\textbf{Systematic Optimization for Optical Coherence Tomographic Imaging}

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\textbf{Abstract:} Optical coherence tomography is a powerful tool that can effectively provide detail information of biological tissue structure. The axis resolution of optical coherence tomography has achieved sub-micrometer and we are interested in its ultrahigh resolution that can be practically utilized for clinical application. In this article, the basic system calibration is discussed; we systematically demonstrated the detail process in optimization of optical coherence tomography for accurately acquiring data. The systematic optimization for optical coherence tomography imaging is discussed here including system calibration and image post-processing.

\section{Introduction}

Optical coherence tomography (OCT) is a non-invasive and high-contrast imaging modality that can display cross-sectional and three-dimensional structure of biological tissue in micron scales [1]. OCT setup is mainly based on low coherence interferometry with broad bandwidth light source, the light in OCT system is separated into two parts, one is delivering into the sample arm and the other one is to the reference arm. When the optical distance of both light arms equal to each other (the difference of light path length is within the coherence length), the recombination of reflected lights from the sample arm and the reference arm forms an interference pattern. On the contrary, when the difference of light path length is out of the range of the coherence length, the interference pattern cannot be clearly investigated. The reflectivity profile is called an "A-scan", which can provide the depth information of tissue structure from the sample. After collecting A-scan, combining a series of these axial depth scans to form a cross-sectional tomography is called a “B-scan”. Up to now, OCT has been already widely used in clinical application such as ophthalmology [2–6] and dentistry [7–10]. OCT is currently divided into two main categories: time-domain OCT (TD-OCT) and frequency-domain OCT (FD-OCT). In time domain OCT, by changing the distance of the reference arm, the reflected lights from the sample arm and the reference arm form interference pattern and to be imaged [1]. On the other hand, in frequency-domain OCT, the optical distance of the reference arm is fixed, by encoding the optical frequency to obtain the interference pattern and the depth information can be obtained immediately by Fourier-transform [11]; FD-OCT includes two different methods: (1) utilizing the high resolution of the spectrometer to separate the different frequencies of light [11–13]; (2) based on the swept-source, the light source rapidly sweeps the spectral frequency band and emitting different frequencies of light [14–16].

\section{System and Methods}

\subsection{System configuration}

We use a laboratory-constructed swept-source OCT (SS-OCT) system, which is shown in Figure 1. A swept-source laser (Santec Technology Inc. HSL-1100-HS) with 1060 nm center wavelength, the scanning range is 78 nm, the scanning speed is 50,000 scans/s and the average power is about 20 mW. The system is built with single mode optical fiber and based on Michelson interferometer. The light firstly passes through the circulator; the circulator is used for protecting the source from the reflected light and returning a fraction of backscattered light to the photodetector. After passing the circulator, the light is delivered into the broadband single mode coupler and separated into 50/50 portions. One part of the light from the coupler is delivered to the reference arm and the other part is to the sample arm. The polarization controller is used to modify...
the polarization state of light in both of the sample arm and the reference arm. At the sample arm, the light comes out from the fiber collimator (F220APC-1064 Thorlabs Inc.) and goes through a two-axis galvanometer scanner, eventually is delivered into an object lens (AC127-019-B-ML, f = 19 mm Thorlab, Inc.). The spot size of laser beam is estimated to be about 23 µm and power on the sample is about 3 mW. The back-scattered light from the sample is recoupled into 50/50 coupler and directed to photo balance detector (PDB150C-AC, Thorlabs Inc.). The signals detected by PBD are sampled by NI PXIe-5612 digitizer (National Instruments Inc.) with 1.25 GHz sample rate and 10-bit resolution. In our present OCT system, the signal is sampled with 4167 points. The frequency calibration is done by rescaling algorithm to fit frequency linearity [17].

### 2.2 System optimization

For setting up a stable OCT system, we have to measure several vital physical properties of the optical components such as insertion loss and efficiency; it can help us to optimize OCT system. Equation (1) is used to determine the insertion loss for each component,

\[
Insertion\ loss_{21} = 10 \log \frac{P_2}{P_1} \tag{1}
\]

\(P_1\) and \(P_2\) are input power and output power of each optical component, respectively.

Using the suitable component can effectively perform the maximum power transmission. For instance, the insertion loss for each port is shown in Figure 2 and the detail is shown in Table 1. For achieving the maximum power transmission, we set Port1 as the input, Port3 and Port4 as output to the reference and the sample, this setting has the most effective split ratios and providing higher power transmissions.

![Figure 1: Swept-source optical coherence tomography (SS-OCT) system configuration. PC: polarization control, ND filter: neutral density filter, Galvo: scanning mirror, FC: fiber collimator, PBD: photo balance detector.](image)

![Figure 2: Coupler port configuration.](image)

### Table 1: Insertion of coupler (unit: dB)

<table>
<thead>
<tr>
<th>Port 1 to 3</th>
<th>2.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1 to 4</td>
<td>2.81</td>
</tr>
<tr>
<td>Port 2 to 3</td>
<td>2.62</td>
</tr>
<tr>
<td>Port 2 to 4</td>
<td>2.62</td>
</tr>
<tr>
<td>Port 3 to 1</td>
<td>1.8</td>
</tr>
<tr>
<td>Port 3 to 2</td>
<td>2.07</td>
</tr>
<tr>
<td>Port 4 to 1</td>
<td>2.67</td>
</tr>
<tr>
<td>Port 4 to 2</td>
<td>2.62</td>
</tr>
</tbody>
</table>

In order to receive the back-reflected light effectively, we first put the mirrors at both of the reference arm and the sample arm to optimize the OCT system. In Figure 3, the incident light path and the reflected light path should overlap each other; it can be done by adjusting the collimator in a correct position to obtain the maximum power from the reflected light.

![Figure 3: Schematic diagram of the light path. The red dotted line represents the tilted light path. The incident light and the reflected light should pass the same straight path in the reference/sample arm to reduce the power loss.](image)

Power efficiency plays an important role in OCT system and it can affect image quality. We have to measure the insertion loss of coupler/circulator to estimate the power efficiency; the loss caused by fiber collimator is ignored.
Figure 4: Two interference patterns with two different conditions: (a) matched optical path distances and (b) mismatched optical distances between the reference arm and the sample arm. (a) shows clearer interference pattern than (b).

The power efficiency is defined by Equation (2) as below,

\[ \text{power efficiency} = \frac{\text{incident power}}{\text{back- reflected power}} \]  

(2)

The power efficiency has to be optimized for acquiring the high-quality image, the higher power efficiency with less loss of the system can maximize OCT signal; in addition to adjust the correct collimator position to optimize, polarization controllers can be also utilized to make the identical polarization states between the reference arm and the sample arm for maximizing the signal. In the present, 98% for the reference arm and 89% for the sample arm are achieved in our system.

On the other hand, theoretically, the clear interference pattern occurs when the optical path distances of the reference arm and the sample arm are matched each other. Two different interference patterns are shown in Figure 4 with different conditions: (a) matched optical path distances and (b) mismatched optical distances between the reference arm and the sample arm.

2.3 Image processing

The NI PXIe-5612 digitizer with a record 200 MHz sampling rate is used. There are total 4084 points for each A-line. The relation among laser scan rate, sampling rate and A-line numbers is shown in Equation (3),

\[ \text{A-line numbers} = \frac{\text{sampling rate}}{\text{scan rate}} \]  

(3)

A-line numbers may be slightly different with different digitizers.

The flow chart of signal processing is shown in Figure 5. The signal is first sampled by digitizer and utilizing Hamming window to reduce the alias signals in the side lobe. After choosing the appropriate window function, Fast Fourier Transform (FFT) is applied and taking the real part to obtain A-line (intensity versus depth). The x-axis represents intensity and the y-axis represents depth information.

Figure 5: The flow chart of OCT image processing.

A cross-sectional image B-scan can be composed by a series of those A-lines. Because the quality of OCT image is influenced by the noise, we subtracts the average background signal (average each A-line of background) to reduce the noise fluctuation, the background image is measured without any sample. Figure 6 shows (a) the original background image and (b) after subtracting the average background signal; the image is performed uniformly after subtraction.

During the background subtraction (Fig. 6 process), in case of eliminating some artifacts, we apply a noise control method on it. The pixel intensity is compared with the average background A-line value after background subtraction, if the pixel intensity value is higher than the average background A-line value; it is regarded as the artifact and forced to be zero. By applying this noise control method, the image contrast can be enhanced without influencing the sample signal.

Furthermore, the saturation is another important issue. The photodetector has a maximum limitation for detecting the power; the intensity is saturated if detecting the high power. The saturation problem can be solved by uti-
Figure 6: (a) The original background image and (b) after subtracting the average background signal (average each background A-line value).

Figure 7: The OCT image of fingertip (a) before background subtraction; (b) after subtracting the background noise. The contrast among different layers of fingertip is increased in (b).

Figure 8: The OCT image of dental calculus: (a) After subtracting background noise; (b) additionally applying noise control method, the image contrast is enhanced. The calculus is marked by the red circle.
lizing the neutral density filter that can reduce the power effectively. The neutral density filter is placed at the reference arm to reduce the power due to that the high reflectivity of the mirror, the reflected power from the sample arm is much less than that from the reference arm because of the high scattering property of the tissue sample; so that we have to balance the power between the reference arm and the sample arm to maximize interference signal.

3 Results

The measurement result of the fingertip is shown in Figure 7. The image quality is improved after effective background subtraction. Fig. 7 (a) is the original OCT image and Fig. 7(b) is the image after subtracting the background noise. The increased contrast of different fingertip layers such as sweat duct, stratum corneum and stratum spinosum can be investigated clearly in (b) compared with that in (a).

The OCT image of dental calculus is shown in Figure 8. Fig. 8(a) is the result of image after first subtracting the background noise; Fig. 8(b) is the result by additionally applying noise control method and the image contrast is obviously enhanced. The calculus is marked by the red circle in Fig. 8(b); based on the different phase retardations induced by the birefringence between the normal tooth and the dental calculus, we can probably quantify the calculus in the OCT image, it may help dentist to detect the calculus in a convenient way.

4 Conclusion

OCT is a powerful technique with high potential that can provide a high feasibility for clinical application. In order to establish a reliable and useful OCT system, the systematic optimization for OCT imaging is necessary and it can be practically used in the long run, we believe that the optimization process of OCT postprocessing will provide the useful information for the fields of optics, biomedical engineering, biophotonics, and clinical applications based on optical coherence tomography.

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References
