Air etalon facilitated simultaneous measurement of group refractive index and thickness using spectral interferometry

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Received 8 May 2014; revised 2 October 2014; accepted 7 October 2014;
posted 8 October 2014 (Doc. ID 211707); published 30 October 2014

A simple method based on air etalons of a transparent cavity is proposed to simultaneously measure the group refractive index and thickness of a transparent optical plate by spectral domain low coherence interferometry. In this method, only a single beam path is needed in contrast to the two beam paths, the reference and sample arms, of the conventional Michelson interferometer. An empty cavity is first constructed in the beam path by two glass plates. Then the transparent plate under test is inserted into the cavity, so that two air gaps are formed in the cavity. A beam of light of low coherence length is then transmitted through the cavity in the normal direction. Measurements of the reflected waves by the air gaps before and after the sample plate is put into the cavity allow us to determine the group refractive index (n_g) and thickness (d) of the sample simultaneously. The relative precision of the results for d and n_g are both approximately 7×10^{-4}. © 2014 Optical Society of America

OCIS codes: (120.3180) Interferometry; (120.4290) Nondestructive testing; (120.4530) Optical constants; (170.4500) Optical coherence tomography.

http://dx.doi.org/10.1364/AO.53.007483

1. Introduction

Thickness and refractive index are the two important parameters of optical materials used as the elements of various kinds of devices. Many methods in measuring these parameters have been proposed in the past two decades [1–14]. Generally, these methods are mainly based on Michelson interferometry, where the system is composed of two spatially separated arms, the so-called reference and sample arms. Light beams propagating in the two arms are retroreflected by the two mirrors in the corresponding beam path, the reference mirror and the sample mirror, and then merged again in the detection system. These methods can be categorized into two types: time domain [1–5] and spectral domain interferometry [6–14]. For the methods in the time domain, the sample under test or the focal lens needs to scan axially to locate the spatial positions of the front and rear surfaces of the sample relative to the surface of the mirror in the reference arm, whereas for the methods in the spectral domain, surfaces of the sample can be located by means of

1559-128X/14/317483-04$15.00/0

Fourier transformation numerically on the measured interference spectrum. Because no mechanically moving parts are needed, swiftness and ease in optical alignment and system control are thus the evident advantages of the methods in the spectral domain over those in the time domain [15,16].

Principally in Michelson interferometry, the mirror in the reference arm provides a reference plane to which those surfaces in the sample arms are related in terms of optical path differences (OPDs). Refractive index and thickness of the sample plate under test are two coupled parameters in terms of OPDs, so that at least two independent relationships are necessary in order to retrieve the two values simultaneously. We have recently proposed a simple method to decouple them [17].

Haruna *et al.* [1,2] used two glass plates to form an empty cavity and put the sample into it. By scanning the sample stage with respect to the focal point, the four surfaces were located relative to the reference mirror. However, in the spectral domain, regarding the relativeness of the OPD, the reference plane does not have to be located in a separate path from the one in which the sample is being tested.

In this paper, we propose a simple method to measure the OPDs in the spectral domain by setting the reference plane collinearly in the testing arm so that the spatially separated reference arm of the conventional Michelson scheme is unnecessary. Consequently, a more compact measurement system can be established to obtain the group refractive index and the thickness of the sample plate simultaneously.

2. Method and Experiments

Figure 1 shows the experimental setup, which consists of a light source with low coherence length, a sample holding system (illustrated below), and a beam splitter (BS) that deflects the waves back reflected by the surfaces in the sample arm to the detecting system. The detecting system is composed of an achromatic focusing lens, a coupling optical fiber, and an optical spectrum analyzer (OSA), model AQ-6315 A (ANDO Electric Co. Ltd.).

The sample holding system consists of an empty cavity formed by two flat glass plates, which are aligned to let the incident laser beam be incident at the normal direction. The light source used in the measurement was an inexpensive laser pointer (laser diode, LD) bought from the market. Its light intensity and its spectral bandwidth are negatively correlated as the driving voltage changes. In the experiment, the LD was driven at a voltage (approximately 2.1 V) to get a maximized intensity as well as the bandwidth. The measured spectrum was centered at 658 nm with 6 nm full width at half-maximum (FWHM) bandwidth. The OSA was working at 0.1 nm resolution.

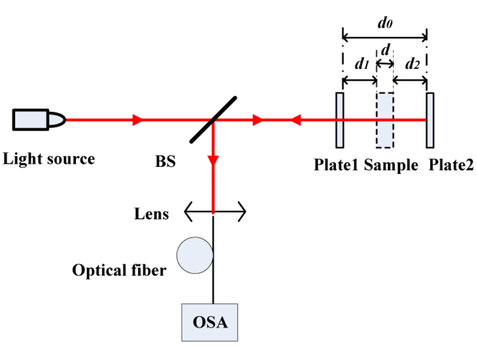

Fig. 1. Schematic of experimental setup. BS, beam splitter; OSA, optical spectrum analyzer.

Before the sample plate under test was put into the cavity, the light beam was transmitted through the empty cavity. The two inner surfaces of the cavity formed an air etalon, which reflected the incoming beam back to the detecting system. The reflected waves interfered in the OSA. By means of Fourier transform, the cavity length represented by d_0 between the two surfaces was obtained.

When the sample under test was inserted into the cavity, two air gaps with four surfaces in the original cavity were formed, and all of them partially reflected the incident light beam back to the detecting system. The single pass OPD between the two surfaces of the solid transparent sample under test is expressed as $d_s = n_g \cdot d$, where the subscript s denotes the sample plate, and n_g and d are the group refractive index and the thickness of the sample plate.

We aligned the sample to make the light beam incident normal to its surface. By measuring the spectrum of the back reflected beams, three peaks corresponding to the three single pass OPDs of the four surfaces in the cavity were obtained.

If the refractive index of the air is taken as 1.0, then the single pass OPDs of the two air gaps are equal to the geometric thicknesses of the two air gaps, as indicated by d_1 and d_2 in Fig. 1. The thickness and the group refractive index of the sample plate d and n_g were obtained as

$$d = d_0 - d_1 - d_2, \tag{1}$$

$$n_g = d_s/d. \tag{2}$$

3. Results and Discussion

The sample used in the measurement was an ITO coated glass. Figure 2(a) shows the interference spectrum reflected by the empty cavity, and Fig. 2(b) shows the normalized spatial spectrum obtained by performing Fourier transform on the interference spectrum of Fig. 2(a). The peak denoted by d_0 is the cavity OPD, d_0.

Figure 3 shows the interference spectrum Fig. 3(a) reflected by the cavity with the ITO glass inserted, and Fig. 3(b) shows the normalized Fourier transformed spatial spectrum. The peaks denoted by d_1, d_2, and d_S are the OPD$_s$ for the two air gaps and the sample plate, respectively.

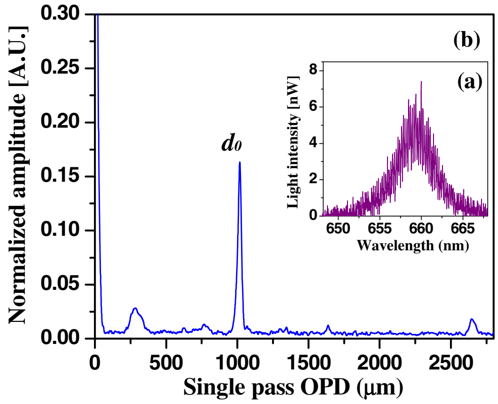

Fig. 2. Interference spectrum of (a) (inset) the empty cavity and (b) its normalized Fourier transformed spatial spectrum.

From Figs. 2 and 3, those values of OPDs are read as $d_0 = 1017.6 \pm 0.3$ μm, $d_S = 1088.6 \pm 0.8$ μm, $d_1 = 121.4 \pm 0.3$ μm, and $d_2 = 188.2 \pm 0.2$ μm, respectively, where the standard error for each of them was obtained by multiple measurements.

According to Eqs. (1) and (2), the thickness and the group refractive index of this ITO glass are readily retrieved as $d = 708.0 \pm 0.5$ μm and $n_g = 1.538 \pm 0.001$, and the relative precisions are 7×10^{-4} and 6.5×10^{-4}, respectively. These results are consistent with our early measurement results [17].

The procedures in the measurements and data analyzing processes described above are very simple and clear in operation, especially in that it is easy to construct the whole system in an all-solid and compact structure with an interfacing port linking to a small OSA. This kind of measurement system might be more compact than a fiber based system and is practical for field-on applications. The precision of this measurement system can be as good as those using complicated stabilized systems [13].

Regarding the measurable depth range (MDR) [10], it can be estimated as

$$z_{\max} = \frac{N}{4}\left(\frac{\lambda_0^2}{\Delta\lambda}\right), \tag{3}$$

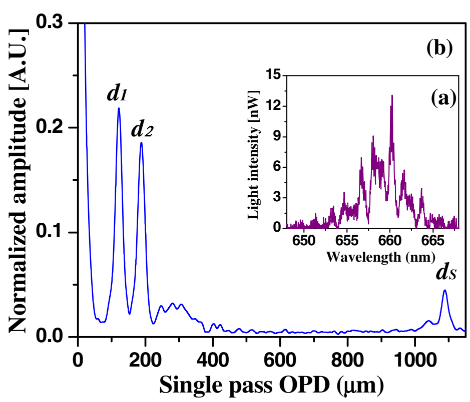

Fig. 3. Interference spectrum of (a) (inset) the cavity with the sample plate inserted and (b) its normalized Fourier transformed spatial spectrum. The sample was a simple ITO coated glass.

where N is the total points of the spectral data, which corresponds to the spectral width ($\Delta\lambda$) in the measurement, and λ_0 is the central wavelength of the spectrum. In our system, $N = 1001$, and the spectrum spans 20 nm in the spectral frame. It is estimated that $z_{\max}$ (in terms of OPD) is about 5.4 mm, which can be applied to measurements on many types of samples, including optical window materials as well as polymer films and plates.

4. Conclusion

Making use of the etalon effect, a simple method of measuring the group refractive index and thickness simultaneously with a single beam path structure in the spectral domain is proposed, which is capable of being made in a more compact structure with sufficient measurement precision.

This work is supported by the Shanghai Committee of Science and Technology with Contract No. 11ZR1403600, and by the Key Laboratory Senior Visiting Scholarship of Fudan University.

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