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Measurement of surface profile and thickness of multilayer wafer using wavelength-tuning fringe analysis

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ABSTRACT

Wavelength-tuning interferometry has been widely used to measure and estimate the surface profile of optical components. However, in multilayer interferometry, the coupling error between the higher harmonics and the phase-shift error causes a considerable systematic error in the calculated phase. In this research, the new $7N - 6$ phase-shifting algorithm was developed using the characteristic polynomial theory. The coupling errors calculated by various types of phase-shifting algorithms were analyzed. The surface profile and optical thickness deviation of the lithium niobate crystal wafer were measured simultaneously using wavelength-tuning Fizeau interferometry and the $7N - 6$ algorithm. The experimental results were compared in terms of observed ripples and measurement repeatability.

1. Introduction

Lithium niobate (LNB) crystal wafers are transparent uniaxial crystals that are widely used in optical modulators such as waveguides and second-harmonic generators because their refractive index can be altered by the superimposed voltage and temperature changes. An LNB crystal, parallel polished to less than 1 mm in geometric thickness with coated dielectric films and a transparent electrode on both sides, is widely used in solar spectroscopy such as in a Fabry-Perot interferometer for the near-infrared to visible wavelength range. For a higher performance of these instruments, the surface profile and optical thickness of the wafer should be measured with nanoscale uncertainties [1].

In the conventional measurement process, the crystal wafer is in optical contact with the supporting plate during polishing and then removed from the supporting plate for the measurement. However, the repeated removal from the supporting plate can increase the risk of damage to the crystal wafer surface. It is therefore desirable for the LNB wafer to measure the surface profile and optical thickness deviation simultaneously while the wafer is still adhering to the supporting plate.

One such approach reported by several authors involves white-light interferometry [2–6], wherein the surface profile and optical thickness deviation are measured simultaneously by alternatively separating the interference fringe using the characteristics that the interference fringe is localized only within a short coherence length. However, when a sample's thickness is greater than a millimeter, the measurement accuracy decreases because the zero-position of the optical path difference of transmitted light differs with each wavelength owing to the sample dispersion. Furthermore, the size of the observing aperture is restricted to 10 mm in diameter because of the difficulty of obtaining an accurate translation of a large reference mirror along the optical axis.

Using a wavelength-tuning interferometer [7–16], the restriction of the aperture size can be resolved, and the same measurement accuracy can be obtained, independent of the sample thickness. However, the observed interferogram comprises the combinations of different interference fringes because of the use of monochromatic light. In order to measure the surface profile and optical thickness deviation simultaneously, it is necessary to separate the phases of each interference fringe. If the source's wavelength is scanned linearly in time, the phase of each interference fringe changes with a different frequency, proportional to the optical path difference of the two interfering beams [10,14,17]. In the case of a scanning width of less than 1 nm, the surface profile or optical thickness deviation can be determined with nanoscale uncertainty [13,14]. In order to extract the phase of a specific interference signal from a multilayer interferogram accurately, it is necessary to use a special phase-shifting algorithm that can be flexibly tuned for each fringe in the frequency domain and reduce the effect of systematic phase errors. Coupling errors between the higher harmonics in multilayer samples such as LNB wafers and phase-shift errors during wavelength tuning can be a significant error source when measuring the surface profile using optical interferometers [18,19]. We already developed the *19*-sample phase-shifting algorithm [20] that can suppress

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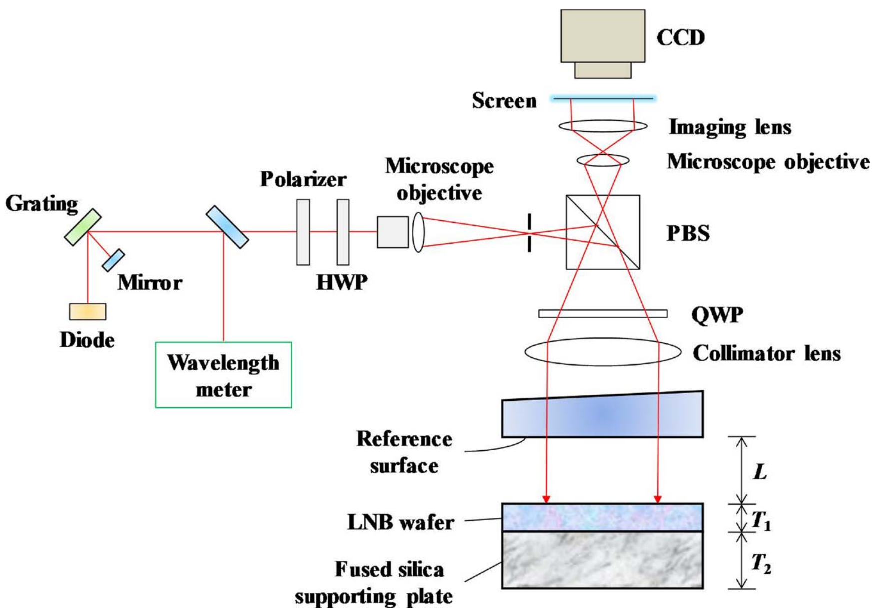

Fig. 1. Wavelength-tuning Fizeau interferometer used to measure the multilayer LNB wafer and FS supporting plate. PBS denotes a polarizing beam splitter, QWP a quarter-wave plate, and HWP a half-wave plate.

the coupling errors occurring in the internal reflection of the transparent parallel plate. However, the *19*-sample algorithm cannot be applied to the simultaneous measurement of a multilayer sample's surface profile and optical thickness.

In this research, the coupling errors that occur in the multilayer LNB wafer were calculated by numerical simulation. Further, the surface profile and optical thickness deviation of the multilayer LNB wafer were measured using a wavelength-tuning Fizeau interferometer and the polynomial window function that can suppress the coupling error strongly. Finally, the calculated results of other conventional phase-shifting algorithms were compared in terms of observed residual ripples and measurement repeatability.

2. Multilayer interferometer

2.1. Wavelength-tuning Fizeau interferometer

First, we specify the experimental configuration in order to discuss the fringe-modulation frequencies in the Fizeau interferometer. Fig. 1 shows the measurement setup (FUJINON G102) for testing multilayer samples, comprising an LNB wafer and a fused-silica (FS) supporting plate.

Fizeau interferometers are the least affected by air turbulence among conventional interferometers. The temperature inside the laboratory was 20.5 °C, and the light source was a tunable diode laser with a Littman external cavity (New Focus TLB–6300–LN) consisting of a grating and a cavity mirror. The source wavelength was scanned linearly in time from 632.8 nm to 638.4 nm, translating the cavity mirror at a constant speed using a piezoelectric transducer (PZT) and a picomotor [21]. The beam was transmitted using an isolator and was divided into two beams by a beam splitter: one beam was sent to a wavelength meter (Anritsu MF9630A) that was calibrated using a stabilized HeNe laser with an uncertainty of $\delta\lambda/\lambda \sim 10^{-7}$ at a wavelength of 632.8 nm. The other beam was incident on the interferometer. The focused output beam was reflected by a polarizing beam splitter. The linearly-polarized beam was then transmitted to a quarter-wave plate to form a circularly-polarized beam. This beam was collimated to illuminate the reference surface and measurement sample. The accuracy of the reference surface is $\lambda/20$ ($\lambda = 632.8$ nm). The reflections from the measurement sample and reference surface were sent back along the same path and were then transmitted through the quarter-wave plate again to achieve orthogonal linear polarization. The resulting beams passed through the polarizing beam splitter and were combined to generate a fringe pattern on the screen (640 × 480 pixels).

2.2. Multilayer LNB wafer

The irradiance signal observed by the CCD detector is formed by multiple-beam interference between the reflection beams from the reference and sample surfaces. The irradiance signal of a function of time t is given by

$$I(x, y, t) = A_0 + \sum_{m=1}^{\infty} A_m \cos[\nu_m t - \varphi_m(x, y)], \tag{1}$$

where m is the harmonic component; A_m and ν_m are the amplitude and frequency of the mth harmonic component, respectively; A_0 is the DC component. We denote the optical path difference D of the two interfering beams in terms of the air-gap distance L, the thickness T_i, and the refractive indices n_i ($i = 1, 2$) of the LNB wafer and FS supporting plate as

$$D = 2(pL + qn_1T_1 + rn_2T_2), \tag{2}$$

where p, q, and r are integers.

Figs. 2 and 3 show the photo and the geometric layout of the reference surface and the LNB wafer that adheres to the FS supporting plate, respectively. LNB wafer has a uniaxial birefringence and has two refractive indices (ordinary and extra-ordinary) in the z and x (or y) directions. The wafer sample used in this measurement was a z-cut crystal, and thus has an isotropic refractive index within the wafer plane. When the measurement sample is a y-cut LNB wafer, it has two refractive indices within the wafer plane. The transmitted light of Fig. 1 generally changes its polarization from circular to elliptic. Therefore, in that case, we probably have to use not circular but linear polarization illumination whose polarization orientation should coincident with one of the two birefringence axes. However, since the present sample is a z-cut wafer, the refractive index is uniform within the wafer plane, which does not change the circular polarization.

The LNB wafer (thickness $T_1 = 5$ mm, diameter of 74 mm, and refractive index $n_1 = 2.27$) that adheres to the FS plate (thickness $T_2 = 16.5$ mm, diameter of 80 mm, and refractive index $n_2 = 1.45$) is separated from the reference surface by the air-gap distance L. The average distance between the LNB wafer and the FS plate during optical contact was measured as 2–3 nm. For details, the p- and s-polarized beams of the linearly-polarized HeNe laser were incident at