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Single camera spectral domain polarization-sensitive optical coherence tomography based on orthogonal channels by time divided detection

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ABSTRACT

We demonstrate a simple polarization-sensitive spectral-domain optical coherence tomography implement by using a single line-scan camera based on time divided detection. Two light shutters were placed on the dual assembly reference arm that provides a divided detection between the orthogonal vertical and horizontal polarized lights. The relative reflectivity and the retardance information were available by recombining the two orthogonal polarization images. This system can be employed to implement high speed polarization-sensitive OCT images.

1. Introduction

Optical coherence tomography (OCT) is a powerful optical technique for micron-resolution imaging of the internal structure of highly scattering objects, and nowadays becomes a recognized method for non-invasive clinical diagnostics [1,2]. Polarization-sensitive optical coherence tomography (PSOCT) [3–5] was employed as a tool to detect polarization properties that are not provided by a conventional OCT.

PSOCT was almost based on frequency domain (FD) OCT including spectral domain OCT (SDOCT) and swept-source OCT (SSOCT) for its high imaging speed [6,7]. However, previous PSOCT system was used to detect two images with two orthogonal polarization states in order to acquire sample birefringence properties, and dual spectrometer cameras were utilized to detect the horizontal-channel and vertical-channel respectively [8,9]. The method made the system cost risen obviously, and needed complex software and has larger-sized apparatuses. In addition, several PS SDOCT techniques used single spectrometer cameras based on free space or polarization maintaining (PM) fiber system have been developed [10–14]. The principal methods focused on reconstruction detection arm and reference arm. Lee et al. used an optical switch to deliver horizontal and vertical polarization light rays to a single spectrometer camera by turns [10], but the polarized beam splitter (PBS) caused crosstalk between the orthogonally channel. A polarization-sensitive beam splitter or Wollaston prism was used to direct the orthogonally polarization information to two contiguous zone of a single-line scan camera [11,12]. Such methods required complex special redesign of the spectrometer, and orthogonally polarized beam components were needed. In addition, the CCD detector array has the uniform sensitivity which is hard to achieve in fact. Fan et al. found a new path that demonstrated a dual reference arms structure to separate the two orthogonal polarization states in reference arm but not in detection arm [13,14]. The two orthogonally polarized images were separated by different optical lengths of the reference arms and located in the opposite sides relative to the zero delay line. This method required a full range imaging technology to eliminate conjugate image firstly. A complex algorithm and extra phase modulation instrument must be utilized, such as piezo-electric transducer (PZT) or a scanning galvo mirror during offset B-scan. Furthermore, the signal to noise ratio of images would be different because the same position of the image has different distances to zero delay line which causes different signal frequency components. In addition, the imaging depth is restricted by the distance of two references mirrors.

In this paper, we demonstrate a new configuration used a single line-scan camera to achieve the polarization sensitive imaging by time divided detection that eliminates the mentioned problems. It provides a reliable solution to obtain PSOCT images without extra algorithms and devices. We use two reference arms, and add a quarter-wave plate (QWP) on sample arm based on the conventional SDOCT System. And almost the whole software of the SDOCT system could continue to be used. So an obvious advantage of this new implement is that could transfer SDOCT to PSOCT with little adjusting of hardware and software.

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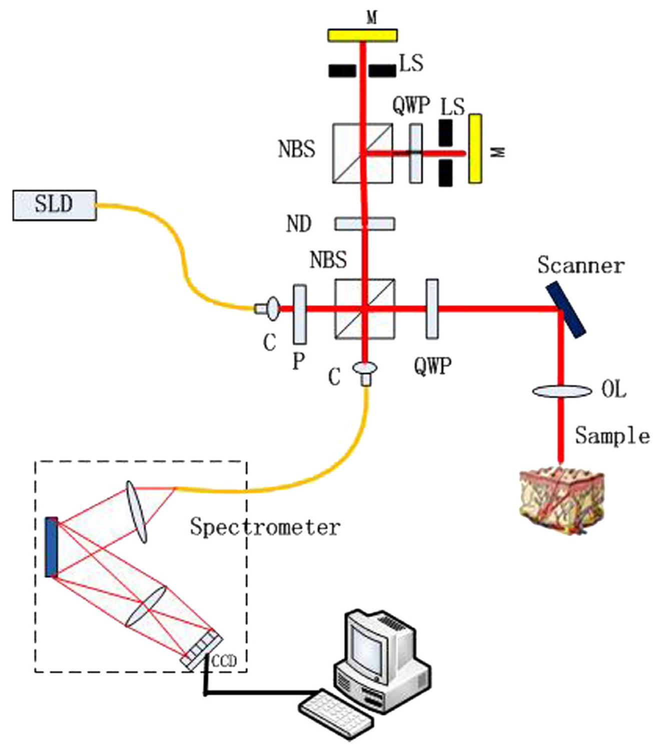

Fig. 1. Sketch of our SD-PSOCT system, SLD: superluminescent diode. C: collimator. P: the linear polarizer. ND: neutral density filter. NBS: non polarization beam splitter. QWP: quarter-wave oriented at 45°. OL: objective lens. M: mirror.

2. Methods

A sketch of our spectral domain polarization-sensitive optical coherence tomography (SDPSOCT) system is shown in Fig. 1. The light source is a 12 mw PM-coupled superluminescent diode (SLD) with a FWHM bandwidth of 85 nm centered at 1310 nm (S5FC1021P, Thorlabs) and output linearly polarized light. The linearly polarized light is delivered into the non-polarized beam splitter (NBS) as vertically polarized (V) light and then to be split into the reference (50%) and sample (50%) arms. The light was split into two beams again by a NBS in the reference arm. One beam was directly reflected by a mirror (M) with vertically linear polarization (V) state; the other back reflected beam has a horizontally linear polarization (H) state by placed a quarter-wave plate (QWP) oriented at 45°in front of the mirror. The two beams were then back to the NBS make up an orthogonally polarization light. Neutral density filter was placed in the beam path to ensure that the light for two beams input the detector has equal strength. The optical length of the two arms was matched to sample arm and strictly equal to each other.

An electronic control light shutter (LS) (SHB05T, Thorlabs) was positioned in front of the mirror of the two reference arms. Only one polarization image could be detected in one moment when the two LS take turns to switch. Therefore, it means that the two orthogonally polarized images could be detected by time divided detection. Polarization-sensitive information was calculated by the orthogonally polarized beam components. In the sample arm, a QWP oriented at 45°to provide a circularly polarized light incident on the sample. A galvo scanning mirror and an achromatic lens with a focal length of 50 mm make up the scanning structure. The detection arm consists of a spectrometer with a single line-scan camera (C-1235-1385, Wasatch Photonics), which contains 2048 pixels.

Because we detect the orthogonally light intensity in turn to calculate sample birefringence properties, single-mode fiber was used to lead the interference signal into spectrometer.

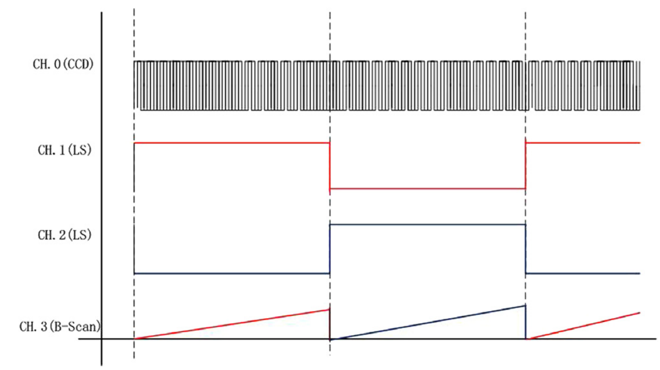

Fig. 2. Signals for hardware synchronization control. CH. 0: camera trigger signal; CH.1, CH.2: LS control signals. CH.3: B-scan signal.

The signals series which controls the scanner, LS and CCD are illustrated in Fig. 2. They were generated from the DAQ card. We set the image acquisition speed at 16 kHz. One square wave (CH.0) used as trigger signal to control CCD, Two TTL pulse trains (CH.1 and CH.2) were generated to control the two LS respectively. One sawtooth wave signal (CH.3) was utilized to drive the scanning galvo mirror to implement the B-scan.

In this study, the signal processing software acquiring the intensity image of the each channel is the same to conventional SDOCT system, and the two channel data processing method is the same to other dual spectrometer cameras system. After acquiring spectral data $I(\lambda)$, we adopted the averaged of 800 A-scans as the DC components, subtracted it and then rescaled the spectrum from λ to k space [8,9]. Finally, an inverse FFT was proceed to retrieve the structure term $I(z)$ after zero padding.

$$I(k,z) \propto A(z)\cos[2k(z)] \tag{1}$$

$$FT^{-1}[I(k,z)] \to \Gamma(z) = A(z)\exp[i\varphi(z)] \tag{2}$$

$A(z)$ and $\phi(z)$ are the amplitude and the phase of the interference signal, respectively, z is unequal optical length of the references arm to sample arm. After inverse Fourier transform algorithm, the phase retardance $\delta(z)$ and the reflectivity $R(z)$ information could be extracted from the magnitudes $A_H(z)$ and $A_V(z)$ of the complex signals on each channel as:

$$R(z) \propto A_H(z)^2 + A_V(z)^2 \tag{3}$$

$$\delta(z) = \arctan\left(\frac{A_H(z)}{A_V(z)}\right). \tag{4}$$

So we can calculate PSOCT images by slightly altering some of the conventional SDOCT software.

3. Results and discussions

In order to demonstrate our SD-PSOCT system, the system reliability was verified and the PSOCT images of the biological sample were provided.

Firstly, the orthogonal spectra from the two reference arms was obtained respectively when light from the sample arm was blocked to ensure that their intensities were equal. Fig. 3 showed the raw interference spectra of the two reference arms with different optical path length when the QWP fast axis placed at 0°, 22.5°, 45°, respectively. Fig. 3(a1), (a2), and (a3) were the interference signals when the optical path different of two reference arm is 0.5 mm, When the QWP fast axes placed at 0°, the light back from two reference arms has the same polarization state, so interference happened as shown in Fig. 3(a1). When the QWP fast axis places at 22.5°, the light polarization will turn 45° after double pass the QWP. The interference signal intensity as shown in Fig. 3(a2) become weaker for only one light component