Optical Coherence Tomography Premiere in Korea

EunSeo CHOI, Young-Jae KIM, Jihoon NA, Changsu LEE, Changsu NA, Byoeng Ha LEE

Department of Information and Communications, Kwangju Institute of Science and Technology,
1 Oryong-dong, Buk-gu, Kwangju 500-712, Republic of Korea
1Division of Electrical and Electric Engineering, The University of Suwon,
San 2-2, Wau-ri, Bongdam, Whasung-shi, Kyungsi-do 445-743, Republic of Korea
2College of Oriental Medicine, Dongshin University, 252 Daeho-dong, Naju-shi, Jeonnam 520-714, Republic of Korea

(Received February 28, 2003; Accepted October 9, 2003)

Optical Coherence Tomography (OCT) is considered as fundamentally new image modality having advantages such as high-speed, real-time cross sectional imaging with non-invasive in vivo investigation of biological tissue and its potential for clinical application is highly evaluated. In spite of these merits, the research activity in OCT has not taken much attention until recently. However the situation in Korea is gradually changing due to understanding of its versatile applications. Active research and commercialization are underway. Bulk optics-based OCT system is changed into align-free fiber-optics system. With our expertise in the fabrication of fiber grating devices and strong background in control of fiber based system, we hope to contribute in developing simplified all-fiber OCT system with better performance. As a leading research group, working on OCT, we have firstly implemented fiber-based OCT system in Korea and demonstrated the imaging performance with glass plate and onion.

**Key words:** optical coherence tomography, white-light interferometry, OCT system implementation, image modality, high resolution

1. Introduction

Optical Coherence Tomography (OCT) is a promising imaging modality to overcome disadvantages of other methods such as low resolution and high cost. OCT is fundamentally different imaging modality, distinguished by featured advantages. OCT can support high resolution\(^1\) in-vivo imaging for investigation of microstructure of biological tissues. High-speed scanning\(^3\) of sample enables real-time imaging\(^5\) of even the living cells without losing the information of the detailed structure. OCT image is reconstructed using back-scattered or back-reflected light from the sample.\(^5\) Therefore the measured signal level is very low. Signal detection time is very short of around few tens of femto seconds for measurement of structure with a resolution of the \(10 \mu m\)\(^1\) which demands high sensitivity ranging and heterodyne detection scheme is required for appropriate performance.

OCT is a potential candidate in the clinical applications. However, it has not caught the attention of academicians and industries in Korea until recently. To date there is little output related to OCT research but fortunately the situation is changing gradually with many researchers working on OCT. Some of the research groups are collaborating with clinical groups to prove the ability and potential of OCT in clinical applications.

OCT system is currently based on fiber optics system because fiber based system can give a flexibility in system design and suggest an align-free advantage with low loss single mode fiber.

As one of the leading research groups in Korea, we have implemented fiber OCT system with low coherence interferometry for the first time and also demonstrated the first OCT performance with experimental results in Korea.

2. OCT System Outline

Figure 1 shows simplified fiber-based OCT system scheme, which is divided into two parts, optical part (upper box) and electrical part (lower box). In the optical part, launched and delivered light propagates through optical fiber. Detailed information of sample is collected by probe beam. The electrical part translates the information into 2-D or 3-D image using collected contents by the optical part. OCT system can be divided into four parts by its function: source, sample arm, delay arm or reference arm, and signal detection & processing part. Source parameters such as center-wavelength and bandwidth, and shape determine the OCT system resolution by the formula,

\[
\Delta x = \frac{2 \ln 2 \lambda_c^2}{\pi \Delta \lambda}
\]

(1)

where \(\Delta x\) is the spatial resolution and \(\lambda_c, \Delta \lambda\) are central wavelength and FWHM of the source respectively. Broadband source provides low coherence length in coherence function, which is directly related to resolution. Hence, wider
broadband source development is required to achieve high-resolution imaging. In the sample arm, focused beam scans across the sample and gathers information of inner structure in the back-reflected light. The scanning speed determines the image acquisition rate. In the delay arm, light experiences different optical path lengths according to the motion and the speed of the translation stage. The moving speed determines Doppler frequency in the interferogram by the formula,
\[ f_D = \frac{2v}{\lambda_c} \]  
where \( f_D \) is Doppler frequency and \( v \) is stage moving speed, and \( \lambda_c \) is center-wavelength of source. The value of Doppler frequency affects electrical process design such as band-pass or low-pass filter. Light combined from sample arm and reference arm makes interference pattern within the coherence length. Photodiode detects interference pattern and converts optical signal into electrical current simultaneously which has to pass through an amplifier, band-pass filter, and envelope detector, to obtain the image of the inner structure of the sample.

3. OCT System Implementation

The implemented OCT system is essentially a fiber optic Michelson interferometer with broadband source in infrared regime. Superluminiscence light emitting diode (SLED; SLED1300S) at 1310 nm center-wavelength with about 50 nm 3 dB optical bandwidth was used as the OCT source. The measured output power of the source is about 1.5 mW. The above mentioned source should provide about 15 μm resolution by eq. (1) (in Fig. 2(a)).

A 2×2 fiber coupler splits power equally into the reference arm and the sample arm of the interferometer. Light in the reference arm is reflected by Al-coated mirror (reflectivity is about 90%) which is mounted on the translation stage (PI, model V-102). The speed of the translation stage is set to ~16 mm/s or ~1.3 Hz and translation length is 6 mm. The speed is relatively slow compared with that of state of art and hence can be increased further. Doppler frequency due to the moving speed is calculated to be ~25 kHz by eq. (2) and measured value is ~22 kHz (in Fig. 2(b)). The difference is due to the turning point at which the translation stage moves in the opposite direction.

In the sample arm, collimated beam is incident on a micro-objective lens (\( f = 10 \) mm, N.A. = 0.35) which focused the beam to about 5 μm in free space. The size of the beam scanning the sample determines the transverse resolution of the system. Micro-translation stage in the sample arm (CHUO SEIKI, MS-C2, resolution = 2 μm) shifts mounted objective lens unit and hence the scanning beam (~5 μm) in steps of 4 μm in the scanning direction. Stacked cover glass (\( r = 200 \) μm, \( n = 1.5 \) at 1.3 μm wavelength) and onion were used as samples. Since information about the thickness and structure of the samples are already known, these are proper candidates to check the imaging performance of our system.

In the detection part, photodetector collects the interference signal, which contains information of sample along with undesired noise. The received signal is weak and hence an amplifier is used to boost the signal power. To filter out the undesired noise, a band pass filter is used with its band pass center at Doppler frequency. Demodulated signal will construct sample inner structure with gray scale image. A/D converter (National Instrument, NI 6110E) transforms analog signal into digital, which is processed using computer. Translation stages in the reference arm and sample arm and digitized signal processing were controlled by LABVIEW program as shown in Fig. 3. We have also tried controlling with Visual C++ program code.

4. OCT System Performance

Electrical processing of OCT system is shown in Fig. 4 using simplified block diagram. Signal collected by photodetector has DC and AC components as shown in Fig. 4(a). DC component comes from reflected signal of both the reference and sample arms out of the coherence length. Noise also contributes partially to DC component. AC signal, which contains information of interfaces between layers within a sample, is formed due to interference, which may be buried in the unwanted DC components. Since the acquired signal

![Fig. 2. OCT system performance, (a) Measured spatial resolution is about 15 μm, (b) Measured Doppler frequency is about 22 kHz.](Image)

![Fig. 3. LABVIEW control program window.](Image)
level is very low, appropriate amplification is necessary to identify the weak signal carrying the information about the sample.

After the pre-amplification, bandpass filter carries discrimination of desired signal from noisy and unwanted components, whose center-frequency is designed to well match with Doppler frequency defined by the translation stage moving speed. The band-pass filter essentially filters out the unwanted DC signal allowing only the signal with frequency around the Doppler frequency as shown in Fig. 4(b). The slowly varying envelope of the AC signal designates interface positions within the sample. To identify the position information from modulated AC component, only the envelope of the signal is taken in envelope detection process. A series of envelopes with different height and same bandwidth can be interpreted as detailed sample structure shown in Fig. 4(c). A series of signal, which contains different interface distribution and different thickness between layers series, depends on the used sample structure. We can distinguish these differences between samples by checking the implemented OCT system imaging performance.

We used two kinds of samples: Transparent and non-transparent samples. Using transparent sample with stacked glasses, thickness between layers can be compared with already known values. With non-transparent sample such as onion, the non-invasive imaging performance of the sample can be proved.

5. Acquired OCT Images

As a transparent sample, stacked glasses were placed in the sample arm. The thickness of each cover glass is about 200 μm in length and the refractive index is 1.5 at 1.3 μm in wavelength range. As shown in Fig. 5, each cover glass is clearly distinguished both in the interferogram and the enveloped signal. The measured thickness is around 200 μm for each glass. Each peak position in the interferogram and detected envelope are well matched without any signal distortion. Air gap between cover glasses, which was measured to be about 45 μm in length, is also evident as shown in Fig. 5. Since absorbed power is not significant for the transparent sample, reflected power from sample is not deeply buried in the noise. However when non-transparent medium, onion is used in the sample arm, the signal is weak and buried in the noise.

Acquired image is shown in Fig. 6. Image size is 1.2 × 1.5 mm and the number of pixels is 240 × 188. The longitudinal and transverse resolution is 15 μm and 5 μm respectively. In the image each cell of onion is distinguishable as a closed structure in the upper layer. However signal is very weak in the lower part of image making it difficult to identify the cell structure. Its insufficient image performance is due to the inadequate SNR ratio of system. For enhancement of SNR ratio, we worked on detailed design of the
6. Conclusions

We implemented the first fiber-based OCT system in Korea and demonstrated the system performance with samples. We used stacked transparent cover glass and onion as samples. We measured the thickness of stacked glasses to compare with the measured results of OCT system. The transparent sample gave good results and resolution while there is still scope for improving the resolution of the non-transparent samples, which could be obtained by improving the SNR of the signal. Our goal is placed on implementation of all-fiber OCT system.

Acknowledgements

This work was partially supported by the Korea Science and Engineering Foundation (KOSEF) through Ultra-fast Fiber Optic Networks Research Center at Kwangju Institute of Science and Technology (K-JIST), by the Korean Ministry of Education (MOE) through the Brain Korea 21 Program, and the Ministry of Commerce, Industry and Energy (MOCIE) through the Industrial Base Funding projects.

References


Fig. 7. Enhanced onion image, Pixel size is 500 x 500 and resolution is 4 x 15μm respectively.

electronics to filter out the noise with which we could acquire better image. In Fig. 7, the images shows the cell structure clearly even at larger depth. Image and pixel size are 2.0 x 6.0 mm and 500 x 500 respectively. Resolution is 15μm and 4μm in axial and transverse direction respectively. Detailed design of the electronics has definitely enhanced the performance with considerable increase in the depth range. However, SNR ratio is still not satisfactory to obtain the image of non-transparent samples and need to be attended to further improve the performance of the system.