Surface and thickness measurement of a transparent film using wavelength scanning interferometry

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Abstract: A wavelength scanning interferometer for measuring the surface and thickness of a transparent film has been studied. A halogen light source combined with an acousto-optic tuneable filter is used to generate a sequence of filtered light in a Linnik interferometer, which leads to a sequence of interferograms captured by a CCD camera. When a transparent thin film is measured, the reflection signals from both the top and bottom surfaces of the film will interfere with the reference signal. At the same time, the multiple reflection signals between the two film surfaces will also interfere with each other. Effective separation of the interference signals from each other is the key to achieving a successful measurement. By performing a frequency-domain analysis, these interference signals can be separated. An optimized Fourier transform method is used in the analysis. Measurements of the top and bottom surface finishes of the film, as well as the film thickness map, have been achieved. The film needs to be more than 3 μm in optical path length, and must transparent with no absorption of light. The film's refractive index needs to be known as a function of wavelength. In this paper, the theoretical analysis and simulation study of wavelength scanning interferometry for transparent film measurement is discussed. Experiments on thin film layers of Parylene N coated on a glass slide surface are studied and analyzed. Comparison study results with other contact and non-contact methods are also presented.

OCIS codes: (120.3180) Interferometry; (240.0310) Thin films; (240.7040) Surfaces.

References and links

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1. Introduction

Thin films are widely used in the optics, semiconductor and materials industries to provide specific functions to the coated devices. Effective measurement of the surface of the film and the film thickness are important to achieve a special function of, and better performance for, a coated device. Recently, scanning white light interferometry has been extended in its application from surface measurement, to film surface and thickness measurement. It can measure the surface finishes of a film as well as film thickness over the whole measurement field [1–3]. This is achieved because the reference mirror is scanned vertically, passing through the surfaces of a film. Due to the short coherence length of the light, the surfaces and thickness can be determined by finding the zero path difference between the two measurement arms.

Wavelength scanning interferometry (WSI) is an effective method for measurement of engineering surfaces and structured surfaces [4, 5]. Its main applications in surface metrology are limited primarily to surfaces with reflections occurring on the uppermost surfaces. WSI has been exploited for the surface and thickness measurement of a thin film [6–9]. When a transparent thin film is measured by wavelength scanning interferometry, the reflection signal from both the top and bottom surfaces of the film will interfere with the reference signal. At the same time, the reflection signals from these two surfaces will also interfere with each other. Effective separation of the interference signals from each other is the key to achieving a successful measurement.

Akiyama etc [6]. proposed a method in which a PZT is used in the reference arm to generate a sinusoidal modulation. Together with the modulation generated by wavelength scanning, the film thickness and film surface signals can be separated and measured. Sasaki etc [7]. suggested for the measurement to be separated into two steps. The first step is to measure the film thickness by blocking the reference signal from the reference mirror. The second step is to measure the surface of the film by removing the block plate in the reference arm. Kin etc [8]. employed the least squares fitting method to determine the three unknowns in its phase model. Ghim etc [9]. used a commercial WSI and a reflectance model for double side polished thin Silicon wafer thickness and profile measurement.

In the European high power laser energy research facility (HiPER), the surface finish on both the top and bottom surfaces of a Parylene N [10] film layer as well as its thickness are critical to applications such as the manufacture of cryogenic target capsules. The film thickness is in the range of several micrometers, to up to a hundred micrometers. In order to achieve a fusion reaction, all the target capsules are expected to be measured accurately before being filled with a deuterium/tritium fuel mix and propelled into the reaction chamber. Performing the measurements quickly and efficiently is one of the key issues in realizing a sustained, controlled fusion reaction. By performing an extensive frequency-domain analysis to separate and reconstruct these interference signals, the measurement of the top and bottom surface finishes of the film, as well as a film thickness map, can be achieved.

In this paper, we propose a simple frequency domain analysis method to separate the interference signals generated between the reference mirror and the two surfaces of the film. An optimized Fourier transform method is used to calculate the optic path differences between each of the two surfaces and the reference mirror. Surface and thickness information can be reconstructed by combining the two measured signals and the refractive index of the thin film. Simulations of the interference signals reveal the limitations of this method.

2. Measurement principle

Figure 1 shows the measurement system, which is composed of two interferometers that share a common optical path. A measurement interferometer, illuminated by a white light source, is used to acquire three dimensional surface data of the sample, in real time. A reference interferometer illuminated by an infrared (IR) Super-luminescent Light Emitting Diode

(SLED) is used to monitor and compensate for environmental disturbance to the normal direction of the system. An Acousto-Optic Tuneable Filter (AOTF) is implemented to select the source light wavelength for the interferometer. The interferogram of the filtered light is detected by the CCD camera.

The selected light wavelength is determined by

$$\lambda = \Delta n \alpha \cdot v_a \Big/ f_a \tag{1}$$

where Δn is the birefringence of the crystal used as the diffraction material, α is a complex parameter dependent on the design of the AOTF, and v_a and f_a are the velocity and frequency of the acoustic wave, respectively. The wavelength of the light that is selected by this diffraction can therefore be varied simply by changing the driving frequency f_a. As a result, different wavelengths of light will pass through the AOTF in sequence so that a series of interferograms of different wavelengths will be detected by the CCD. The absolute optical path difference (OPD) is given by

$$h(x, y) = \frac{\Delta\varphi(x, y, \Delta k)}{2\pi\Delta k} \tag{2}$$

where $h(x, y)$ is the OPD on pixel (x, y) and k is the wave number which is the reciprocal of wavelength. It can be calculated in real time through analyzing the interferogram captured by the CCD by means of FFT analysis or convolution [4, 5].
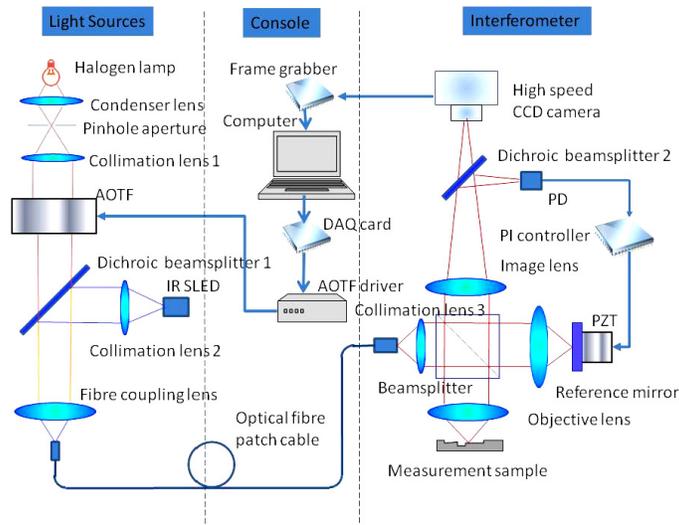

Fig. 1. Schematic diagram of the WSI system.

For the WSI system, reflected signals from both the top and bottom surfaces of a film can produce interference signals with wavefronts from a reference, as well as each other. Figure 2 shows all the reflected and transmitted waves in a film of thickness t and index n. The OPD is h between the reference mirror and the top surface of the film. The incident and reflected amplitudes are A and A_r for the measurement and reference arm respectively. The amplitude reflection and transmission coefficients are ρ and ρ', τ and τ' where the primes indicate reflection or transmission from within the film. The phase difference between successive reflected beams is the same and can be expressed as

$$\Delta\varphi_f = 4\pi n t \cos(\theta')\Big/\lambda \tag{3}$$

where $\theta^{'}$ is the angle inside the film. If no absorption happens in the film we have $\tau\tau'+\rho^2=1$. The reflected interference can be expressed as

$$I_r = I_0\left(F\sin^2\left(\Delta\varphi_f/2\right)\Big/\left(1+F\sin^2\left(\Delta\varphi_f/2\right)\right)\right) \qquad (4)$$

and F is defined as $F=\left(2\rho\big/\left(1-\rho^2\right)\right)^2$. The interference signals generated between the reference signal A_r and each of the reflections of the film, together with the reflected interference of the film, are collected by the CCD camera.
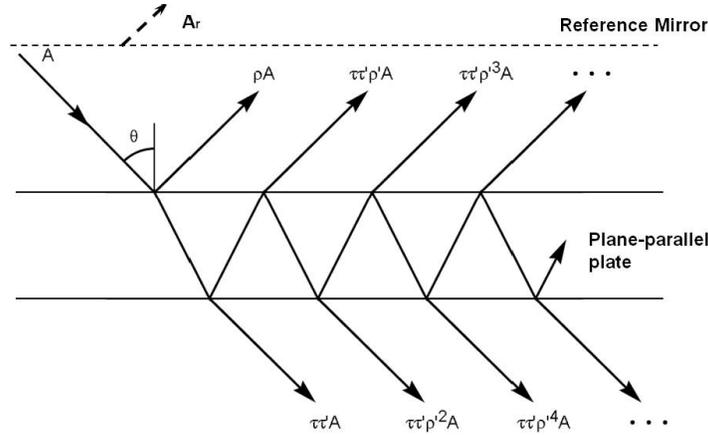
Fig. 2. Multiple beam interference of the two film surfaces and the reference mirror.

(a)

(b)
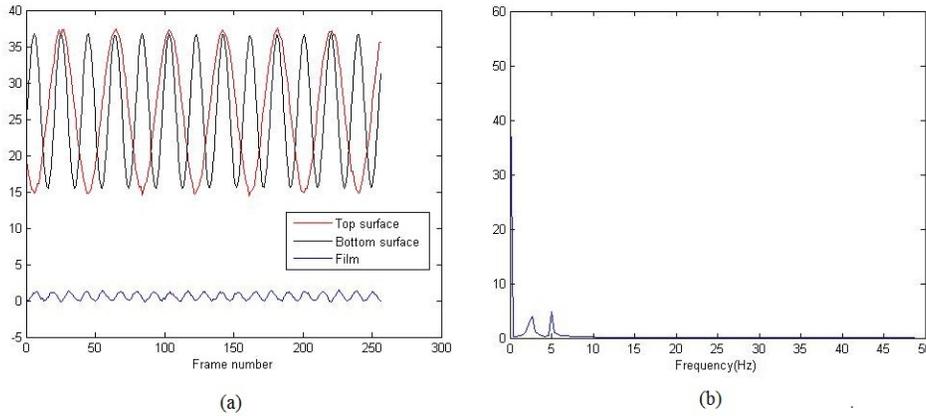
Fig. 3. (a) The three interference signals in the captured signal. (b) FFT analysis result.

Effective separation and identification of the interference signals is the key to film thickness and coating surface measurement. On the basis of the above analysis, a simulation of the interference using Matlab has been conducted. White noises are added to the simulation signals. Assume $A = A_r = 5$, $\rho = 0.05$, $h = 10~\mu m$, $t = 10~\mu m$, $n = 1.51$, and 256 frames are captured as the wavelength is scanned from 682.8nm to 552.8nm. The simulation results show that the two interference signals generated by the reference mirror and each of the first two reflections are the dominant signals compared to the rest of the interference. The amplitudes of the two dominant interference signals are about equal. The amplitude of the

interference between the two film surfaces is approximately 5% of the amplitude of the dominant signals. The other interferences can be ignored.

Figure 3 shows the simulation results using the above parameters. Figure 3(a) shows the three interference signals in the captured signal. Figure 3(b) shows the FFT analysis result of the captured signal. It shows that only the two dominant signals appear in the frequency analysis. This is still true if the parameters h and t change. This simulation shows that a simple FFT analysis can be applied to separate the two surfaces of the film. The surfaces and the film thickness can be reconstructed after filtering the unwanted signals out. The simulation also reveals that the minimum film thickness that this method can measure is 3 μm. The maximum measureable film thickness is restricted by the coherence length of the light.

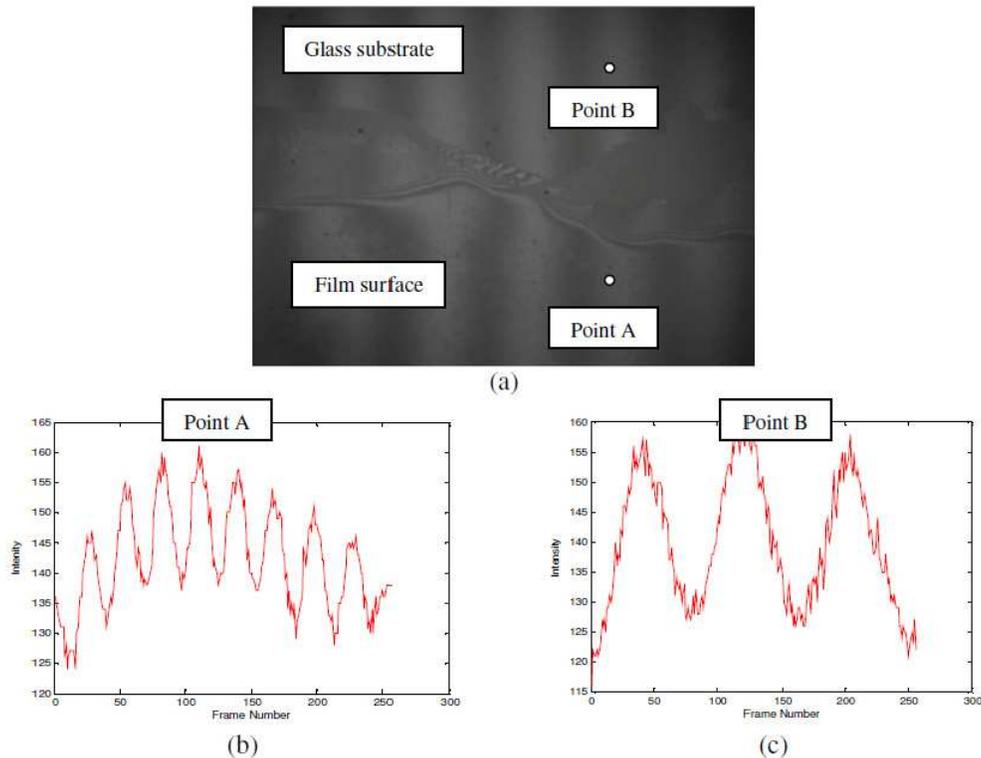## 3. Measurement results and discussion

Fig. 4. (a) Measured image of the sample surface. (b) Interferogram on the film surface. (c) Interferogram on glass substrate.

A Parylene N film with 10 μm nominal thickness, provided by the HiPER target fabrication group, was measured using WSI. The film was coated onto a glass microscope slide, with a refractive index of 1.51. Parylene N is a polymer which is made of highly crystalline material. It is a primary dielectric, exhibiting a very low dissipation factor, high dielectric strength, and a dielectric constant invariant with frequency [10]. It is widely used as a thin film coating material. The refractive index of the Parylene N film is 1.661. In order to make the measurement results more assessable, a cut was made to the sample to form a step of the coating film on the glass substrate. A measurement at the edge of the step was made by WSI. A measured image is shown in Fig. 4(a). A measured interferogram at point A of the Parylene N film surface is shown in Fig. 4(b). This interferogram contains information on the

interference between the reference mirror and the two film surfaces. Figure 4(c) shows the interferogram at point B of the glass substrate.

The measured signals were then analyzed by applying the signal analysis strategy discussed in the previous section. The two reconstructed surfaces of the film are shown in Fig. 5. Figure 5(a) shows the top surface of the film forming a step upwards on the glass substrate. Figure 5(b) shows the bottom surface of the film forming a step downwards on the glass substrate.

The step heights of the films were analyzed using Surfstand, proprietary software developed at the Centre for Precision Technologies for the analysis of surface measurement data. The step height of the top surface is measured as 11.0 μm, which is equivalent to the film thickness. The step height of the bottom of the film is measured as −6.6μm. This yields a total optical path through the film of 17.6 μm. When the refractive index of the Parylene N film is taken into consideration, the measured physical film thickness is found to be 10.6 μm.
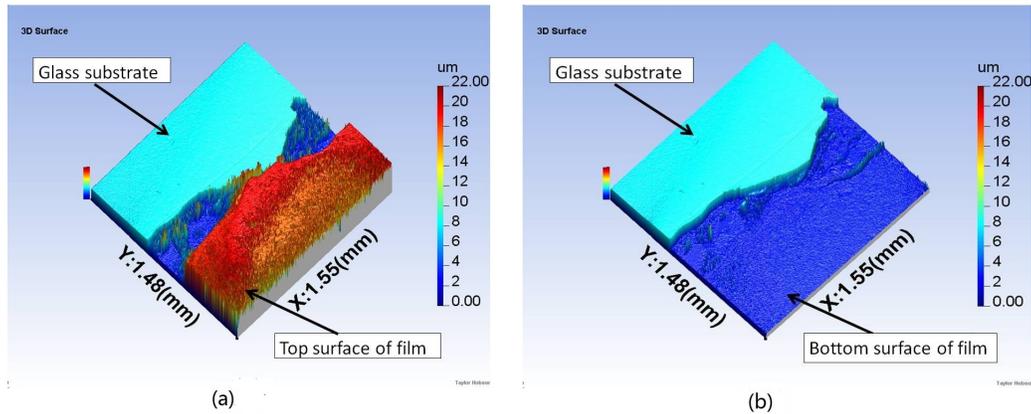

Fig. 5. Measurement data from one area showing: (a) Top surface of the film and glass substrate. (b) Bottom surface of the film and the glass substrate.

Parylene N and glass are both dielectric materials. For normal incidence, the phase change on reflection at the interface of Parylene N and the glass substrate is 180°, due to the lower refractive index of the glass substrate. Conversely, there is no phase change on reflection at the air/Parylene N interface. Given this, the actual film thickness is approximately 10.9 μm, which is half a nominal wavelength more than the original determined value. The measured step heights are shown in Fig. 6. Figure 6(a) shows the analysis at the top surface of the film. The measured signals from the top surface of the film are quite noisy. This is because the interference signals are located just at the edge of the coherence length of our system. Figure 6(b) shows the analysis from the bottom surface of the film. The signals are much improved as the interference occurs within the coherence length of the system.
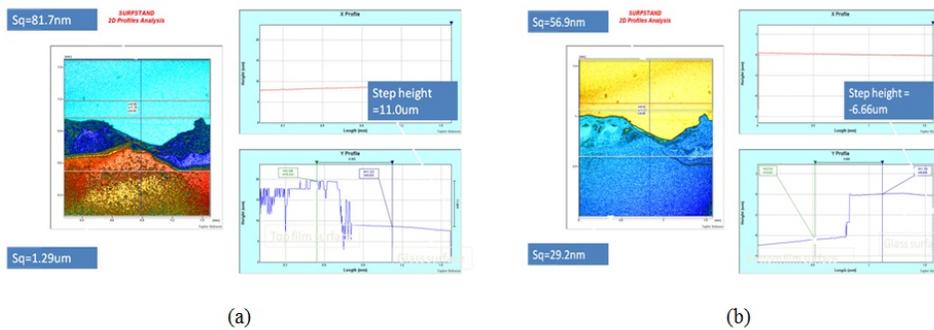
Fig. 6. (a) Reconstructed top surface of the film. (b) Reconstructed bottom surface of the film.

The same sample was also measured using a commercial vertical scanning white interferometer (VSWLI) and a stylus instrument. The measured step heights of the film were 10.23 μm and 10.42 μm respectively. The results for the commercial VSWLI and the subsequent step analysis are shown in Fig. 7. The variation in the measured values of the film thicknesses may be caused by the sampled areas being slightly different for each of the measurements.
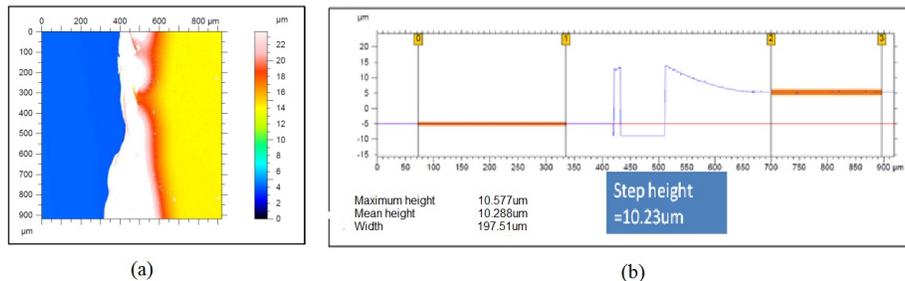

Fig. 7. (a) Measured image of the film on glass substrate by a commercial white light scanning interferometer. (b) Step height analysis of the measured step height.

The above simulation studies, and the measurement on Parylene N film by WSI, is a feasibility study which demonstrates that WSI is able to measure both the top and bottom surfaces of a transparent film, as well as the film thickness, under the condition that the refractive index is known a priori. It provides a method that can quickly evaluate the surface form errors, surface roughness and film thickness in many applications, including the manufacture of cryogenic target capsules for HiPER. Further studies on different films and substrates are necessary.

Acknowledgments