# Sinusoidal wavelength-scanning common-path interferometer with a beam-scanning system for measurement of film thickness variations

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## ABSTRACT

Two light beams reflected from a front and rear surfaces of a glass film of 20 micron thickness interfere with each other in a common path interferometer. Sinusoidal wavelength-scanning light with the scanning amplitude of 5 nm and frequency of 15 KHz is used to generate a sinusoidal phase-modulated interference signal with the modulation amplitude of 2.6 rad. The phase of the interference signal provides the thickness variation of the film, whose measurement accuracy is a few nanometers. Moreover, in order to achieve a high spatial resolution and a wide measurement region a focused beam is scanned on the surface of the film with a rotating mirror.

**Keywords**: interferometer, wavelength scanning, sinusoidal phase modulation, thickness measurement, thin film

## 1. INTRODUCTION

Measurements of front and rear surface profiles and thickness distribution of thin films are important for the manufacturing process of devices such as semiconductors and liquid crystals displays. Several measurement methods by interferometers have been proposed [1-4]. The interferometers and the computation processing for the interference signals become complicated to measure the positions of the front and rear surfaces of a thin film with a high accuracy of a few nanometers. If variation of the film thickness is required to be measured, the configuration of the interferometer becomes simple because the reference wave is not necessary. However how to provide a carrier signal to the interference signal must be considered. Since the interference signal is generated from the two beams reflected by the front and rear surfaces of the thin film, the incorporation of a carrier signal into the interference signal is not easy. The possible method of the incorporation is only the use of wavelength scanning of the light source. When the wavelength is scanned linearly with time, the interference signal becomes a sinusoidal signal whose period is proportional to the film thickness. The phase of the sinusoidal signal represents a fine value less than a half of the wavelength about the thickness of the film. However in the linear wavelength-scanning it is difficult to detect accurately the phase of the interference signal because the data length of the interference signal is not always equal to the integral multiple of the sinusoidal wave period. When the wavelength is scanned sinusoidally, the interference signal becomes a sinusoidally phase-modulated signal for which the sinusoidal phase-modulating interferometry [5] can be utilized. In this inteferometry the phase-modulation amplitude is proportional to the film thickness and it can be also measured from the interference signal. The phase-modulation amplitude suitable for the measurement of the phase is adjusted by the amplitude of the sinusoidal wavelength-scanning. The measured phase provides the variation of the film thickness with a high accuracy of a few nanometers.

In this paper, the sinusoidal wavelength-scanning is used to measure the thickness variation of a thin film.

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The configuration of the interferometer is a common path one which is not sensitive to mechanical vibrations. Moreover, in order to achieve a high spatial resolution and a wide measurement region a focused beam is scanned on the surface of the film with a rotating mirror of a scanner. For this scanning interferometer the sinusoidal wavelength-scanning is most suitable because the interference signal is continuous with time. The interference signal is detected with a configuration of a confocal imaging to eliminate undesired light reflected by other points except one measurement point on the film surface. In experiments, the wavelength scanning of 15 KHz is carried out with an acousto-optic tunable filter and a superluminescent diode. The amplitude of the wavelength scanning is 5 nm with a central wavelength of 844 nm so that the phase-modulation amplitude becomes a suitable value of 2.6rad for a glass film of 20 micron thickness. A thickness variation is measured at 180 points along a line of 12mm with a measurement time of 13 ms. A thickness variation with the magnitude of 177 nm over the 12mm line is measured with an error less than 12 nm.

## 2. PRINCIPLE

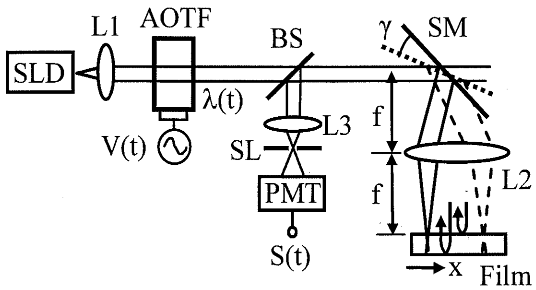


**Fig. 1** Sinusoidal wavelength-scanning interferometer for measuring thickness variation of a thin film.

Figure 1 shows an interferometer for measuring thickness variation of a thin film. The output beam from a superluminescent diode (SLD) is collimated by lens L1 and incident on an acousto-optic tunable filter (AOTF). The wavelength of the first-order diffracted beam from the AOTF is proportional to a frequency of the acoustic wave generated in the acoustical transducer of the AOTF. Appling a sinusoidal signal having a DC bias to the AOTF, the wavelength of the beam from the AOTF is scanned as follows:

$$\lambda(t)= \lambda_0+\Delta\lambda(t)=\lambda_0+b\cos(\omega_b t), \qquad (1)$$

where $\lambda_0$ is the central wavelength determined by the DC bias. The intensity change in the beam is neglected because it is very small. The beam is incident into mirror SM attached on a scanner passing through beam splitter BS. The beam reflected by SM passes through lens L2 to generate a focused beam in a film surface. Two beams reflected by the front and rear surfaces of the film go back to the BS through the L2 and the SM. The BS reflected the two beams to reach to photomultiplier tube PMT on whose surface the two beams interferes with each other in a confocal imaging system. It is assumed that the film has a thickness distribution along the x-axis expressed by

$$d(x)=d_0+\Delta d(x) \qquad (2)$$

where variation $\Delta d$ is very small compared to a constant thickness $d_0$. Then the phase of the interference signal detected with the PMT is approximated as

$$\phi(t) = 2\pi L/\lambda(t) = -2\pi[\Delta\lambda(t)/\lambda_0^2](2nd)+ (2\pi/\lambda_0)(2nd) = -Z_b\cos(\omega_b t)+\alpha\ , \qquad (3)$$

where $Z_b=(2\pi b/\lambda_0^2)(2nd_0)$ , (4)

$\alpha= (2\pi/\lambda_0)(2n\Delta d)$ , (5)

and n is the refractive index of the film. In derivation of $Z_b$, d is approximated to be $d_0$. In derivation of $\alpha$, $(2\pi/\lambda_0)(2d_0)$ is regarded to be equal to the integral multiple of $2\pi$. Thus the interference signal is expressed by

$S(t) = A+ B\cos(Z_b\cos\omega_b t-\alpha)$ , (6)

where A and B are constant with time. This interference signal is a sinusoidally phase-modulated signal and the phase-modulation amplitude $Z_b$ and the phase $\alpha$ can be exactly calculated through Fourier transform of S(t) [5]. The value of $Z_b$ is adjusted to be 2.6 rad with the wavelength-scanning amplitude b. The variation $\Delta d$ of the film is obtained from the phase $\alpha$ in the region between $-\lambda_0/2$ and $\lambda_0/2$.

To get a distribution of the thickness variation along the x-axis the focused beam in the film is scanned by rotating the mirror attached on the scanner as shown in Fig.1. Assuming that the maximum scanning angle of the scanner is very small with the angular speed of $\gamma$, the scanning speed is given by $v=f\gamma$ where f is the focal length of lens 2. The coordinate of the beam is given by $x=f\gamma t$. The interference signal S(t) is sampled by a A-D convertor with the sampling frequency of $8f_b$ for the signal processing using Fourier transform, where $f_b=\omega_b/2\pi$. The phase $\alpha$ is calculated from the frequency components obtained from 8 values sampled during one period of the frequency $f_b$. Therefore the interval of the measurement points is given by $\Delta x=8\Delta s=f\gamma/f_b$, where $\Delta s=v/f_b$ is the interval of the sampling points.

## 4. EXPERIMENTS

We constructed the interferometer shown in Fig. 1. The central wavelength and spectral bandwidth of the SLD was 844 nm and 25 nm, respectively. The central wavelength $\lambda_0$ of the first-order diffracted light from the AOTF was 844 nm, and its spectral bandwidth was about 4 nm. The wavelength-scanning width 2b was about 10 nm, and the scanning frequency $f_b$ was 15 KHz. The constant thickness $d_0$ and the refractive index n of the film were 20 μm and 1.46, respectively, and the phase-modulation amplitude $Z_b$ was equal to 2.6 rad. The diameter of the collimated beam was about 12mm and the diameter of the beam focused by the lens 2 with the focal length f of 100 mm was about 10μm. The scanning velocity of the focused beam was 89cm/s and the interval $\Delta s$ of the sampling points was 7.4 μm. Figure 2 shows the interference signal detected with the PMT. The number of the sampling points was 1616 in the measurement region of 12mm with the scanning time of 13 ms. The film was fixed by being sandwiched between two plates which have a circular hole of 12 mm diameter. At the edges of the circular hole or x=0 mm and x=12 mm, the amplitude of the interference signal were almost zero. Figure 3 shows a part of the interference signal to explain how to calculate the phase $\alpha$. One value of the phase was calculated from the eight values of the interference signal sampled during one period of the sinusoidal wavelength-scanning, assuming that the phase value was almost constant during one period. Thus the interval of the measurement points was $\Delta x=8\Delta s=0.059$ mm. The phase distribution calculated from the interference signal of Fig.2 is shown in Fig.4. The phase was also measured at intervals of 1mm along the x-axis of the scanning line on the surface when the focused beam was at rest on the each point. The values of the phase are shown in Fig.4 with a rectangular mark. The values measured with the moving beam are not equal to those measured with the stationary beam at many measurement points. The difference between the two measured values is larger where the phase change along the x-axis is larger. The maximum difference was about 0.25 rad or 12 nm in thickness. To examine the reason why the difference arose, interference signals were detected when the focused beam was at rest on the surface. At x=6mm the difference was zero, and Figure 3 is the interference signal generated with the moving beam around x=6mm. The form of the signal is almost constant in the interval of 1mm. Figure 4 shows the interference signal as a function of time t which was detected at x=6mm with the stationary beam, and the form of the signal is almost the same as that in Fig.3. On the other hand, at x=10mm the difference was about 0.2 rad. The interference signal generated with the moving beam around x=10mm is shown in Fig.5. Figure 6 shows the interference signal detected at x=10mm with the stationary beam. The form of the signal in Fig.5 varies along the x-axis and the signal form at x=10mm in Fig.5 is not identical to that in Fig.6. Therefore the difference was caused by the change of the thickness variation along the scanning line. From these comparisons it was made clear that the measurement error was about less than 12 nm.

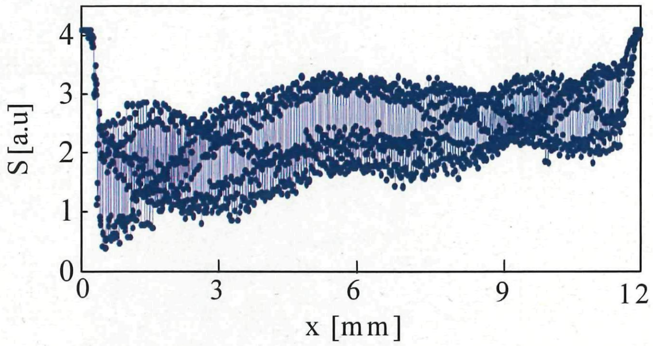


**Fig. 2** Detected interference signal..

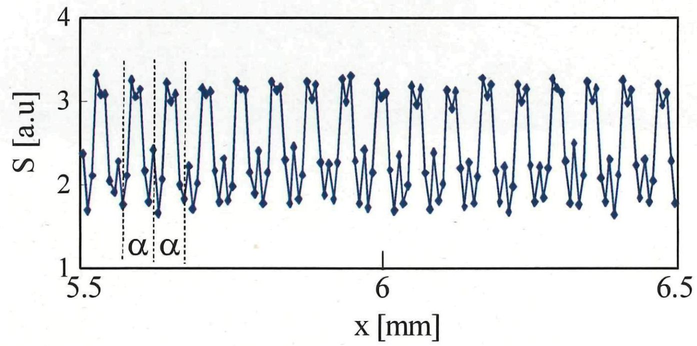


**Fig. 3** Interference signal magnified in a region of 1mm centered at x=6mm.

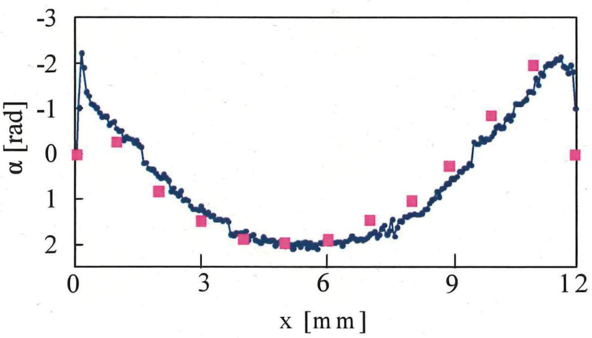


**Fig. 4** Phase distribution calculated from the interference signal of Fig.2 and phase calculated from the interference signal detected when the focused beam was rest at a point on the film surface.

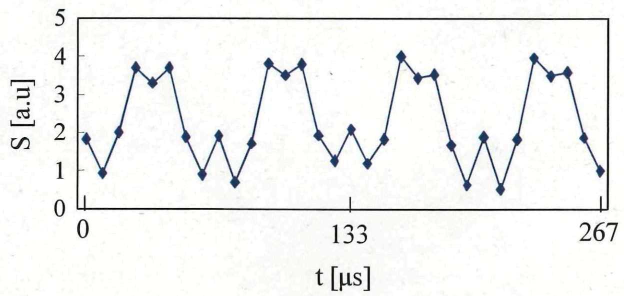


**Fig. 4** Interference signal detected when the focused beam was rest at a measurement point of x=6mm on the film surface.

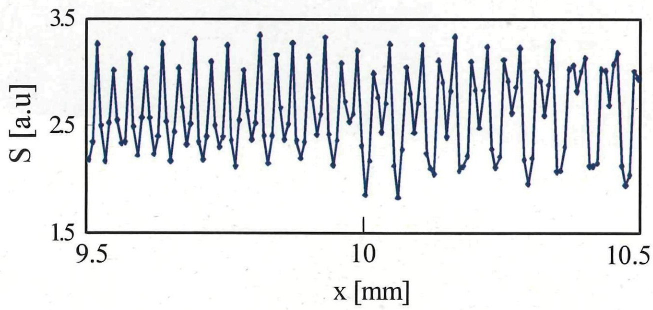


**Fig. 5** Interference signal magnified in a region of 1mm centered at x=10mm.

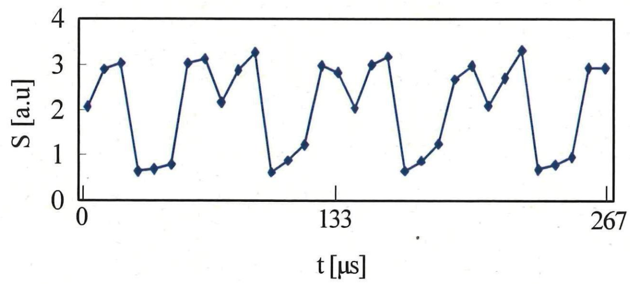


**Fig. 6** Interference signal detected when the focused beam was rest at a measurement point of x=6mm on the film surface.

## 5. CONCLOSION

Thickness variation of the glass film with 20 μm thickness was measured with the common-path interferometer where the sinusoidal wavelength-scanning with a frequency of 15KHz was performed to incorporate the sinusoidal phase-modulation into the interference signal. The scanning amplitude was 5 nm with a central wavelength of 844 nm. The focused beam was scanned on the film surface at a speed of 89 mm/s with the rotating mirror. The interference signal was sampled at a frequency of 15×8 KHz, and one value of the phase in the interference signal was calculated from 8 sampled data. In these conditions the interval of the measurement points was 59 μm. The distribution of the thickness variation measured over the scanning line of 12mm was a concave curve with the depth of 177 nm. By comparing the result described above with the result obtained from the interference signal detected when the focused beam was rest at the measurement point, it was made clear that the measurement error was less than 12nm.

## REFERENCES

1. S. W. Kim and G. H. Kim, "Thickness-profile measurement of transparent thin-film layers by white-light scanning interferometry," Appl. Opt. 38, 5968-5973 (1999).
2. D. Kim, S. Kim, H. J. Kong and Y. Lee, "Measurement of the thickness profile of a transparent thin film deposited upon a pattern structure with an acousto-optic tunable filter," Opt. Lett. 27, 1893-1895 (2002).
3. D. Kim, S. Kim, "Direct spectral phase function calculation for dispersive interferometric thickness profilometry," Opt. Express. 12, 5117-5124 (2004).
4. H. Akiyama, O. Sasaki, and T. Suzuki, "Sinusoidal wavelength-scanning interferometer using an acousto-optic tunable filter for measurement of thickness and surface profile of a thin film," Opt. Express 13, 10066-10074 (2005).
5. O.Sasaki and H.Okazaki, "Sinusoidal phase modulating interferometry for surface profile measurement," Appl. Opt. 25, 3137-3140 (1986).