Self-referenced spectral interferometry for simultaneous measurements of thickness and refractive index

Jihoon Na,¹ Hae Young Choi,¹ Eun Seo Choi,² ChangSu Lee,³ and Byeong Ha Lee¹,*

¹Department of Information and Communications, Gwangju Institute of Science and Technology, 261 Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, South Korea
²Department of Physics, Chosun University, 375 Seosuk-dong, Dong-gu, Gwangju 501-759, South Korea
³Department of Electronic Engineering, University of Suwon, 445-743, San 2-2, Wau-ri, Bongdam-up, Whasung-shi, Kyunggi-do, South Korea
*Corresponding author: leebh@gist.ac.kr

Received 21 January 2009; revised 23 March 2009; accepted 13 April 2009; posted 13 April 2009 (Doc. ID 106621); published 23 April 2009

We present a method for simultaneously measuring the thickness and the group refractive index of a specimen using self-referenced spectral-domain fiber-based interferometry. By removing the scanning part and using the fiber-based configuration, the system complexity and stability could be significantly improved. To minimize the system drift, we utilized the signals originated from the fiber ends of both arms. Implementing in a self-referenced configuration, we could improve the measurement accuracy down to a decimal place. Experimental measurements were made with a 1.555 mm thick fused silica plate. At 814 nm the thickness was measured as 1.5546 ± 0.0002 mm, and at the same time, the group index was obtained as 1.4627 ± 0.0002. © 2009 Optical Society of America

OCIS codes: 120.3180, 120.4290, 170.4500.

1. Introduction

Optical measurements of the refractive index and the thickness of transparent specimens such as glass plates, thin films, and biological tissues or living cells are increasingly essential in the optical engineering [1,2] and biomedical [3–5] fields. Typically, the thickness measured by conventional optical methods is not the geometric thickness but the optical thickness, defined by the product between the refractive index and its geometric or physical thickness. To differentiate the geometric thickness from its optical thickness, a number of methods have been suggested [6–8], some based on time-domain low-coherence interferometry or/and confocal optics [2,6,9].

Recently, we have reported the simultaneous measurement technique that could separate the phase index, the group index, and the geometric thickness of an optically transparent object by combining time-domain optical low-coherence interferometry and confocal optics [10]. In practice, however, such an optical interferometric system is easily affected by external or environmental condition changes such as vibration, temperature drift, and air turbulence. The situation may in fact be worsened with a time-domain interferometer since mechanical scanning is necessary in either the sample or the reference arm of the interferometer. Thus, for practical applications, it is evidently desirable to minimize the scanning parts in the measurement system. Further, if possible, getting or extracting the signal that can report the system drift could highly increase the measurement accuracy also.

We present a technique for self-referenced measurements of the physical thickness \( t \) and the group index \( n_g \) of a specimen by using fiber-based spectral...
interferometry. We report that the measurement stability is improved by adapting the spectral-domain scheme, and the system complexity is highly reduced by using the fiber-based configuration. Additionally, by using the interference signal originated from the free ends (FEs) of both arms of the interferometer, the system drift is appreciably compensated. For subsequent verification of the system, measurements are made with a 1.555 mm thick fused silica plate at three different wavelengths (814, 1050, and 1310 nm). The measurement results are fully analyzed and evaluated.

2. Methods

The schematic of the experimental setup is shown in Fig. 1; it is a fiber-based spectral interferometer. A light beam from a superluminescent diode (SLD) is launched to the input port of a 3 dB fiber coupler and then split into the reference and the sample arm ports. The beams reflected from both arms are recombined by the same coupler and interfered with each other at the detection port of the coupler. The wavelength spectrum of the interference signal is then measured and recorded using an optical spectrum analyzer (OSA). Of course, by doing the inverse fast Fourier transform (IFFT) with the spectrum [11], the depth information, including the thickness and the refractive index of the specimen, is extracted.

Figure 2 illustrates the measurement processes. At first, the wavelength spectrum of the interference signal is measured without placing the specimen at the sample arm. The IFFT of this spectrum, shown at the right-hand side of Fig. 2(a), gives the coherence function generated by the interference between the beams reflected from the flat reflector (FR) at the sample arm and the beam from the reference mirror (RM) at the reference arm. With this measurement, the length of the reference arm is adjusted to ensure that the optical path-length difference (OPD) between both arms are within an approximately 2 mm range. As the second step, the same measurement is made with the specimen as shown with Fig. 2(b). In this case, the IFFT gives two coherence functions resulted from the front surface (FS) and the rear surface (RS) of the specimen, in addition to the original signal from the FR of Fig. 2(a). In the figure, the distance between the signals from FS and RS is denoted as \( \Delta t \), which corresponds to the optical thickness of the specimen. Note that, with the specimen, the signal from FR is shifted by \( \Delta \), as denoted with the dotted and the solid arrows at the right-hand figure in Fig. 2(b). From the measurands, \( \Delta t \) and \( \Delta \), it is well-known that the desired variables \( t \) and \( n_g \) of the specimen are simply extracted as [12]

\[
t = \Delta t - \Delta,
\]

\[
n_g = \frac{\Delta t}{t}.
\]

However, as mentioned, the interferometer itself is easily affected by the environmental variation. Further, the actual measurements might have additional signals due to unattended facets in the interferometers and/or multireflections. Therefore, by analyzing these additional signals, we might extract the information that can compensate the system drift, thus increasing the measurement accuracy. The detail process is followed and analyzed with real measurements.

3. Experimental Results

A. Sample Measurements

Figure 3 shows the interference spectrum experimentally measured without [Fig. 3(a)] and with [Fig. 3(b)] a specimen, a piece of fused silica plate having a thickness of 1.555 mm. The light source was an SLD having a center wavelength of 1310 nm and a 3 dB bandwidth of 40 nm. The depth information obtained by taking IFFT of the measured spectra, Figs. 3(a) and 3(b), are shown with Figs. 3(c) and 3(d), respectively [11]. In Fig. 3(c), the no-specimen case, we can see a strong peak at \( \sim 2.0 \text{ mm} \), originating from the interference between the FR of the sample arm and the RM of the reference arm. The small peak near 1.1 mm, denoted as FE\( \sim \)FE\( \text{initial} \), is confirmed to be resulted from the FEs of both arms. The FE is the end facet of a fiber in each arm of the fiber-based interferometer, out of which the beam can go to free space. With the specimen, as Fig. 3(b)
shows, the wavelength spectrum became complicated, and several additional peaks appeared in its IFFT figure [Fig. 3(d)]. First, the two new strong peaks at 0.25 and 2.5 mm were resulted from the FS and the RS of the specimen plate, respectively. Second, the signal from the FR that had appeared at ∼2.0 mm in Fig. 3(c) was observed at a shifted position of ∼2.7 mm, as indicated by FR’ in Fig. 3(d). Interestingly, the FE–FE peaks were the same in both measurements. We could also see several small peaks, as denoted by “A,” resulting from the autocorrelation of the signals coming out of the specimen [11].

To analyze the origins of the big and small peak signals in Fig. 3, a series of measurements were performed. As Fig. 4(a) shows, at first, the interference spectrum of the system was measured after blocking both the sample and the reference arms of the interferometer. We could see well-developed interference fringes. The IFFT signal of it, Fig. 4(c), showed a single dominant peak resulted from the FE–FE interference as mentioned before. Next the sample arm was opened while keeping the reference arm closed, which gave the autocorrelation signals of the sample arm in addition to the FE–FE signal as shown with Figs. 4(b) and 4(d). All measured data for Figs. 3 and 4 were converted to a linear scale and applied a Hamming window to mitigate spectral leakage [13]. Additionally, the IFFT signals were normalized with the strength of the FE–FE signal.

With the background measurements of Fig. 4, the measurements in Fig. 3 could be precisely clarified. Figure 5 simultaneously shows the two measurements made in Fig. 3, taken without (dotted curve) and with (sold curve) the specimen, in which the FE–FE signal and the autocorrelation signal were successfully removed by subtracting the signal of Fig. 4 from the one of Fig. 3. With these background measurements, as can be seen in Fig. 5, we could clearly resolve the optical path-length of the sample Δℓ and the amount of shift Δ induced by the group index of the sample. The remaining task is then the simple calculation of the desired variables t and n_g by using Eqs. (1) and (2). The nonindicated small peaks of Fig. 5 are believed to be originated from multiple reflections at the sample boundaries.

B. Self-Referenced Measurements

As mentioned, since the FE–FE peak is not affected by the specimen presence but moves with the system drift, it could be used as the reference for compensating the system drift. In the actual measurements, we observed a small deviation in the absolute position of each peak. The deviation, or the system drift, was thought to be due to vibration, temperature drift, and/or air turbulence around the interferometer.

---

Fig. 3. (Color online) Spectra measured (a) without and (b) with a specimen and their inverse Fourier transformed signal (c) for spectrum (a) and the signal (d) for spectrum (b). The measurements were made with a 1.555 mm thick fused silica plate at a wavelength of 1310 nm. FR’, shifted FR; A, autocorrelation signal.
Experimentally, there was no appreciable problem in obtaining $\Delta \ell$ since it was a relative value. It was taken with a single measurement, thus not affected by the system drift. However, the shift $\Delta$ was taken as the difference between the two values, $F_{R}'$ and $F_R$, obtained at two different measurements, thus could be under system drift. In our experiment, the shift in $\Delta$ was observed as much as a few micrometers in successive measurements.

To overcome this system drift problem, the FE–FE signal is utilized because it is also affected by the system drift. The shift $\Delta$ in Fig. 5 was defined as the difference between two absolute values as

$$\Delta = F_{R}' - F_R.$$  \hspace{1cm} (3)

This is also expressed with the difference between two relative values as

$$\Delta = [F_{R}' - (F_{E}-F_{E})_{\text{sample}}] - [F_{R} - (F_{E}-F_{E})_{\text{initial}}].$$  \hspace{1cm} (4)

Since the FR signal and the FE–FE signal are moving with the system drift at a similar rate, we can overcome the system drift problem by taking the difference in each measurement of Fig. 3. The best advantage of the proposed scheme is that, once we made the initial measurement of Fig. 3(c), without the specimen, we do not need any more reference measurements. The single measurement with a specimen is enough to get the thickness and the refractive index of the specimen even under system drift. The FE–FE signal could work as the reference

![Image](https://example.com/image.png)
moving with the system under drift. Practically, under normal laboratory conditions, the OPD of the fiber-based interferometer can be fluctuated in the order of a few micrometers, which directly influences the refractive index measurement in the order of $10^{-3}$ when the specimen thickness is in the order of millimeters.

C. Measurement Results

With a fused silica plate of approximately 1.555 mm thickness, the refractive index measurements, the group index in this case [10], were made with the shift $\Delta$ of Eq. (3) and the proposed one of Eq. (4) and then compared to each other. Ten identical measurements were made successively with the same scheme; the scheme with the $\Delta$ value of Eq. (3) for Fig. 6 and with Eq. (4) for Fig. 7. As can be seen from the figures, the system drift was appreciably reduced by utilizing the FE–FE signal. Including the physical thickness measurements, the experimental results are summarized in Table 1. The experiments were made at three different wavelengths of 814, 1050, and 1310 nm, with the full width at half maximum bandwidths of 35, 50, and 40 nm, respectively.

Without moving the sample specimen, ten measurements were made with each SLD source, and the data were averaged. The reference geometric thickness of the fused silica plate, 1.555 mm, was obtained by using a digital micrometer having a resolution of 1 $\mu$m. The reference group index of the fused silica was calculated with the Sellmeier equation [14]. The table says that the measured values are well matched with the reference values, not only in the group index but also in the thickness measurements, for both schemes, with and without the proposed self-referencing. However, the standard deviation of the ten measurements, or the measurement error, became almost ten times smaller with the self-referencing. Therefore, we can conclude that the measurement accuracy can be significantly increased by using the FE–FE signal as the self-reference of the measurement.

4. Discussion

As one knows, the sample illumination area mainly depends on the numerical aperture (NA) of the focusing optics and the diameter of the input beam. In our experiment, an achromatic objective (5x, NA 0.1) was used, but we did not put much attention on the lateral resolution, because the sample specimen was just a flat and thin glass plate. Of course even a collimated beam can be used in this simple case. However, when the lateral structure of the sample is complicated, thus sample scanning is necessary, the lateral resolution should be carefully considered. In our case, the lateral resolution or the illumination area was calculated to be 26 $\mu$m (at 814 nm), 32 $\mu$m (at 1050 nm), and 42 $\mu$m (at 1310 nm). If we want to measure the thickness distribution of a laterally complicated sample such as a living cell with a high resolution, we can think of utilizing a full-field optical coherence tomography (FFOCT) scheme [15,16]. With the FFOCT system, we can expect a submicrometer order of later resolution; however, it is out of the scope of this work, unfortunately.

On the other hand, the depth resolution $\Delta z$ of the interferometry is limited by the coherence length $\ell_c$ of the light source and is given by the well-known equation of

$$\Delta z = \frac{\ell_c}{2} = \frac{2 \ln 2}{\pi} \left( \frac{\lambda_0^2}{\Delta \lambda} \right),$$

where $\Delta \lambda$ is the spectral bandwidth and $\lambda_0$ is the center wavelength of the light source. With this equation, the depth resolution or the coherence length was calculated as 8 $\mu$m (at 814 nm), 10 $\mu$m (at 1050 nm), and 19 $\mu$m (at 1310 nm) and experimentally measured as 10, 11, and 20 $\mu$m, respectively. However, since we could have a well-developed
coherent function signal from the sample, owing to its simple structure, reading the center of the Gaussian-like coherent function could be made with high accuracy, in a submicrometer range. The optical resolution of the OSA determines the measurable range of the system. As is well-known, the spectral frequency of the interference signal increases as the OPD increases, and the sampling rate should be two times higher than the highest signal frequency, according to the sampling theorem [13]. With this consideration, the measurable depth range is given by [11]

\[ z_{\text{max}} = \frac{1}{4n} \left( \frac{\lambda^2}{\delta \lambda} \right), \]

where \( n \) is the refractive index of the specimen and \( \delta \lambda \) is the spectral resolution of the OSA. In our setup, the resolution of the OSA was 0.06 nm so that the measurable ranges were calculated as 1.8 mm (814 nm), 3.1 mm (1050 nm), and 4.8 mm (1310 nm), with the assumption of \( n = 1.5 \). Of course, by shifting the reference arm of the interferometer, we can always increase the measurable depth range.

5. Conclusion

We have presented a method for measuring the geometric thickness and the group refractive index of a transparent specimen using the self-referenced spectral-domain fiber-based interferometry. By adopting the spectral-domain scheme, we could obtain the physical variables—thickness and refractive index—of a specimen without any mechanical scanning or asking any prior information about the specimen. By implementing the system in a fiber-based configuration, the system complexity and compactness could be highly improved. Furthermore, by using the signal inherently generated from the fiber ends of both interferometer arms as the self-reference, the drift problem of the system could be highly reduced. With a 1.555 mm thick fused silica plate, the geometric thickness was measured at a standard deviation of \( 2 \times 10^{-4} \) mm. With a deviation of \( 2 \times 10^{-4} \), the group index was obtained as 1.4667 at a wavelength of 814 nm, 1.4629 at 1050 nm, and 1.4613 at 1310 nm. We expect that the proposed measurement technique can be applied to various fields, including optical engineering, material science, and biomedical measurements.

This work was partially supported by Korea Science and Engineering Foundation (KOSEF) grants funded by the Korea government Ministry of Education, Science, and Technology (MEST) (grant no. R01-2007-000-20821-0 and NCRC grant no. R15-2008-006-02002-0) and by a grant from the Institute of Medical System Engineering (iMSE).

References


<table>
<thead>
<tr>
<th>Sample</th>
<th>Wavelength [nm]</th>
<th>Group Index ((n_g))</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused</td>
<td>814</td>
<td>1.4667 ± 0.0019</td>
<td>1.5526 ± 0.0020</td>
</tr>
<tr>
<td>Silica</td>
<td>1050</td>
<td>1.4625 ± 0.0009</td>
<td>1.5563 ± 0.0010</td>
</tr>
<tr>
<td></td>
<td>1310</td>
<td>1.4612 ± 0.0005</td>
<td>1.5557 ± 0.0005</td>
</tr>
</tbody>
</table>

