement scheme, the measurement system is immune to harsh environmental condition of a production line, and the measurement results are not affected by the swaying motion of the panel. With the preliminary experimental setup with scanning speed of 100 mm/s, the measurement repeatability was 3 nm for the waviness component of the thickness profile, filtered with a Gaussian filter with cutoff wavelength of 8 mm.

OCIS codes: (120.3180) Interferometry; (120.0120) Instrumentation, measurement and metrology; (120.4630) Optical inspection.

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1. Introduction

Thickness uniformity of glass panels plays an important role in the performance of flat panel displays (FPDs). Thus, glass panels have tight tolerance on the thickness variation, and this variation should be monitored and controlled precisely during the manufacturing process. Among the three components of thickness profile – form error, waviness, and roughness [1] –, the waviness component which can be obtained by filtering the thickness profile, is of major concern because the features which may induce a lens effect and deteriorate the visual quality of the display lie within the waviness regime.

While maintaining the thin thickness of about 0.7 mm, the size of the panels is ever increasing, and panels of size 2.2 m × 2.5 m are being used in the eighth generation production line. Such large and thin glass panels are quite flexible so that they are apt to sway while they are translated by a moving stage with relatively high speed of several hundred millimeters per second. To enhance the production efficiency, it is desired to inspect the thickness variation of the glass panel with nanometric resolution while the panel is being translated. The tactile measurement method, which is the most primitive method to measure thickness variation of glass plates, cannot be used when the glass is moving, and thus an optical method has to be chosen. Existing optical reflection-type glass thickness measuring methods cannot be used, since with the sway motion of the moving glass panel, the reflected beam will be lost by the detector [2–8]. Thus, a transmission-type measurement method has to be used which is relatively less sensitive to sway motion of the glass. Existing transmission-type methods for thickness variation include heterodyne polarimetry, differential heterodyne interferometry, astigmatic method, and excess fraction method with a wavelength-tuning interferometer [9–12]. Whereas these methods have pros, they also have cons such as being sensitive to intensity fluctuation (polarimetry) [9], having limitation for spatial resolution (heterodyne interferometry) [10], having not enough accuracy (astigmatic method) [11], and being not applicable to moving objects (excess fraction method) [12].

In this paper, a new technique for measuring thickness variation of a moving glass panel in high speed with nanometric resolution is proposed. The keyword of the new technique is “common-path differential interferometer.” It is based on Young’s double-slit interferometry [13]. A double-slit which is usually thought of as a representative optical element to demonstrate the diffraction and interference of light, can be used as a powerful element for a common-path interferometer. Since the two slits are placed very closely (less than one millimeter), the optical paths of the interfering beams are almost the same, which means the interference pattern is highly insensitive to vibration or other external noises. The detailed operating principle of the technique will be described in the next Chapter.

2. Principle of the technique

When a collimated laser beam of wavelength λ is incident on a double-slit whose slit-width is *b* and center-to-center separation of the slits is *a*, it is well known that the intensity of the interference pattern at the detector plane can be expressed as

$$I(\theta) = I_0 \left(\frac{\sin\beta}{\beta} \right)^2 \cos^2\alpha, \tag{1}$$

provided that

$$\beta = \frac{kb\sin\theta}{2}, \tag{2}$$

$$\alpha = \frac{ka\sin\theta}{2}, \tag{3}$$

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where $k = 2\pi / \lambda$ is the wavenumber, I_0 is the intensity at the central peak of the interference pattern, and the angle θ is measured from the x-y plane (See Fig. 1).

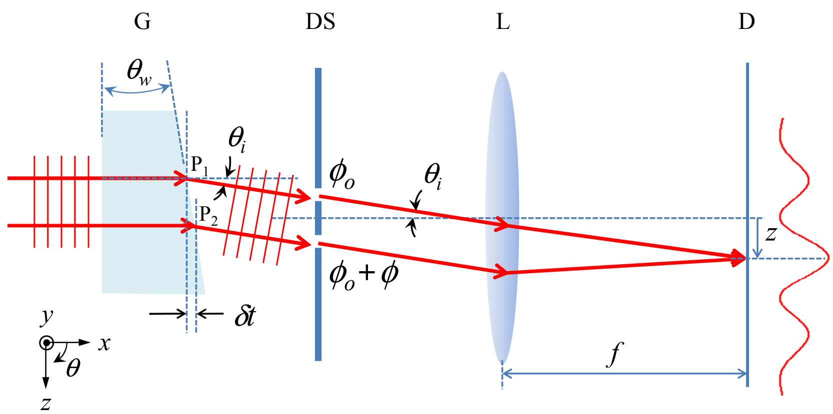

Fig. 1. Schematic diagram of the double-slit interferometer. G: glass panel; DS: double-slit; L: lens; D: detector plane

Equations (1)-(3) hold under the condition that the electric fields entering the slits are in-phase. If there is an initial phase difference, ϕ, between the electric fields at the slits, Eq. (1) has to be modified as

$$I(\theta) = I_0 \left(\frac{\sin\left(\beta - \frac{b\phi}{2a}\right)}{\beta - \frac{b\phi}{2a}} \right)^2 \cos^2\left(\alpha - \frac{\phi}{2}\right). \tag{4}$$

The central peak of the interference pattern will appear in the direction

$$\theta_{cp} = \sin^{-1}\frac{\phi}{ka}. \tag{5}$$

This means that the double-slit can be used as a tool to measure phase difference at the slits by monitoring the double-slit interference pattern. Since a glass plate of non-uniform thickness placed in front of a double-slit will induce phase difference of electric fields at the slits, we use the double-slit to measure the thickness variation of glass panels.

Assume that a glass panel, whose refractive index is n, is placed in front of the double-slit. The glass panel can be modeled as a series of infinitesimal optical wedges whose wedge angle, θ_w, varies with position. Thus when we focus on a local area, the glass panel can be thought of as an optical wedge as shown in Fig. 1. The collimated incident beam will be refracted by the glass plate and enter the double-slit with incident angle, θ_i.

$$\theta_i = \sin^{-1}(n\sin\theta_w) - \theta_w. \tag{6}$$

As a result, there will be an initial phase difference between the electric fields entering the slits. Since this phase difference is equal to

$$\phi = ka\sin\theta_i, \tag{7}$$

the central maximum will occur in the direction same as that of the inclined angle of the incident beam,

$$\theta_{cp} = \theta_i. \tag{8}$$

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When the glass thickness difference between two positions P_1 and P_2 near the slits is denoted by δt, the wedge angle of the glass, θ_w, could be approximated as $\tan^{-1}(\delta t / a)$, and the central peak position of the interference pattern at the detector plane becomes

$$\begin{aligned} z &= f \tan\theta_i \\ &= f \tan\left[\sin^{-1}\left\{ n \sin(\tan^{-1}\frac{\delta t}{a}) \right\} - \tan^{-1}\frac{\delta t}{a} \right] \\ &\approx f(n-1)\frac{\delta t}{a}, \end{aligned} \tag{9}$$

where f is the focal length of the imaging lens, and $z = 0$ is the peak position when there is no phase difference at the slits. Thus the local thickness difference between the two neighboring points P_1 and P_2 can be found as

$$\delta t = \frac{az}{(n-1)f}. \tag{10}$$

The proposed method is similar to angular displacement measurement using an autocollimator in that the first line in Eq. (9) has the same form as that used for autocollimators. The major difference between the two methods is that the double-slit method provides higher spatial resolution determined basically by the separation of the slits, whereas the autocollimator measures only the averaged angle over the whole beam size. Thus the double-slit system allows to measure thickness change between neighboring points separated by several tens of micrometers, which cannot be achieved with the autocollimator method.

By monitoring the peak intensity position of the central interference fringe on the detector plane while translating the glass plate, the differential thickness profile of the glass panel can be easily measured. The thickness profile of the glass panel is obtainable by integrating the measured differential profile. If the waviness component of the thickness profile is the matter of interest, it can be obtained by filtering the integrated profile by a Gaussian filter. The Gaussian filter is a continuous weighting function defined by Eq. (11)

$$g(t) = \frac{1}{\alpha\lambda_c} \exp\left[-\pi \left(\frac{\mathrm{t}}{\alpha\lambda_c} \right)^2 \right], \tag{11}$$

where $\alpha = \sqrt{\log 2 / \pi} = 0.4697$, λ_c is the cutoff wavelength of the filter, and t is the distance from the center of the weighting function [14].

3. Experimental setup

The schematic diagram of the experimental setup for measuring thickness variation of glass panels is shown in Fig. 2. A broadband super luminance diode (SLD) whose center wavelength and coherence length are 1020 nm and 10.4 μm, respectively, is used as a light source to prevent the interference between the beams transmitted and multi-reflected from the glass surfaces. Light transmitted through an optical fiber is collimated and sent through the glass panel placed in front of the double-slit. Diffracted light from the double-slit forms an interference pattern on the CCD camera through a lens located at its focal length distance from the CCD camera. The glass panel under inspection is attached on a computer-interfaced motorized stage. The computer controls the motorized stage and receives the encoder signals from the stage. The encoder signals are used as trigger signals for the CCD camera to capture the images. While the glass panel is translated, the position of the central peak on the CCD is found in real-time using the zero-crossing algorithm. The camera has a 640 × 480 CCD array with pixel size of 7.4 μm × 7.4 μm. The focal length of the imaging lens is 500 mm. The width of the opening of the slits and the spacing between the center of two slits are 50 μm and 100 μm, respectively ($a = 100\,\mu$m, $b = 50\,\mu$m).

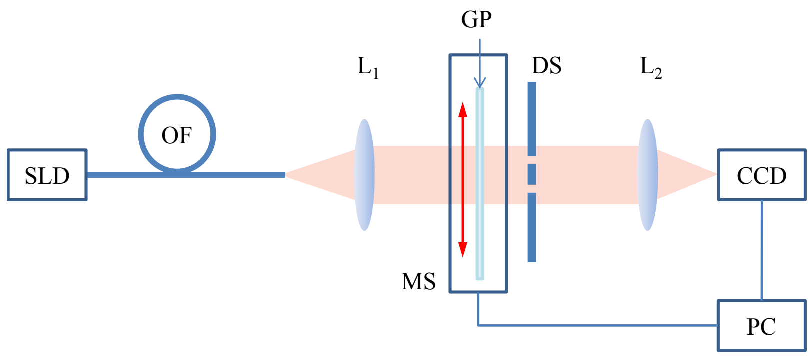

Fig. 2. Schematic diagram of the experimental setup. SLD: super luminance diode; OF: optical fiber; L_1: collimation lens; GP: glass panel; MS: motorized stage; DS: double-slit; L_2: lens; CCD: charge coupled device camera; PC: personal computer.

4. Experiments

A glass plate of 0.7 mm thickness which is used for liquid crystal displays was measured using the proposed measurement method. Data sampling was made every 100 μm, which is same as the spacing of the slits. The width and height of the glass plate were 200 mm and 280 mm, respectively, and the measured length was 140 mm in the width direction. The translation speed of the stage was set to 100 mm/s, which was limited by the speed of the CCD camera. The interference pattern occupied 640 × 120 pixels of the CCD array, and after 1 × 4 binning in the vertical direction, 640 × 30 intensity data were obtained.

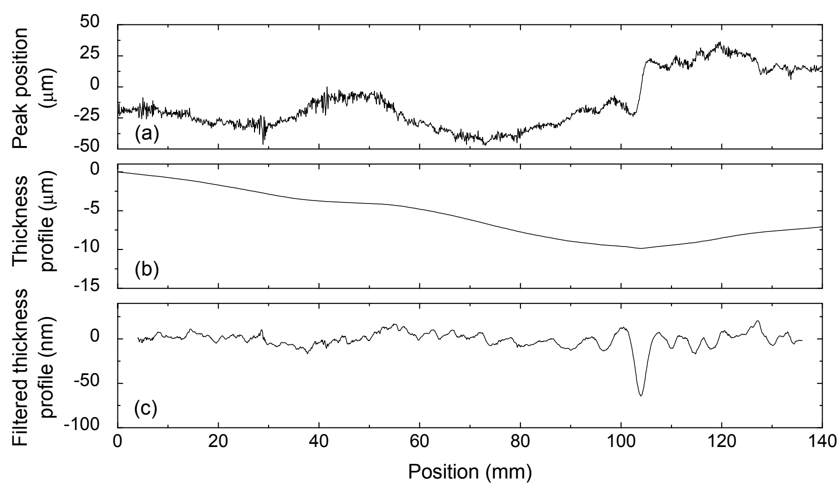

Fig. 3. Example of measurement profiles. (a) Raw data which is the position of central peak of the interference pattern. (b) Thickness profile. (c) Filtered profile (waviness component of (b) with cutoff wavelength of 8 mm).

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Figure 3(a) shows the raw data which is the position of central peak of the interference pattern. The peak position is converted to the differential thickness of the glass plate using Eq. (10). The thickness profile obtained by integrating the differential thickness is shown in Fig. 3(b), and the waviness component of the thickness profile obtained using a Gaussian filter is shown in Fig. 3(c). The cutoff wavelength of 8 mm, which is commonly used in flat glass panel industry, was used in the filtering process.

To check the consistency of the measurement, a glass plate was measured twice, before and after flipping the glass plate horizontally. The results and the difference of the two measurements are plotted in Fig. 4.

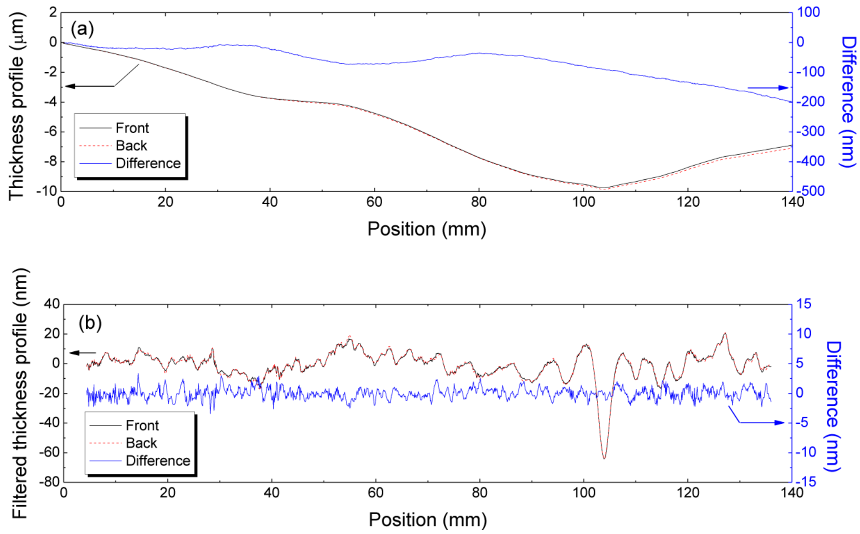

Fig. 4. Comparison of thickness profiles and filtered profiles obtained before and after flipping the glass plate horizontally. (a) Thickness profiles and difference. (b) Filtered profiles and difference.

The two profiles agreed well with their difference being less than 200 nm (see Fig. 4(a)). The difference increased in the same direction to which data analysis is performed. This is because each thickness profile might have error due to the integrating process where low frequency error due to noise could be accumulated. This is the typical property of differential measurement techniques which always requires an integration process. However, for the waviness component of the thickness profile, the two profiles agreed more closely and their difference was within ± 2 nm. This is because low frequency components including integrating error were removed through the filtering process.

To test the robustness of the measurement system, repeated measurements were made using translation speed of 100 mm/s. Standard deviations calculated from 10 repeated measurements were less than 120 nm for the thickness profile, and less than 3 nm for the waviness component. The standard deviation of the thickness profile was linearly increasing with position of the glass plate, due to the aforementioned reason. On the other hand, the waviness component shows excellent repeatability, and this proves that the proposed measurement method would be very useful for inspecting waviness component of thickness profile of glass panels.

Next experiment was performed to evaluate the insensitiveness to harsh environmental condition of production lines. To simulate the sway motion of the glass panel, we vibrated the glass panel using an air blower during the movement of the glass panel. The amplitude and frequency of the vibration were about 10 mm and 1 Hz, respectively. Figure 5(a) shows the thickness profiles measured with and without vibration, and their difference. It can be seen from the figure that the measured thickness profiles and the waviness profiles are almost not affected by the sway motion of the glass panel. In case of the waviness component, the

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difference of profiles obtained with and without vibration is within ± 2 nm, which is about the same level as the measurement repeatability without vibration. This is the main strong point of the proposed measurement method. Considering the fact that the waviness component is of major concern in inspecting glass panels, these experimental results prove that the proposed measurement technique could be very useful in flat panel manufacturing industry.

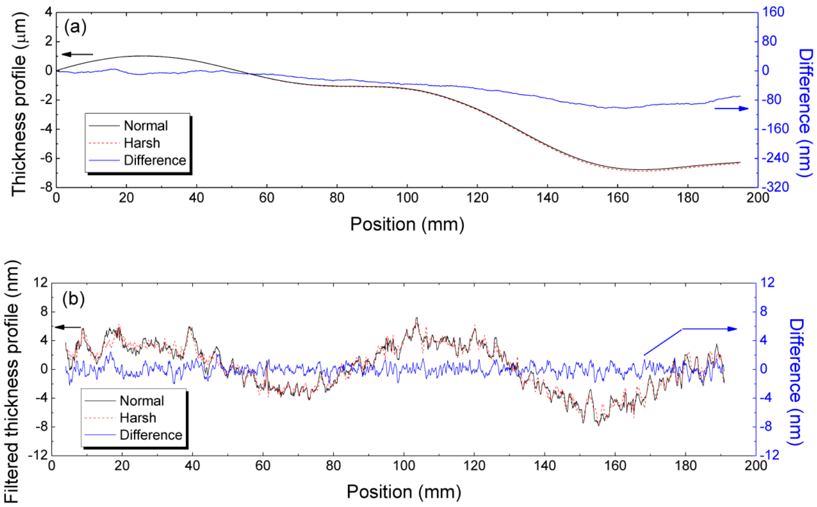

Fig. 5. Comparison of the thickness profiles and filtered profiles measured with and without vibration. (a) Thickness profiles. (b) Filtered profiles.

5. Discussion

The proposed measurement method is based on a double-slit interferometry. It is capable of measuring the waviness component of the thickness profile in nanometric repeatability while the glass panel is moving with a sway motion. If we focus on the refraction of light due to local thickness variation of the glass panel as shown in Fig. 6, however, it can be seen that although data sampling is made in a constant spacing interval triggered by the encoder signal of the stage, the points on the glass panel where the local thickness difference is measured will not be equally spaced. To evaluate the amount of shift, we introduced a parameter, Δ, which denotes the shift between the center of the sampling points and that of the slits. Let us consider the situation where the center-to-center distance of the double-slit is a, the distance between the center of the double-slit and the glass surface is l, the thickness difference between two measuring points separated by a is δt, local wedge angle of the glass panel is θ_w, and the incident angle of light onto the slit is θ_i, as shown in Fig. 6.

Considering the geometrical configuration and using Eq. (6), the shift Δ can be calculated by solving the following quadratic equation

$$\left(\tan^2\theta_w - \frac{1}{\tan^2\theta_i}\right)\Delta^2 + \left(2l\tan\theta_w + a\tan^2\theta_w\right)\Delta + \left(l^2 + al\tan\theta_w + \frac{a^2}{4}\tan^2\theta_w\right) = 0. \quad (12)$$

The amount of shift is linearly dependent on the distance between the glass plate and the double-slit. Under practical condition of interest, where a = 100 μm, $l \leq 100$ mm, and δt < 15 nm, the shift of object points is less than 7 μm, which is about 7% of the sampling distance. Although this shift has little effect on the waviness profile of glass panels, it can be minimized by adopting a relay-optic system. Figure 7 shows one of such optical system, which is the 4-f system. It puts the image of the glass panel onto the double-slit position, so that effectively the distance between the object points and the slits becomes almost zero, thus minimizing the amount of shift, Δ.

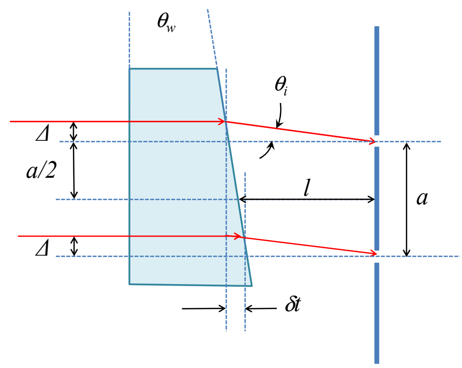

Fig. 6. Parameters used to evaluate the amount of shift occurring between object points and the slit centers due to refraction of light.

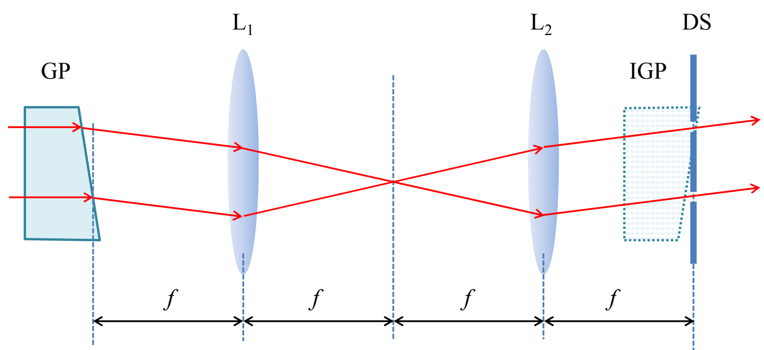

Fig. 7. An optical 4-f system to minimize the shift between object points and slit centers. GP: glass panel; L_1, L_2: lenses; IGP: image of glass panel; DS: double-slit.

The measurable range of the local thickness difference can be described as a dynamic range. The dynamic range of the proposed method is determined according to Eq. (10), where the allowable maximum shift of the central fringe on the CCD array is inserted in z. To increase the dynamic range, a CCD camera with a larger CCD array and a lens having shorter focal length could be selected. However, since the focal length is also related to the measurement sensitivity, a compromise should be made. In the current experimental setup, the dynamic range is about 0.4 μm which corresponds to the wedge angle of 4 mrad.

While the proposed method showed excellent performance in the measurement of the waviness component of thickness profile, it showed a kind of systematic error in the measurement of unfiltered thickness profile, which increased along the measurement position as shown in Fig. 4(a). This is the typical error pattern in the differential measurement scheme which includes an integration procedure. The standard deviation of 10 repeatedly measured unfiltered thickness profiles was less than 120 nm, but this could be reduced by applying several solutions in the respect of a system design and an operating procedure as follows. Because the main error source is a low frequency component such as the drift of the central peak position, we need to increase structural and thermal stability of the measurement system. To remove the offset error of the peak position which results in the slope error in the measured thickness profile, the reset of zero position should be made precisely just before the start of measurement.

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6. Conclusion

A measurement method for measuring the thickness profile and its waviness component of flat glass panels is proposed. The method is based on Young's double-slit interferometer, and is capable of measuring thickness variation while the glass panel is moving with speed of several hundred mm/s. The measurement data obtained from our preliminary experimental setup showed excellent repeatability (standard deviation less than 120 nm for thickness profile and 3 nm for its waviness component). Since the measurement system is a common-path differential interferometer, it is immune to vibration or even to sway motion of the glass panel. By experiment, the effect of sway motion (10 mm amplitude and 1 Hz frequency) of the moving glass panel was found to be negligible. The proposed measurement technique can be applied to in-line inspection of thickness profile and its waviness component of glass panels in flat panel manufacturing.

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