Research article

An intelligent method for measuring high refractive index based on optical coherence tomography and image processing

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ABSTRACT

This study introduces a new method to measure high refractive index (RI) materials with irregular shapes based on optical coherent tomography (OCT) images. Since the optical path length is the critical parameter to calculate RI, image fusion, thresholding, boundary extraction, and Hough transform were adopted in a well-organized sequence to extract this parameter when analyzing OCT images. Hough transform plays a key role in target recognition and parameter extraction. Glass and diamond were used as samples to test the validity of this method. The measurement result has reasonable consistency with the standard value. The method introduced in this paper has the potential to raise the automation and intelligence level of the existing research. A bright application prospect can be expected in industrial fields, such as optical glass, jewelry, and mineral substance.

1. Introduction

Refractive index (RI) is an important parameter to characterize the optical property of material [1]. A solid sample with regular-shaped, parallel input and output faces can be put in the sample beam of a two-beam interferometer. Based on Snell’s law, the lateral and angular deviation and critical angle could be used for measuring its RI. According to the degree of polarization of light, Brewster’s angle also could be used to complete the measurement [2, 3, 4]. Even so, the measurement accuracy of the above three methods is not satisfying. However, there is no better option for solid samples with irregular shapes and high RI values (>1.7) than the index matching method. This method observes samples through the Becker line test [5, 6] by immersing them in a matching liquid with a known RI. The experiments demand frequent replacement of the matching liquid and observation, which is usually time-consuming and laborious. Therefore, finding a simpler and more straightforward method to handle this problem is worth studying.

Optical coherence tomography (OCT) has recently emerged and been widely used in medical and biological research as a powerful imaging technique [7, 8, 9, 10]. So far, a few interesting studies have demonstrated its feasibility in the RI measurement of some biological and medical materials [11, 12, 13, 14, 15, 16]. The two current methodologies are focus-tracking and optical path matching. Focus-tracking always employs a high-precision translation stage to realize the focus shift [12, 17, 18, 19, 20]. Some alternatives to this method still rely on other hardware, such as multimodal multiphoton microscopy [21, 22, 23]. Introducing this hardware has complicated the process, requiring more work to be widely and maturely applied. While optical path matching, as another parallel and mainstream approach, has a simple and rapid measurement specialty [24, 25, 26, 27, 28]. Most relevant studies need to adopt signal-processing technologies to extract the optical path length to calculate the RI. Some image processing technology should be helpful to speed up the measurement efficiency, which is not discussed detailly in this paper [27, 28].

Hence, we conceived that a more comprehensive and in-depth exploration of OCT images should be a better and wise choice. The following research will provide a new method of processing OCT images to calculate RI. We believe the application range of this method is quite broad, not only limited to solids with irregular shapes and high RI but also brings simplicity and convenience in many other scenarios. In addition, it is worth mentioning that the technology involved in this method has matured, which provides conditions for a large-scale promotion.

In summary, this paper will exhibit our endeavor and its corresponding results organized as follows. In Section 2, the physical principle of the measuring method is explained. In Section 3, the image processing algorithm is introduced. In Section 4, the experiment results are

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exhibited and discussed. In Section 5, results and discussion of the paper is given. In Section 6, the summary is given.

2. Physical principle

Derived from the Michelson interferometer, OCT can generate a tomography image of materials by using optical interference. The optical interference occurs only when the optical path lengths of the sample and reference arms are matched within the coherence length of a light source. Therefore, the image distance between the upper and lower boundary obtained from OCT images correspond to the optical path length in the sample. This principle convincingly and logically guides us to adopt the corresponding image-processing technologies.

Figure 1 illustrates the principle and major operation step to measure the RI of the sample in the SD-OCT system. This SD-OCT system applies a single super luminescent diode with an 830 nm central wavelength and an over 20 nm spectral bandwidth as the light source. Before placing the samples, we adjust the distance between the light source and the object stage surface to acquire the first OCT image. Ordinarily, there is a straight line in the middle of this image, corresponding to the surface of the object stage, and we name it ‘baseline’ and set its position as \( x_0 \). The distance between the light source and the object stage remains the same, and then the sample will be put on the object stage and scanned to get the second image. The lower boundary of the sample will be labeled as \( x_2 \), while the upper boundary will be labeled as \( x_1 \). The image distance between \( x_2 \) and \( x_1 \) corresponds to the optical path length. The image distance between \( x_0 \) and \( x_1 \) corresponds to the thickness of the sample. After fusing two OCT images, the RI of the sample can be calculated by a simple formula.

Denote the refractive index of the sample as \( n \), then we can get from Figure 1: the thickness \( d \) is calculated as

\[
d = |x_2 - x_1| \quad (1)
\]

The optical path difference between the upper and lower surfaces is

\[
d = |x_2 - x_1| \quad (2)
\]

Combined formulas (1) and (2), the refractive index of the sample can be calculated by

\[
n = \frac{|x_2 - x_1|}{|x_1 - x_0|} \quad (3)
\]

We adopted a critical algorithm to extract the position information in formula (3) from the OCT image automatically.

3. Image processing algorithm

As mentioned above, two OCT images are required. The first OCT image contains the baseline, and the other is a cross-sectional image of the sample. The distance between these three straight lines could be calculated automatically based on the fusion image.

However, detecting these straight lines is a significant issue in the image. After image edge detection, points or pixels may be missed on the desired curves and spatial deviations will appear between the ideal edge and the noisy edge points. Hough transform (HT) is applied to address this issue, which performs an explicit voting procedure over a set of parameterized image objects. Figure 3 depicts the strategy and the principle of the HT.

In this work, HT is applied to find the boundary. In general, the straight-line \( y = mx + b \) can be represented as a point \((b, m)\) in the parameter space. Duda and Hart [29] proposed the use of the Hesse standard form

\[
x \cos \theta + y \sin \theta = \rho \quad (4)
\]

In formula (4), \( \rho \) is the distance from the origin to the closest point on the straight line, and \( \theta \) is the angle between the \( x \)-axis and the line connecting the origin to that closest point. Therefore, if a point on edge belongs to a certain straight line, a vote will be given to the
corresponding element in the discrete parameter space \((\rho-\theta)\). Finally, the element with the maximum votes will stand up a certain straight-line. Once the parameters \((\rho-\theta)\) of straight lines are obtained, the length of the optical path can also be calculated, which is the key to the calculation of RI. Furthermore, a program encoded by MATLAB based on these image processing technologies is given, which carries out RI calculation automatically.

Figure 4 shows the flow chart of the program, which contains 8 steps. Firstly, two OCT images are fused into one image. A median filter algorithm is used to eliminate image noise. The filtered image is converted to a binary image getting ready for the edge-extraction. Eventually, the HT is used to extract the linear equation parameters, which help to obtain the optical path length. The calculation of the refractive index was completed by formula (3). For statistics, the measurement will be repeated several times.

4. Equipment and materials

The primary instrument (Figure 2) in this study is a spectral domain optical coherence tomography (SD-OCT) system (Nanjing Fureiling Biotechnology Co., Ltd). This SD-OCT system applies a single super luminescent diode with an 830 nm central wavelength and an over 20 nm spectral bandwidth as the light source. It has a high lateral resolution (~12 \(\mu m\) in the air) and axial resolution (~8 \(\mu m\) in the air.) Its imaging depth is ~2 mm. A broad bandwidth spliced fiber coupler (Ziyin
5. Results and discussion

Figure 5 shows the original OCT images and processing results of the slide sample with a higher RI. First, the baseline was obtained as in Figure 5(A). Two straight lines corresponding to the upper and lower boundaries of the slide are shown in Figure 5(B). Figure 5(C) is the fusion image from which the HT algorithm extracts the parameters of the linear equation (ρ–θ). These parameters can infer the sample's thickness d and optical path nd. Figure 5(D) shows the redrawn line (green line) of the extracted boundary based on the parameters (ρ–θ). After repeating the measurement three times, the measuring RI of the slide is 1.74 ± 0.02, which is very close to the standard value (RI = 1.7306).

Figure 6 exhibits the processing results of an ordinary glass fragment with an irregular surface. Its reconstructed 3D image can be seen in Figure 6(A). To further verify the availability of this method in complex and irregular-shaped samples, a piece 2D OCT image of this glass fragment was picked out randomly and processed (see Figure 6(B)). After noise filtering and binary formatting, this image's edges could be extracted using Canny operators as shown in Figure 6(C). Since the boundary of this OCT image is an unexpected continuous curve, we carefully and purposively choose two small sections of the border in which the upper and lower parts have the longest image distance, which could improve the measuring accuracy according to formula (2). HT algorithm could be applied to these short segmented curvy lines by taking them as straight lines. Figure 6(D) shows the redrawn green lines of the upper and lower borders and the baseline.

Table 1. Statistics of measurement.

| Section   | Lines | Theta (°) | Rho | X (μm) | d (μm) | nd (μm) | RI     |
|-----------|-------|-----------|-----|--------|--------|---------|--------|
| Upper     | 90.0  | 43.1      | x1  | 211.2  | 322.8  | 1.53    |
| Section 1 | Baseline | 90.0  | 96.2 | x2    | 213.6  | 330.8  | 1.55    |
| Lower     | 89.0  | 122.1     | x3  | 216.4  | 320.4  | 1.48    |
| Upper     | 87.2  | 37.5      | x1  | 148.4  | 225.6  | 1.52    |
| Section 2 | Baseline | 81.3  | 91.1 | x2    | 152.8  | 227.6  | 1.49    |
| Lower     | 87.4  | 114.0     | x3  | 156.4  | 237.6  | 1.52    |

Theta: Different lines theta in polar coordinates. Rho: Different lines rho in polar coordinates. X: Different x coordinates in the same section. d: Thickness of the sample. nd: Optical path between the upper surface and the lower surface of the sample. RI: Refractive index.
The optical path length was calculated by substituting the abscissa of three different points, and the RI was calculated by formula (3). After statistical processing of the data in Table 1, the average RI is 1.52, and the standard deviation is 0.02, so that the final measurement RI of this glass fragment is 1.52 \pm 0.02.

Figure 7 shows the processing results of the diamond, a well-known high RI material. The sample's baseline and original OCT images are shown in Figure 7(A) and (B), respectively. After noise filtering, the fused OCT image was converted to a binary format by threshold. The edges could be extracted using Canny or Prewitt operators, as shown in Figure 7(C). Not a simple plane, a section of the diamond image's boundary needs to be selected and processed by the HT algorithm. Figure 7(D) shows the redrawn green lines of the upper and lower boundaries and the baseline of the manually selected part of the image. Scale bar is 200 μm.

Table 2. Statistics of measurement.

| Section | Lines | Theta (°) | Rho | X (μm) | d (μm) | nd (μm) | RI     |
|---------|-------|-----------|-----|--------|--------|---------|--------|
| Section 1 | Upper | 31.6 | 81.5 | 1 | 283.08 | 680.88 | 2.41   |
|         | Baseline | 82.6 | 173.5 | 2 | 289.08 | 697.52 | 2.41   |
|         | Lower  | -21.5 | -67.5 | 3 | 295.04 | 714.16 | 2.42   |
|         | Upper  | 31.6 | 82.0 | 1 | 255.36 | 610.76 | 2.39   |
| Section 2 | Baseline | 82.6 | 174.0 | 2 | 285.24 | 691.76 | 2.43   |
|         | Lower  | -22.4 | -71.5 | 3 | 315.16 | 722.8 | 2.45   |
|         | Upper  | -44.6 | 59.7 | 1 | 285.88 | 700.48 | 2.45   |
| Section 3 | Baseline | 82.6 | 175.5 | 2 | 276.76 | 668.48 | 2.42   |
|         | Lower  | 18.4 | 233.2 | 3 | 305.64 | 742.84 | 2.43   |
|         | Upper  | -44.7 | 58.8 | 1 | 319.32 | 791.04 | 2.48   |
| Section 4 | Baseline | 83.7 | 173.5 | 2 | 297.28 | 719.28 | 2.42   |
|         | Lower  | 18.4 | 238.3 | 3 | 292.8 | 703.2 | 2.40   |

Theta: Different lines theta in polar coordinates. Rho: Different lines rho in polar coordinates. X: Different x coordinate in the same section. d: Thickness of the sample. nd: Optical path between the upper surface and the lower surface of the sample. RI: Refractive index.

The optical path length was calculated by substituting the abscissa of three different points, and the RI was calculated by formula (3). After statistical processing of the data in Table 1, the average RI is 1.52, and the standard deviation is 0.02, so that the final measurement RI of this glass fragment is 1.52 \pm 0.02.

Figure 7 shows the processing results of the diamond, a well-known high RI material. The sample's baseline and original OCT images are shown in Figure 7(A) and (B), respectively. After noise filtering, the fused OCT image was converted to a binary format by threshold. The edges could be extracted using Canny or Prewitt operators, as shown in Figure 7(C). Not a simple plane, a section of the diamond image's boundary needs to be selected and processed by the HT algorithm. Figure 7(D) shows the redrawn green lines of the upper and lower borders and the baseline of the manually selected part of the image according to the parameters of these segmented straight lines.

Table 2 shows the diamond’s original data, extracted parameters, and final calculation results. According to the established micro-element segmentation strategy, different parts in Figure 7 (C) were randomly selected, similar to short straight lines. We extracted the parameters of the corresponding straight-line equation \((p, \theta)\) with the help of the HT. The optical path length was calculated by substituting the abscissa of three different points, and the RI was calculated by formula (3). After simple statistical processing, the measurement RI of this diamond is 2.43 \pm 0.02, and the industrial standard RI of this pure diamond is 2.417.

6. Summary

OCT has become a mature standard technology in some fields of medical and biological, especially ophthalmology. This study further reveals the application potential of OCT technology. Combined with digital image processing technology, it can improve the analytical capabilities of the existing field and broaden the measuring scope. This study exhibits its validity and potential in measuring the RI of solid materials.

Declarations

Author contribution statement

Fu Hongbo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Liu Yang; Gao Weijian: Performed the experiments.

Lan Yintao: Analyzed and interpreted the data.

Zhong Fangyu; Cheng Mengmeng: Contributed reagents, materials, analysis tools or data.

Jian Zhang, Ph.D.: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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