Long Path Industrial OCT
High-precision Measurement and Refractive Index Estimation

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Abstract: Long-path optical coherence tomography was developed for industrial use. The system is compact and easy variable to change the measurement speed and range. In this study, its precision and long-path were designed as 1μm and 100mm, respectively. Refractive index of water was analysed by changing the temperature. The results well coincided with the theoretical curve of group index of refraction.

1 INTRODUCTION

Recently, needs of high-precision optical measurement devices are increased in the industrial field due to the technology development of outer shape measurement and in-vivo measurement of materials. 3 dimensional outer shape measurement based on optical measurement technology is essential to the industrial field. Recently non-contact optical probe takes the place of the contact type on the 3 dimensional measurement. Many of principles for it are proposed and commercialized.

The traditional high-precision measurement technology is optical interference technology in industrial field. These technology installs laser and white-light source into it. Laser interferometer, laser displacement meter, and white-light interferometer are commercialized. In these high-precision optical measurement devices, long path measurement is included. Combinational lens such as telescopic lens is essential to evaluate and analyse their lenses matching to optimize their performance. In the case of crystal growth and material compounding operation, the feedbacks from the interior condition sensing to the temperature and concentration controls are important. On the other hand, the long path measurement on the laser and white-light interferometers utilizes linear stage, and they are lack of repeatability. Furthermore, these apparatuses are large and expensive. They have restriction to use.

The optical coherence tomography : OCT , which is developed in medical field, is recently adapted to the industrial use. The OCT technology is the low coherent interferometer and obtains the cross-sectional image by non-invasive and non-destructive measurement, Mainly it is used in ophthalmology.(Danielson 1991, Huang 1991, Brezinski 1999) The combination of super luminescent diode : SLD and optical fiber interferometer adds the flexibility of measurement to the device and also compactness. In this study, a portable OCT scanner has been developed for industrial use.(Shiina 2003, 2009, 2014) In this report, to improve the repeatability on the long path measurement, we state the development of long path industrial OCT, which has the rotational optical path change mechanism. It can repeat the measurement, and also change the measurement range by adjusting the rotational radius of mechanism. We evaluate the accuracy and applied it to the refractive index measurement. We aimed the concrete accuracy of 1μm within the measurement range of 100mm to verify the measurement result with the five-figure accuracy.

2 LONG PATH INDUSTRIAL OCT

The low coherence interferometer changes its reference path length, and interferes it with the sample path, where the same optical path length inside the specimen. Due to the optical path change, interior information of the specimen is visualized.

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Therefore, it is important to scan precisely the optical path change. Our long path industrial OCT utilizes the rotational optical path change mechanism. The rotation radius and speed decides the measurement range and scan rate, respectively. This scanning mechanism consists of a rotating corner reflector and a fixed mirror. The optical path change is represented by equation (1).

$$
\begin{aligned}
l_{All} &= l_1 + l_2 + (l_1 - l_4) - 2s \\
&= 2l_1 + l_2(1 - \sin 2\theta) - 2s \\
l_1 &= (r+s)\sin\theta - \frac{(r+s)(1-\cos\theta)}{\tan(\pi/4+\theta)} \\
l_2 &= \frac{l_3}{\cos(\pi/4+\theta)} \qquad (1) \\
l_3 &= 2s + \frac{(r+s)(1-\cos\theta)}{\sin(\pi/4+\theta)} \\
l_4 &= l_2 \sin(2\theta)
\end{aligned}
$$

Figure 1 shows the geometrical arrangement of the mechanism with the optical path of l_1 – l_4. θ is rotation angle [deg], r is rotation radius, s is the offset length from the optical axis. The fixed mirror reflects the thrown beam to the same path. The optical path change becomes the approximately linear motion. The optical path change of the rotation radius of 10mm is shown in Fig.2. The actual motion has the distortion from the linear motion. It becomes an ogive. The distortion is about 1 – 2% within the rotation angle of +/-20 deg. The long path industrial OCT has a rotation disk of 60mm radius, of which measurement range reaches 100mm.(Fig.3) A servo motor is installed. To stabilize the rotation, the rotation disk is balanced its weight. The motor has a rotary encoder to monitor the rotation jitter.The optical setup of the long path industrial OCT is illustrated in Fig.4.

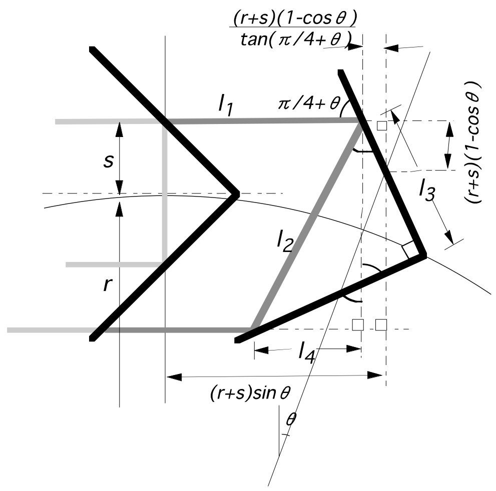

Figure 1: Optical path change by rotating reflector.

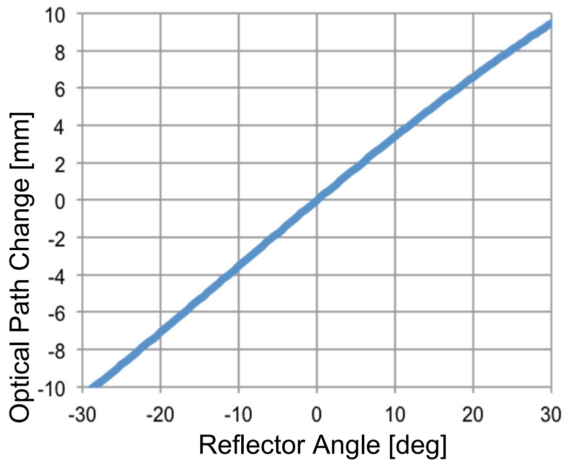

Figure 2: Optical path length.

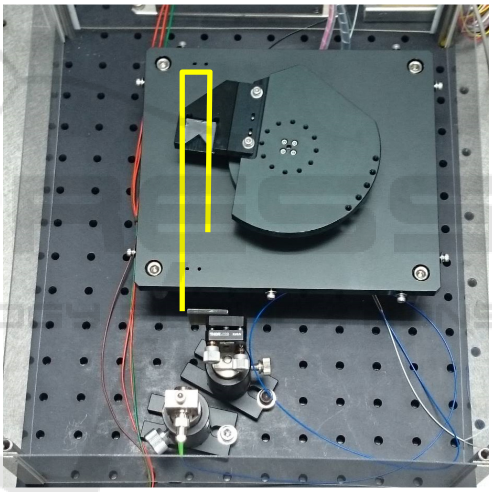

Figure 3: Optical path change mechanism.

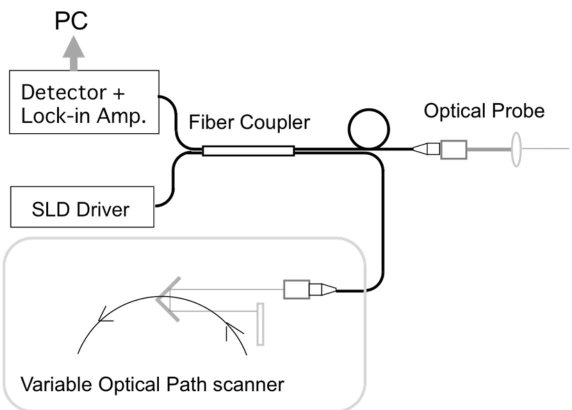

Figure 4: Structure of long path industrial OCT.

The interferometer consists of an optical fiber coupler. SLD beam (Anritsu Co. Ltd) is divided by the coupler, one goes to the reference path and the other goes to the measurement path, which has the optical probe to focus it to the specimen. Both of reflected beam are combined and cause the interference within the same coupler, and detected by the photodiode.

3 ACCURACY EVALUATION

The SLD source of 800nm-band is installed into the long path industrial OCT. As the rotation radius of the reflector is 60mm, the measurement range reaches 100mm. Here it is restricted to 80mm by the reflector size. The rotation speed is 200rpm. The interference signal is detected as the Gaussian envelope through amplifiers and filter circuits.

At first, the system was evaluated its accuracy. The sample is a mirror on the linear stage. By alternating the measurement length, the interference position was obtained. The linear stage (Mitsutoyo Co. Ltd) is 1m long and its accuracy was 5µm. Figure 5 shows the experimental result. The Z-phase signal of the rotary encoder is utilized as trigger and becomes the zero position through the measurement range of 80mm. The optical path change becomes approximately linear change. In the measurement, T1, T2, and T3 [ms] were obtained. T1 and T2 are rise-up and fall-down times of A-phase signal of the rotary encoder when the peak position as time T3 of the interference-envelop signal appeared.

The rotation motor controls its rotation with 6-pole coils, and its rotation speed slightly fluctuates. Therefore, T1 – T3 has a little bit fluctuations. It should be compensated. How to compensate it is explained in Fig.6. As T1 average of 10 times measurement is standard, T3 value is corrected, which is called T1 correct. As T2 average of 10 times measurement is standard, T3 value corrected, which is called T2 correct.

Converting the measured interference signal time to the position, its average time is taken the place of the optical path length with equation (1). Each value of Fig.5 is corrected T3 average on each path length. The approximation line is slightly s-curve (ogive). In this study, 3rd approximate curve is adapted on this corrected result. Standard variation of 10 times measurement at each path length is summarized in Fig.7. To search the peak position of the interference signal, moving average and center search program, which pursued due to the interference signal height, are used. T2 correct on the center search program minimized the standard variation as 1.43µm. The goal value of 1µm was not accomplished, while we decided it the extensional accuracy to progress the experiment.

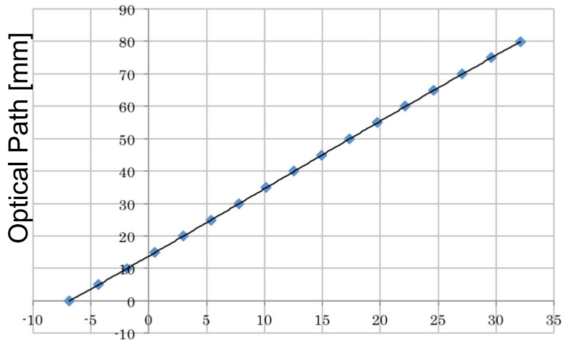

Figure 5: Experimental result and 3rd approximation line.

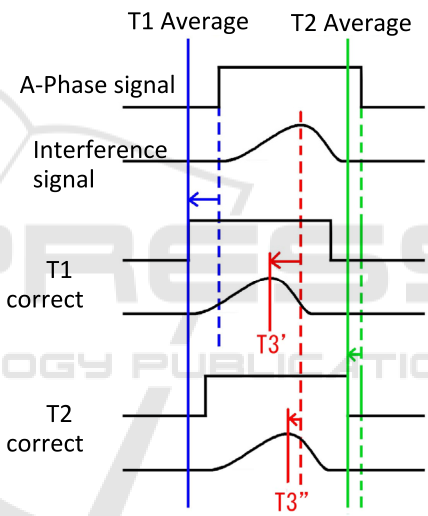

Figure 6: Jitter correction for reflector rotation.

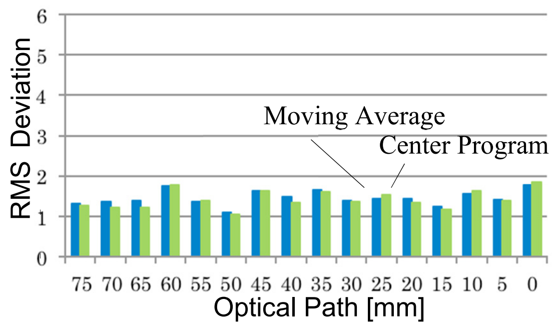

Figure 7: Jitter correction result at each measurement points.

4 REFRACTIVE INDEX MEASUREMET

4.1 Apparatus

As the application of the long path industrial OCT, the refractive index measurement was conducted. The experimental set up and water tank measurement part are shown in Fig.8 and Fig.9, respectively. The measurement target is 5cm x 5cm water tank (small tank). 15cm x 15cm water tank (large tank) has a cooler terminal, and control the water temperature including the inner small tank. In the measurement, water temperature is lowered, and the refractive index, which depend on the temperature, was calculated by measuring the optical path change between the inside glass walls of the small tank. To stabilize the controlled temperature inside the small tank, a stirrer rotates the large tank water slowly. The temperature distribution of the small tank was monitored by a thermo camera.

The OCT measurement probe was set to enter the small tank within the measurement range. The interference signals of the small tank were obtained at four positions from its glass walls (each side of the walls). Figure 10 shows the interference signals. The refractive index was calculated by the optical path length between the inner water-sides of the small tank walls. The temperature was controlled from the 25 to 2 degrees at the step of 0.5 degrees.

T2 correct with the center search program was adapted into the refractive index calculation to fix the maximum interference signal and to compensate the rotation jitter. As the concrete calculation, 3rd approximation curve on Fig.5 was utilized, that is, the refractive index was estimated by changing the 3rd approximation curve to the linear equation.

Here, the 3rd approximation curve is represented as follows,

$$y = -0.00010456x^3 + 0.0035485x^2 + 2.0526x + 13.845 \quad (2)$$

while the linear change equation obtained by the whole measurement range is expressed as follows.

$$y = 2.0636 + 14.023 \quad (3)$$

To change the equation (2) to the equation (3) is conducted by calculating the difference between them, which is shown in Fig.11. The optical path length of 12mm became the center and the distortion of ogive from the linear line was balanced. The difference was changed as the distortion value to the linear one.

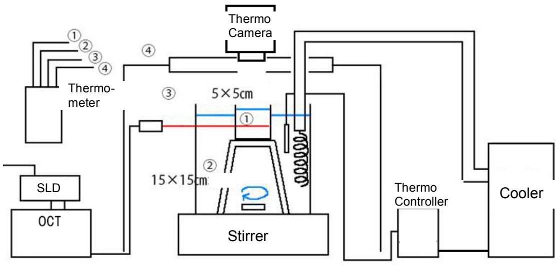

Figure 8: Water refractive index measurement by long-path OCT.

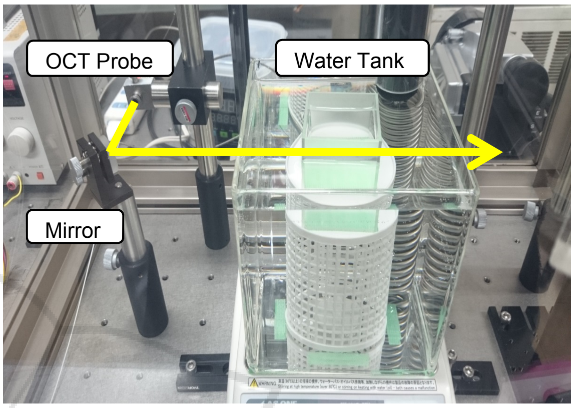

Figure 9: Measurement of water refractive index.

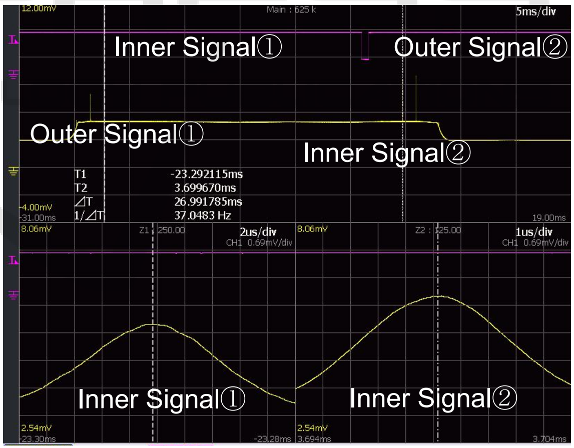

Figure 10: Interference Signals on long-path OCT.

4.2 Group Index Estimation

The refractive index depends on material density, temperature, and incident wavelength. Absolute refractive index equation shown as equation (4) is a regression formula due to the above parameters based on Lorentz-Lorentz equation.

$$\frac{n^2+1}{n^2+2}\cdot\frac{1}{\bar{D}}=a_0+a_1\bar{D}+a_2\bar{T}+a_3\bar{\lambda}^2\bar{T}+\frac{a_4}{\bar{\lambda}^2}+\frac{a_5}{\bar{\lambda}^2-\bar{\lambda}_{UV}^2}+\frac{a_6}{\bar{\lambda}^2-\bar{\lambda}_{IR}^2}+a_7\bar{D}^2 \quad (4)$$

$$\bar{D}=D/D_0,\qquad \bar{T}=T/T_0,\qquad \bar{\lambda}=\lambda/\lambda_0$$

where n is the absolute refractive index of pure water, $\bar{D}$ is density scale represented by the ratio between the pure water density D and the standard density D_0 [kg/m^3], $\bar{T}$ is temperature scale represented by the ratio between the pure water temperature T [K] and the standard temperature T_0(=273.15K). $\bar{\lambda}$ is wavelength scale represented by the ratio between the wavelength in vacuum λ and the standard wavelength λ_0 (=0.589μm). $a_0 - a_7$ are optimized coefficients and λ_{UV} and λ_{IR} are UV / IR resonances. [7]

The OCT light source (here, SLD light source) has wide spectrum. It disperses in a material, and difference of speed (group index) due to the refractive index occurs. That is, the refractive index estimated by the OCT system becomes group index of refraction n_g. It is expressed as equation (5).

$$n_g=n(\lambda)-\lambda\frac{dn(\lambda)}{d\lambda} \quad (5)$$

Figure 12 shows the absolute index calculated by the equation (4) and the group index calculated by the equation (5) against the wavelength of 859.681nm, which is same as the experiment. The experimental results were compared with this group index.

The estimated experimental result is shown in Fig.13. The measurement was conducted by lowering the temperature from the room temperature to 2 degrees. In the figure, the results are represented as average and the center search program with 10 times measurement. Both of the estimations well matched with the theoretical value of group index. The maximum errors from the theoretical curve of the average and the program were 0.00070 and 0.00057, respectively. Both of the estimations get the five-figured accuracy. The maximum error occurred on the longest path length. It is caused by the 3rd approximation curve we used.

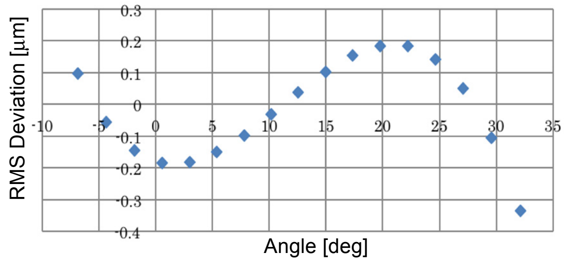

Figure 11: debiation between 3rd approximation and linear motion.

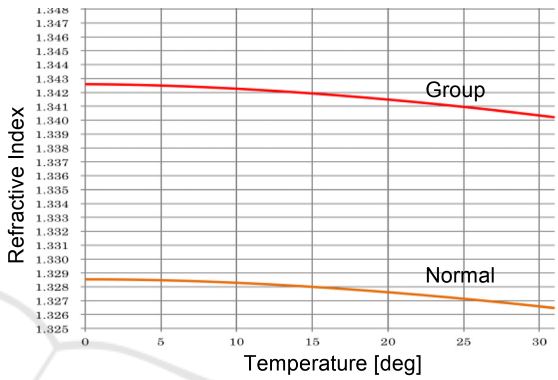

Figure 12: Absolute refractive index and calculated group refractive index.

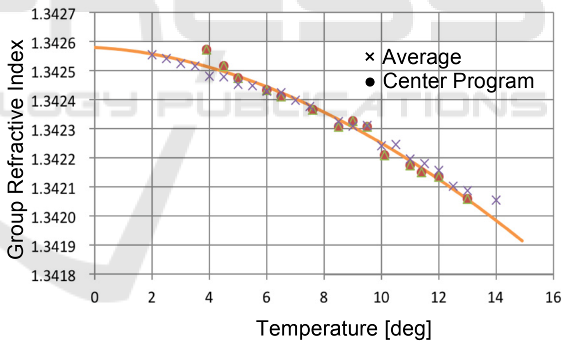

Figure 13: Group refractive index of experiment and theoretical values.

5 SUMMARY

In this study, we set our goal to the high-precision of 1μm in the measurement range of long path length of 100mm. It means five-figured accuracy. As a result, the measurement accuracy achieved 1.43μm as standard variation. The main reason not to get less than 1μm accuracy is indetermination of the linear stage we used (5μm). The rotation motor has the rotation jitter of 0.00036 degrees as standard variation. It is equal to 0.74μm of the fluctuation of the optical path difference. It means that the experimental result has room for improvement. At the next step, we prepare the high-precision linear stage to verify the high accuracy of our long path system.

In this report, the refractive index of pure water was estimated successfully with the five-figured accuracy. This application is not only to the pure water, but also to the mixed liquid solution to confirm the mixing ratio and the concentration. By scanning the OCT probe against the optical axis, the concentration distribution and its fluctuation of the liquid solution and temperature distribution can be evaluated.

The measurement range can be enlarged by magnifying the rotation radius. The rotation disk, however, is difficult to rotate stably. In this study, plural reference paths make it possible to expand the measurement range with the same accuracy with this experiment.(Harvey 1998) We seek the improvement of the measurement range and its new applications.

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