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Abstract. An improved structure for the optical coherence tomography (OCT) scheme based on a 4×4 fiber coupler for simultaneously measuring the refractive index and thickness of optical samples is presented. The proposed structure incorporates the optical path length difference of interference light and is used to calculate the refractive index and thickness of an unknown sample without any prior knowledge of the sample parameters. Two methods (time-domain and Fourier-domain OCT) of obtaining information about an unknown sample are proposed, and a high-speed high-resolution OCT system was developed. [DOI: 10.1117/1.OE.53.4.044108]

Keywords: optical coherence tomography; refractive index; thickness; fiber loop mirror.

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1 Introduction

Optical coherence tomography (OCT) is a novel, noninvasive high-resolution imaging technique that can be used to analyze the inner structure of a detected sample in detail. The researchers frequently use OCT to inspect elements in the biomedical and industrial fields. Generally, OCT can be divided into two categories: time-domain OCT (TD-OCT) and Fourier-domain OCT (FD-OCT). TD-OCT and FD-OCT can be used to scan complex samples. These noninvasive approaches have become vital techniques for medical diagnosis because they have the advantages of revealing the surface of an organism in high resolution. The OCT technique continues to develop with the expansion of the diagnosis region and improvements in high-quality analysis. The most common application of OCT is in ophthalmology[1] for retinal imaging to detect quantitatively the thickness of nerve fibers and produce high-resolution retinal images. As the OCT technique has been developed, it has been used to measure the inner structures of biological samples to provide high sampling rates and sensitivity, and to facilitate three-dimensional imaging analysis.[2–5]

OCT is a new biomedical detection technique in which a Michelson interferometer, Mach-Zehnder interferometer, or a common-path interferometer is often used as the system structure. The earliest OCT application, proposed a few decades ago, involved the combined structure of a white-light interferometer and Michelson interferometer, which was used as a one-dimensional optical length detection technique.[6] Recent studies have presented numerous designs and OCT methods for measuring the optical parameters of a substance. Several studies have adopted ellipsometry techniques to determine the refractive index and thickness of a subject by using the Fresnel equation.[7,8] Jin et al. proposed a method for measuring the geometrical thickness and the refractive index of a silicon wafer by using spectral domain analysis. The geometrical thickness was determined without the use of any moving parts.[9] Swillo et al. described an optical fiber coherence tomography system characterized by a Fizeau-based configuration with doubled pulses. This method was used to calculate the transmission coefficient of a sample by comparing suitable amplitudes of harmonic components in the detected signals.[10] Chen et al. presented a simple fiber-optic sensor based on the Fabry-Perot interference for measuring the optical glass refractive index.[11] Verma et al. demonstrated the use of common-path spectral-domain OCT for measuring the refractive index of a biomimetic material and a single biological cell.[12] Tsai et al. demonstrated a new method for evaluating the properties of indium tin oxide conduction glass and identifying its defects. This approach can be used to estimate several parameters simultaneously, including thickness, refractive index, reflection coefficient, and transmission coefficient.[13] Several previous studies have incorporated a wavelength-tuning interferometer for measuring the absolute optical thickness of a mask glass[14] or the thickness and refractive index of a transparent plate simultaneously.[15,16]

Based on the previous discussion of simultaneously measuring thickness and refractive index,[17] and the subsequent improvement achieved using a fiber loop mirror to reduce the experimental time for convenience and speed,[18] FD-OCT was used in this study to expedite the overall experimental measurements. Compared with previously used free-space OCT,[17] this construction offers the advantages

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of compactness, portability, low cost, and low complexity, and reduces the alignment time. Moreover, the same optical design can be used to measure the refractive index and thickness of an optical sample by performing FD-OCT. FD-OCT can be used to acquire information on a sample immediately by analyzing the spectrum of the interference signal, such as the direct current (DC) term, autocorrelation term, and conjugate terms, and, therefore, requires less time for detection than TD-OCT does. In addition, the position of the reference mirror in the reference arm does not need to be changed when using the scanning device to acquire axial depth information on the sample.

2 Theory and Analysis Methods

Figure 1 shows a sketch of the proposed structure. All optical components are connected by a 4×4 fiber coupler (25% splitting ratio). This structure consists of a low-coherence light source, an optical spectrum analyzer (OSA), a photodetector, a data acquisition (DAQ) card, a 4×4 fiber coupler, two collimators, two mirrors, the sample (S), and a fiber loop mirror. In addition, the mirror M_1 is placed on a movable stage with a speed that is controlled by a computer. In this optical path design, the arm with mirror M_1 is the reference arm, and the arm with M_0 is the detection arm. The fiber loop mirror is the other reference arm in this design. The optical direction indicates that the light reflected from the reference and detection arms are coupled by the 4×4 fiber coupler, and the coupled light is transmitted to the photodetector containing the DAQ card and OSA for analysis. Finally, information on the unknown sample can be acquired by analyzing the interference signals of the reference and detection arms. By using the photodetector containing the DAQ card and OSA, conducting two methods of analysis, TD-OCT and FD-OCT, is possible. Both methods involve using the optical length difference corresponding to the interference between M_1 and the fiber loop mirror, between M_1 and the left side of the sample surface, between M_1 and the right side of the sample surface, and between M_1 and the mirror M_0.

Figure 2 shows that P_1, P_2, P_3, and P_4 are the optical path lengths of reflected light from the two samples' surfaces, M_0, and the fiber loop mirror, respectively. Therefore, before measuring the unknown sample, adjusting the mirror M_0 to obtain the same optical path length as that of the fiber loop mirror is necessary. At this step, the arm of mirror M_1 is inserted in the shutter for preventing unnecessary interference. According to Fig. 2, the relationships among P_1, P_2, P_3, and P_4 can be described as follows:

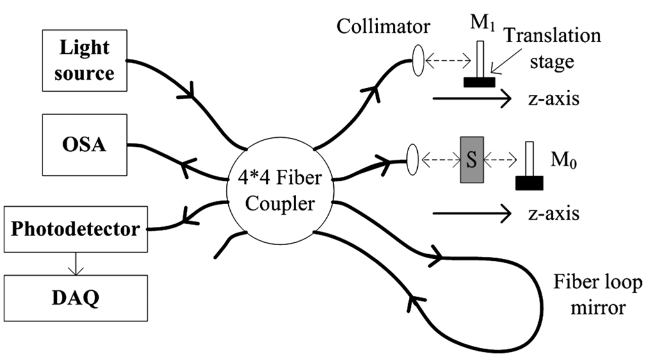

Fig. 1 Schematic drawing of the improved structure. This structure consists of a low-coherence light source, an optical spectrum analyzer (OSA), a photodetector, a data acquisition (DAQ) card, a 4×4 fiber coupler, two collimators, two mirrors (M_0 and M_1), the sample (S), and a fiber loop mirror.

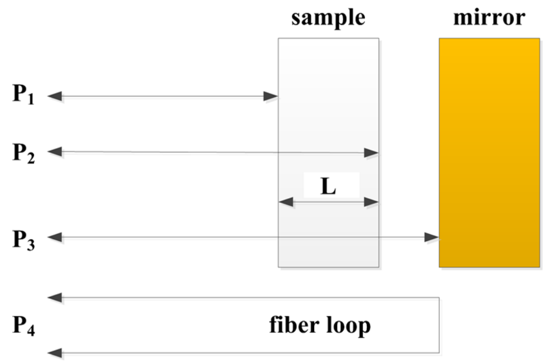

Fig. 2 Schematic diagram of optical path in detection arm.

$$d_1 = P_2 - P_1 = n_s \times L, \tag{1}$$

$$d_2 = P_3 - P_4 = (n_s - n_a) \times L, \tag{2}$$

where d_1 and d_2 are the optical path length difference between P_1 and P_2, and P_3 and P_4, respectively; n_s and n_a are the refractive indices of the unknown sample and air, respectively; and L is the thickness of the sample. The refractive index of air was $n_a = 1$ in this experiment. However, this formula is based on a homogeneous medium. By solving Eqs. (1) and (2), deriving Eq. (3) for measuring the refractive index of an unknown sample, and substituting the refractive index n_s back into Eq. (1), determination of thickness L is possible.

$$n_s = n_a \frac{d_1}{d_2 - d_1}. \tag{3}$$

This analysis indicates that knowing any parameters of the unknown sample in advance is not required. It is only necessary to obtain the optical path length difference between each path to calculate the refractive index and thickness. Two methods can be used to obtain the optical path length difference: TD-OCT and FD-OCT analysis. These methods involve the use of only a few mathematical operations to obtain the optical path lengths P_1, P_2, P_3, and P_4.

To perform measurements by using TD-OCT, before the unknown sample is inserted, adjusting the optical path length between the arm with mirror M_0 and the fiber loop mirror is necessary. This can be achieved by modifying the position of mirror M_0. In this process, a light shutter in the reference arm M_1 is used to prevent unnecessary interference signal reflections caused by mirror M_1.When the optical path length of the arm with mirror M_0 is the same as that of the fiber loop mirror, the unknown sample can be inserted into the position between the collimator and M_0, and then the measuring process can begin. Thereafter, mirror M_1 is placed in a suitable position for the scanning process. The unknown sample, mirror M_0, and the fiber loop mirror remain stationary when the scanning operation is performed by using the translational stage to move the reference arm with M_1 at a constant velocity. When the reference arm with M_1 changes the optical path length, it generates interference signals. Finally, the optical path length can be acquired by multiplying the time intervals between the interference signals by the constant velocity of the translation stage. The refractive index and the thickness of the unknown sample can be obtained using Eqs. (1), (2), and (3).

For performing measurements by using FD-OCT, first, the optical path difference between the arm with mirror M_0 and the fiber loop mirror is adjusted to zero before beginning the measurement process. The unknown sample is then inserted, and the reference arm with mirror M_1 is adjusted to an appropriate position and fixed for the following measurement. When beams are backscattered and reflected from the reference arm and sample arm at the coupler, the interference signal is detected by the OSA. By using Fourier transform on the spectrum of the interference signal, calculating the interference in the z axis, which contains the information on the depth of the sample arm, is possible. Thus, the interference signals can be obtained, and the optical path difference between each signal can be calculated. Finally, the information on the unknown sample, including the refractive index and thickness, can be obtained using Eqs. (1), (2), and (3) during TD-OCT analysis. Figure 3 shows the flow chart for TD-OCT and FD-OCT.

3 Experimental Results and Discussion

The experimental setup includes an ASLD155-200 light source with a power of 17.5 mW, a central wavelength of 1550 nm, and a spectral bandwidth of 61.92 nm. In the proposed OCT system, the axial resolution Δz is determined by the coherence length l_c of the light source. The axial resolution can be calculated as follows if the spectrum of the light source has a Gaussian distribution:

$$\Delta z = \frac{l_c}{2} = \frac{2\ \ln 2}{\pi} \frac{\lambda_0^2}{\Delta\lambda} \approx 0.44 \cdot \frac{\lambda_0^2}{\Delta\lambda}, \tag{4}$$

where λ_0 is the central wavelength of the light source and $\Delta\lambda$ is the bandwidth. Equation (4) shows that the resolution of the proposed system is $\sim$17.072 μm. Therefore, under this restriction, the thickness of the tested sample cannot be smaller than the system resolution, or the proposed method cannot be performed successfully. The performance of the proposed system in measuring the thickness and the refractive index of the glass sample was evaluated using an optical sample with a thickness of 1.090 mm and refractive index of 1.516. The parameters of the optical sample were measured using TD-OCT and FD-OCT.

In TD-OCT analysis, the two-step calibration procedure described in Sec. 2 was performed prior to the measurement process. TD-OCT was conducted using a Labview software package, which interacted directly with the translation stage and the photodetector. The interference signal was received by the photodetector containing the DAQ card in the time domain from 0 to 10 s. The translation stage was acquired from Sigma Koki Co., Ltd. (Model SGSP 20-35, Japan). During the scanning experiments, the stage was moved with a constant velocity of 0.5 mm/s while performing TD-OCT. The translation stage was controlled using a GSC-0 stage controller (Sigma Koki Co., Ltd.) through the RS-232C interface of a personal computer.

As Fig. 4 shows, the four interference signals (A, B, C, and D) between the reference arms and the detection arm can be identified after scanning. These four interference signals correspond to the left (A) and right (B) surfaces of the sample and the surfaces of mirror M_0 (C) and the fiber loop mirror (D). The optical path distance shown in Fig. 4 can be obtained by multiplying the time intervals between the interference signals by the constant velocity of the translation stage in the reference arm. Therefore, Eqs. (1) and (2) were used to obtain the values of d_1 and d_2, respectively. From Eq. (3), the refractive index of sample n_s was determined to be $n_s = 1.544$. After obtaining the value of the refractive index, n_s was substituted back into Eq. (1) to determine the thickness of the optical sample, which was $L = 1.069$ mm.

Table 1 shows five repeated measurement results obtained from the same glass sample ($n_s = 1.516$, $L = 1.09$ mm). The mean values of the refractive index and the thickness were calculated to be 1.542 and 1.072 mm, respectively. The standard deviations of the refractive index and the thickness obtained from the five repeated measurements were 0.0046 and 0.0047 mm, respectively. According to Table 1, the maximal error and average error of the refractive

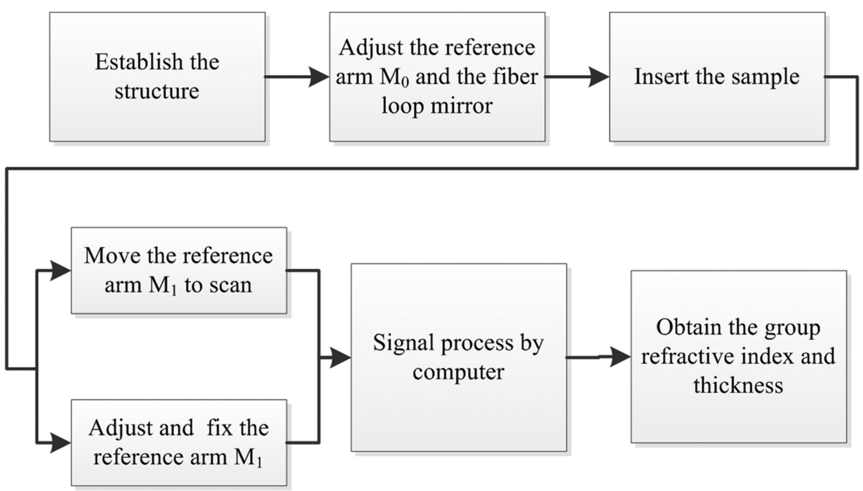

Fig. 3 Flow chart of postprocessing steps of the measurement.

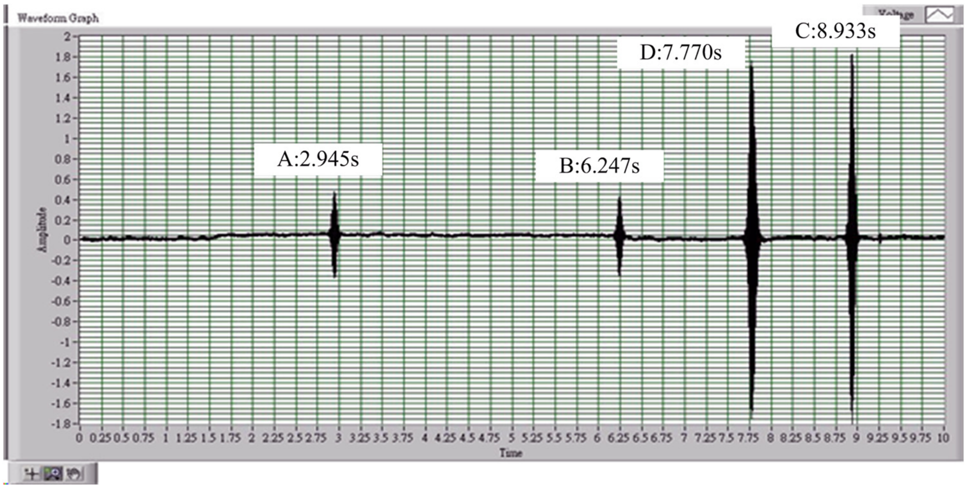

Fig. 4 The interference signals are obtained by Labview in time-domain analysis.

index between the measured results and the real parameters of the glass sample at 1550 nm were −2.11 and −1.74%, respectively. Furthermore, the maximal error and average error of the thickness between the measured results and the real parameters of the glass sample were 2.20 and 1.65%, respectively. Comparisons between the measured and real parameters of the glass sample indicated good agreement. Using the proposed TD-OCT scheme has the advantage of simultaneously measuring the refractive index and the thickness of the sample.

In FD-OCT analysis, the two-step calibration procedure described in Sec. 2 was performed prior to the measurement process. The optical spectrum of the interferogram in FD-OCT was measured using an OSA (Anritsu MS9710C) with a resolution of 0.1 nm (from 1500 to 1600 nm, 1001 sampling points). The depth range of FD-OCT is determined by the maximal number of fringes within the spectral width recorded using the OSA. The maximal depth position $z_{\max}$ is limited by the OSA wavelength resolution $\delta\lambda$ and is given by

$$z_{\max} = \frac{\lambda^2}{4\delta\lambda}. \tag{5}$$

Therefore, in this experimental setup, $z_{\max}$ was 6 mm. To increase the depth range, increasing the spectral resolution or the number of sampling points is necessary.

Figure 5 shows the signals produced using FD-OCT, and the inverse Fourier transform (IFT) of the interference spectrum detected by the OSA. Three signals were obtained using the IFT calculation: the DC term, autocorrelation term, and the interference signals produced by sample and mirror surfaces (A, B, C, and D) and its conjugate terms. In Fig. 5, the four interference signals correspond to the left (A) and right (B) surfaces of the sample and the surfaces of mirror M_0 (C) and the fiber loop mirror (D). The signals produced by the surfaces include A, B, C, and D, which are 1.170, 2.820, 4.554, and 3.996 mm on the z axis as shown in Fig. 5, respectively. The autocorrelation term signal may affect the determination of the

Table 1 Five repeated measurement results of a glass sample with time-domain optical coherence tomography.

	A (s)	B (s)	C (s)	D (s)	$d_1 = B - A$ (s)	$d_2 = C - D$ (s)	$n_s = d_1/(d_1 - d_2)$	$L = (d_1 \times 0.5)/n_s$ (mm)
1	2.945	6.247	8.933	7.770	3.302	1.163	1.544	1.069
2	1.572	4.873	7.869	6.701	3.301	1.168	1.548	1.066
3	2.400	5.711	7.996	6.840	3.311	1.156	1.536	1.078
4	2.414	5.724	8.006	6.845	3.310	1.161	1.540	1.075
5	4.145	7.455	9.005	7.839	3.310	1.166	1.544	1.072
						Mean	1.542	1.072
						Standard deviation (σ)	0.0046	0.0047
						Mean $\pm\, \sigma$	1.542 ± 0.0046	1.072 ± 0.0047
						Real parameters of glass sample	1.516	1.090
						Maximum error (%)	−2.11	2.20
						Average error (%)	−1.74	1.65

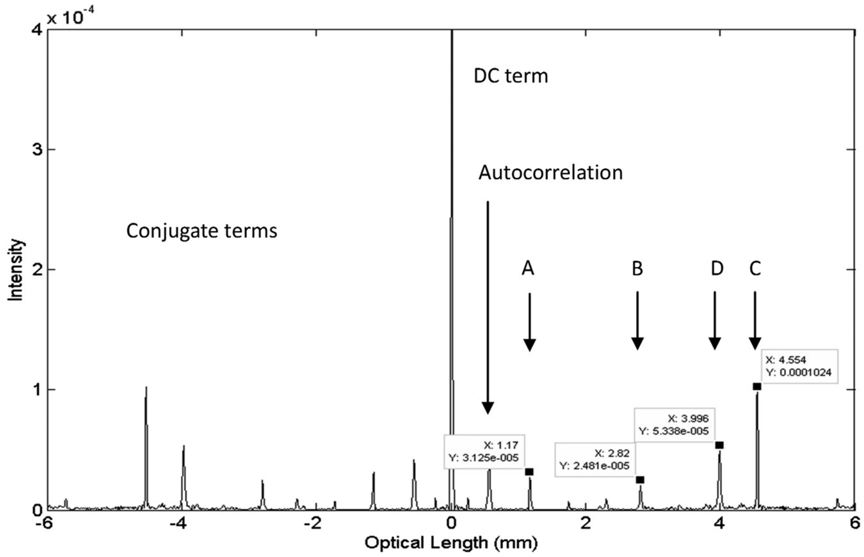

Fig. 5 The demodulated signal of the interferogram along the z axis.

Table 2 Five repeated measurement results of a glass sample with Fourier-domain optical coherence tomography.

	A (mm)	B (mm)	C (mm)	D (mm)	$d_1 = B - A$ (mm)	$d_2 = C - D$ (mm)	$n_s = d_1/(d_1 - d_2)$	$L = d_1/n_s$ (mm)
1	1.170	2.820	4.554	3.996	1.650	0.558	1.511	1.092
2	2.988	4.638	5.436	4.884	1.650	0.552	1.503	1.098
3	1.224	2.868	5.304	4.734	1.644	0.570	1.531	1.074
4	1.080	2.730	4.632	4.068	1.650	0.564	1.519	1.086
5	2.520	4.164	4.968	4.410	1.644	0.558	1.514	1.086
						Mean	1.516	1.087
						Standard deviation (σ)	0.0104	0.0089
						Mean $\pm$ σ	1.516 ± 0.0104	1.087 ± 0.0089
						Real parameters of glass sample	1.516	1.090
						Maximum error (%)	−0.99	1.47
						Average error (%)	0.03	0.26

correct interference signals, but the sample signals and autocorrelation term signal can be distinguished. Lengthening the optical path length difference between reference arm M_1 and the left surface of the sample in the sample arm to increase the distance between the sample signals and the autocorrelation term signal is possible. Therefore, d_1 (i.e., $d_1 = B - A$) and d_2 (i.e., $d_2 = C - D$) in Eqs. (1) and (2) can be obtained by calculating each interval in Fig. 5. Finally, the refractive index of the optical sample was $n_s = n_a \times 1.650/(1.650 \times 0.558) = 1.511$. The thickness of the optical sample was acquired by substituting the value of n_s back into Eq. (1) as follows: $L = d_1/n_s = 1.092$ mm.

The five repeated measurement results obtained using FD-OCT analyses are shown in Table 2. The mean value of refractive index and thickness were calculated to be 1.516 and 1.087 mm, respectively. The standard deviation of the refractive index and thickness derived from the five repeated measurements were 0.0104 and 0.0089 mm, respectively. According to Table 2, the maximal error and average error of the refractive index between the measured results and the real parameters of the glass sample at 1550 nm were −0.99 and 0.03%, respectively. Furthermore, the maximal error and average error of the thickness between the measured results and the real parameters of the glass sample were 1.47 and 0.26%, respectively. As shown in Tables 1 and 2, the measurement results were similar to the real parameters of the glass sample.

4 Conclusion

In this study, a fiber-based OCT structure was developed for simultaneously measuring the refractive index and thickness of a sample without any previous information. This structure involves the use of two methods for measuring the sample:

TD-OCT and FD-OCT. The experimental results indicate only a minimal difference between the experimental values obtained using these methods. The two methods have advantages and disadvantages. In general, TD-OCT requires an extensive period for performing the scan; consequently, the measurement speed is low. However, TD-OCT has several advantages: it is low cost because the structure comprises a photodetector containing a DAQ, and it does not require complex calculations. Conversely, FD-OCT can be used to acquire information on a sample immediately by analyzing the spectrum of the interference signal, such as the DC term, autocorrelation term, and conjugate terms and, therefore, requires less time for detection than the TD-OCT does. In addition, using the scanning device is not required to change the position of the reference mirror in the reference arm while acquiring the axial depth information of the sample. However, although FD-OCT involves the use of a low-cost spectrometer, which is constructed by combining a diffraction grating and a charge-coupled device detector, the price is higher than that of using TD-OCT, and the analysis and calculations are more complex. In the experiments conducted in this study, the dispersion effect of the sample was not considered, which may have affected the experimental results and the system resolution.

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