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Simultaneous interferometric measurement of the absolute thickness and surface shape of a transparent plate using wavelength tuning Fourier analysis and phase shifting

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ABSTRACT

The absolute optical thickness and surface shape of optical devices are considered as the fundamental characteristics when designing optical equipment. The thickness and surface shape should be measured simultaneously to reduce cost. In this research, the absolute optical thickness and surface shape of a 6–mm-thick fused silica transparent plate of diameter 100 mm was measured simultaneously by a three-surface Fizeau interferometer. A measurement method combining the wavelength tuning Fourier and phase shifting technique was proposed. The absolute optical thickness that corresponds to the group refractive index was determined by wavelength tuning Fourier analysis. At the beginning and end of the wavelength tuning, the fractional phases of the interference fringes were measured by the phase shifting technique and optical thickness deviations with respect to the ordinary refractive index and surface shape were determined. These two kinds of optical thicknesses were synthesized using the Sellmeier equation for the refractive index of fused silica glass, and the least square fitting method was used to determine the final absolute optical thickness distribution. The experimental results indicate that the all the measurement uncertainties for the absolute optical thickness and surface shape were approximately 3 nm and 35 nm, respectively.

1. Introduction

Optical thickness and surface shape are important characteristics for the design of optical devices in various types of industries. Bigger transparent plates were fabricated with larger diameters for use in the semiconductor and display industries to satisfy the requirements of mass production and reduce cost. As transparent plates continue to increase in size, the demand for the precise measurement of optical thickness and surface shape grows. Although the accuracy of measurement of surface shape using optical interferometry is typically of the order of $\lambda/20$ or 30 nm, the measurement accuracy of the optical thickness of a transparent plate is of the order of a few microns, which is far worse than that of the surface shape. Many approaches were developed for measuring the optical thickness of a transparent plate.

The measurement of optical thickness of a transparent plate using white light interferometer and confocal microscopy was reported by several authors [1–4]. In this technique, the diameter of the observing aperture is restricted to <10 mm because the accurate translation of a large reference mirror along the optical axis is difficult. As the thickness of the test plate increases, the correlation length of white light fringes also increases because of the refractive index dispersion, which degrades the measurement accuracy. The measurement is thus mainly used for a thin small-aperture sample with a typical thickness of a few hundred micrometers and diameter less than a centimeter.

Wavelength tuning interferometry has also been used for the optical thickness measurement with respect to the group refractive index of a transparent plate [5–11]. Wavelength tuning Fizeau interferometer is easily scalable to a large diameter and is insensitive to the refractive index dispersion. In these measurements, the beams reflected from the reference surface of the interferometer and from the front and rear surfaces of a test plate generate several combinations of interference fringes on the detector. Wavelength tuning interferometry can separate these overlapped interference

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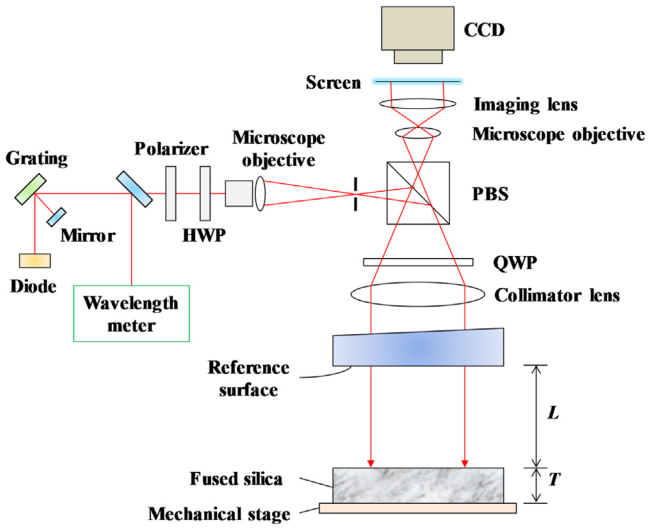

Fig. 1. Wavelength tuning Fizeau interferometer for measuring the absolute optical thickness and surface shape of a transparent plate. PBS denotes the polarization beam splitter; QWP is the quarter-wave plate; HWP is the half-wave plate. The geometric thickness of the sample and the air gap distance are T and L, respectively.

signals in the frequency domain and detect each phase of the signal using phase shifting algorithms. However, conventional measurements using wavelength tuning were limited to measuring the deviation of the optical thickness only because the tuning width of the source wavelength was not large, because of which the synthetic wavelength of the measurement was of the order of a millimeter. There has not been also any consideration of the performance of used phase shifting algorithm.

In this study, the absolute optical thickness and surface shape of a 6–mm-thick transparent plate of diameter 100 mm was measured simultaneously by a three-surface Fizeau interferometer. A measurement method combining the wavelength tuning Fourier analysis (discrete Fourier analysis) and phase shifting technique was proposed. The absolute optical thickness that corresponds to the group refractive index was determined by wavelength tuning Fourier analysis. At the beginning and end of the wavelength tuning, the fractional phases of the interference fringes were measured by the phase shifting technique and optical thickness deviations with respect to the ordinary refractive index and surface shape were determined. These two kinds of optical thicknesses were synthesized using the Sellmeier equation for the refractive index of fused silica glass, and the least square fitting method was used to determine the final absolute optical thickness distribution.

2. Measurement principle

2.1. Wavelength tuning fizeau interferometer

Fig. 1 shows the optical setup for measuring the absolute optical thickness and surface shape of a transparent plate. The temperature inside the laboratory was 20.5 °C (±0.1 °C). The source is a tunable diode laser with a Littman external cavity (New Focus TLB–6300–LN) comprising a grating and cavity mirror. The source wavelength is scanned linearly in time from 632.8 nm to 638.4 nm, translating the cavity mirror using a piezoelectric (PZT) transducer and picomotor with a constant speed [13]. The beam is transmitted using an isolator and divided into two by a beam splitter: one beam goes to a wavelength meter (Anritsu MF9630A), which was calibrated using a stabilized HeNe laser with an accuracy of $\delta\lambda/\lambda \sim 10^{-7}$ at a wavelength of 632.8 nm, and the other is incident on an interferometer. The focused output beam is reflected by a polarization beam splitter. The linearly polarized beam is then transmitted to a quarter-wave plate, becoming a circularly polarized beam. This beam is collimated to illuminate the reference surface and measurement sample. The reflections from the multiple surfaces of the measurement sample and reference surface travel back along the path, and then they are transmitted through the quarter-wave plate again to attain an orthogonal linear polarization. The resulting beams pass through the polarization beam splitter and combine to generate a fringe pattern on the screen with a resolution of 640 × 480 pixels. The measurement sample is placed horizontally on a mechanical stage with an air-gap distance of L.

The measurement sample, made of synthetic fused silica ($n_p \sim 1.45$ at 632.8 nm), is 6-mm-thick and has a diameter of 100 mm. The three dominant reflection beams from the top and rear surfaces of the sample and from the reference surface are combined to generate three different interference fringe patterns because the sample is parallel to the reference surface. The modulation frequency of each interference fringe is proportional to the optical path difference of each pair of interfering beams [14,15] as given by the following equation:

$$\nu_m = \frac{D}{\lambda^2}\cdot\left(\frac{\mathrm{d}\lambda}{\mathrm{d}t}\right), \tag{1}$$

where D and ν_m are the optical path difference and frequency of the mth harmonic, respectively.

In order to separate these signals completely in the frequency domain [14], the distance L (=26.1 mm) was approximately adjusted to $3n_gT$ (~8.7 mm), which was three times the optical thickness of a transparent plate n_gT. The three main signal frequencies ν_1, ν_3 (=$3\nu_1$), and ν_4 (=$4\nu_1$) corresponding to the optical thickness of the transparent plate, surface shape, and rear surface shape, respectively, appear in the frequency domain by setting L as $3n_gT$.

2.2. Wavelength tuning fourier analysis and phase measurement

When the wavelength is scanned from λ_1 to λ_2 ($\lambda_1 < \lambda_2$), the optical thickness of a transparent plate at each wavelength is defined as

$$n_{1,2}T = \frac{\lambda_{1,2}}{2}\left(N_{1,2} + p_{1,2}\right), \tag{2}$$

where $N_{1,2}$, $p_{1,2}$, and $n_{1,2}$ are the interference orders, fractions, and refractive indices at each wavelength. The refractive index and optical thickness are functions of the wavelength. The absolute optical thickness is calculated from Eq. (2) as follows:

$$\frac{n_1+n_2}{2}\left(1-\frac{\lambda_1+\lambda_2}{n_1+n_2}\cdot\frac{n_2-n_1}{\lambda_2-\lambda_1}\right)T = \frac{\lambda_1\lambda_2}{2\left(\lambda_2-\lambda_1\right)}\left(N_1-N_2+p_1-p_2\right). \tag{3}$$

The right-hand side of Eq. (3) is proportional to the interference order displacement $N_1 - N_2 + p_1 - p_2$, which is the number of variations in the interference fringes during the wavelength tuning. The absolute optical thickness is proportional to the product of the displacement and synthetic wavelength $\lambda_s = \lambda_{1\lambda 2}/(\lambda_2 - \lambda_1)$ [17]. The coefficient on the left-hand side of Eq. (3) reduces to the group refractive index of the transparent plate at the central wavelength $\lambda_c = (\lambda_1 + \lambda_2)/2$ when the dispersion of the material is small.

$$n_g = \frac{n_1+n_2}{2}\left(1-\frac{\lambda_1+\lambda_2}{n_1+n_2}\cdot\frac{n_2-n_1}{\lambda_2-\lambda_1}\right) \approx n\left(1-\frac{\lambda}{n}\cdot\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right). \tag{4}$$

Using Eq. (3), the absolute optical thickness at the central wavelength can be rewritten as

$$\left[n_gT\right]_{meas} = \frac{\lambda_s}{2}\left(N_1-N_2+p_1-p_2\right). \tag{5}$$

Note that the product of the synthetic wavelength and order displacement represents not an ordinary optical thickness but one