Novel Polarization-sensitive Spectral Domain Optical Coherence Tomography using Single Camera Spectrometer

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ABSTRACT

We propose novel spectral domain polarization sensitive optical coherence tomography with single camera spectrometer including a multiplexed custom grating, camera lenses and high-speed multi-line CCD camera. Two polarization beams are measured on different lines of high speed CCD camera. Due to slightly different incident angle of two beam collimators, two orthogonal polarization channel beams are separately measured by different lines of CCD camera each other. After the system is implemented, signal acquisition is performed for polarization-sensitive imaging of various samples.

Keywords: Optical coherence tomography, Polarization-sensitive optical coherence tomography, Spectral domain optical coherence tomography, Single camera spectrometer, Multiplexed grating

1. INTRODUCTION AND BASIC PRINCIPLES

Optical coherence tomography (OCT) is a promising imaging embodiment that generates high-resolution, cross-sectional non-invasive image. Conventional OCT measures the spatial morphology of the sample from the intensity of the reflected beam. However, polarization-sensitive optical coherence tomography utilizes the polarization properties of the back-reflected light to extract the additional biochemical information in addition to the structure of the tissue sample. Highly organized bio-molecules in a sample that change the polarization of the incoming light includes collagen, cholesterol crystals, actin-myosin complexes, retinal nerve fibers (myelin), and calcium hydoxyapatite (enamel and dentin). The polarization state of incoming light in biological substance can be changed through the mechanisms: birefringence, diattenuation, dichroism, and optical rotation [1].

The first polarization-sensitive optical coherence tomography based on time domain scheme is devised by Hee *et al.* [2]. The experimental measurement of first polarization sensitive optical coherence tomography based on the spectral domain scheme is conducted under various polarization states which can yield 4 or 16 final images containing the information of Müller matrix elements of the tissue [3]. However, the image acquisition speed of the system is very slow due to the one dimensional mechanical lateral scanning. In 2005, the high speed spectral domain polarization-sensitive optical coherence tomography is suggested by Erich Götzinger *et al.* [4]. This system utilized two spectrometers that work in parallel at 20000 A-lines/s each. However, the high-precision alignment is required due to translational shifts and tilts between these two spectrometers other than high cost and complexity. Recently, therefore, various polarization-sensitive spectral domain optical coherence tomography based on the single camera spectrometer have been researched [5-7]. Bernhard et al. demonstrated the system that the spectra of the horizontal and vertical polarization channels are measured adjacent to each other as 1024 pixels for each channel [5]. Barry Cense et al. presented the system using phase modulator and custom made Wollaston prism at the spectrometer [6]. However, these systems have the reduced number of pixels available for each spectrum which yield the reduction of measurable depth range. Chuanmao Fan et al. presented the configuration composed of a reference delay line assembly that results in the reduction of imaging speed [7].

In this work, we present novel polarization-sensitive spectral domain optical coherence tomography based on single camera spectrometer including a customized multiplexed grating and a multi-line CCD camera. The system is possible to achieve full imaging speed determined by maximum line rate of the CCD camera.

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2. SYSTEM DESIGN AND IMAGING METHOD

The schematic diagram of the spectral domain polarization-sensitive optical coherence tomography (SD PS-OCT) system using new designed single spectrometer is illustrated in Fig.1. The polarization-sensitive spectral domain optical coherence tomography system is usually composed of a broadband light source, a reference arm and a sample arm and a spectrometer for detection. A broad lighter (Broadlighter D830, Superlum Ireland) which is very low coherent light source based on the combination of two pigtailed Superluminescent diode (SLD) module's emission using single mode fiber couplers. Two Superluminescent diode modules have different emission spectra each other and their total output power is around 7.82 mW. Beam from a superluminescent diode laser with a center wavelength at 826.4 nm and a bandwidth of 84.7 nm is emitted after being 90-degree linearly polarized. The broadband light source with the wavelength of 826.4 nm and its FWHM bandwidth of 84.7 nm yields the axial resolution less than 4 ㎛ theoretically. The beam from the SLD laser is vertically polarized via linear polarizer. The beam of Michelson interferometer is divided by a non polarizing beam splitter (NPBS) into a reference and a probe beam. And then the reference beam transmits twice a quarter wave plate oriented at 22.5-degree. It makes the reference beam a 45-degree linearly polarized, which can provide same reference power in two orthogonal channels of the spectrometer. The reference beam has p-polarized beam and s-polarized beam components. Also the reference beam is reflected by reference mirror after going through variable neutral density filter (ND-filter) which can adjust the power of reference beam corresponding to the power of probe beam. The probe beam passes a quarter wave plate (QWP) oriented at 45 degree, which provides circularly polarized beam to the sample. And 2-axis galvano mirror unit can give 3-dimensional images. The reference beam is interfered with the probe beam backscattered or back-reflected from the each layers of a sample after recombination at the NPBS. The p-polarized reference beam is interfered with the p-polarized component of probe beam backscattered from the sample; the s-polarized reference beam is also interfered with the s-polarized component of probe beam. After passing through the NPBS, the interference beams are divided into each polarization beam, p-polarized and s-polarized by polarizing beam splitter (PBS).

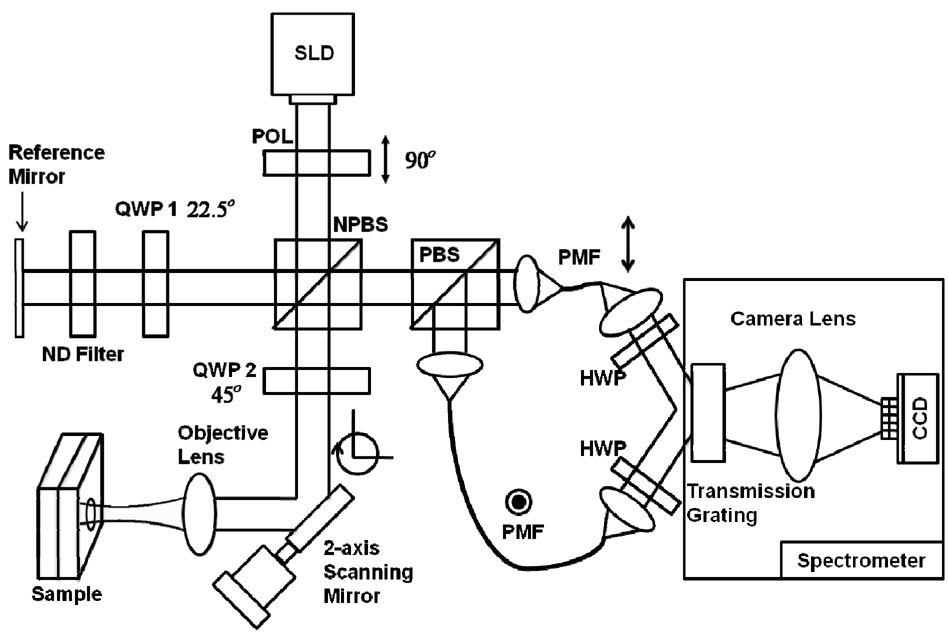


Figure1. Schematic diagram of the polarization-sensitive spectral domain optical coherence tomography system using single camera spectrometer. The system is composed of a broadband Superluminescent diode laser (SLD), Michelson interferometer using polarization optics and a home-made spectrometer including a high speed camera module and camera lenses. POL (linear polarizer), NPBS (non-polarizing beam splitter), PBS (polarizing cube beam splitter), ND-filter (variable neutral density filter), QWP (quarter wave plate), PMF (polarization maintaining fiber), HWP (half wave plate)

Two orthogonal polarized beams are connected into two polarization maintaining fibers (PMF) and directed towards the home-built single camera spectrometer which has three-line CCD pixels. In order to take only one polarization mode in each PMF, the birefringent axis of the two PMFs are aligned parallel to the p-polarized and s-polarized incoming beams each other. Also, two half-wave plates (HWP) are incorporated in front of the transmission grating to maximize the diffraction efficiency of the transmission grating. As shown in Fig 2, two orthogonal beams with a small different incidence angle on y-z plane are arrived on the different line of the CCD camera. The incidence direction of two collimators is controlled by each precision kinematic adjustment screw.

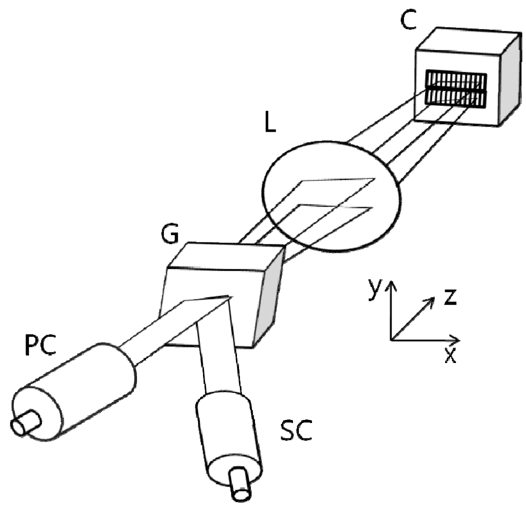


Figure 2. Schematic diagram of the single camera spectrometer PC: P-polarization collimator, SC: S-polarization collimator, G: Multiplexed custom transmission grating, L: Designed camera lenses, C: High-speed three-line CCD camera

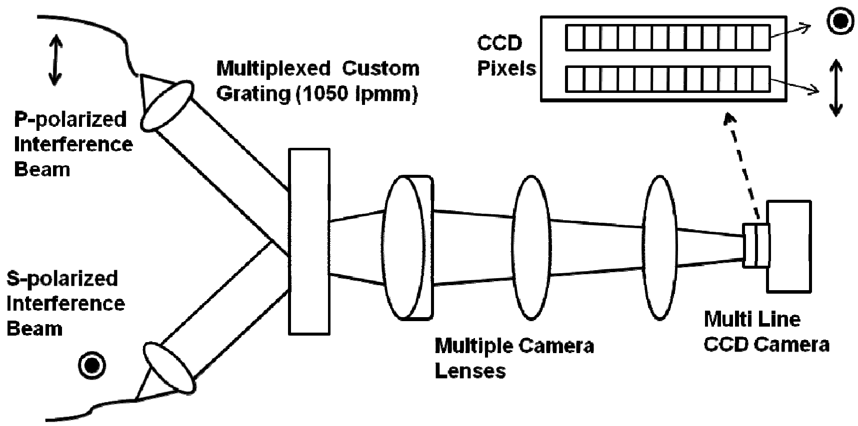


Figure 3. Home-built spectrometer designed by commercial software (ZEMAX). The effective focal length is 120mm.

The spectrometer was designed as a homemade one which includes a multiplexed transmission grating (1050 limes/mm, Wasatch Photonics), three-element air-spaced camera lens and a multi-line CCD camera (Basler Vision Technology, with 2098 elements per line (14 ㎛ x 14 ㎛, 2098 pixels x 3 lines). The multiplexed grating with AR coating was specially customized with the size of 25 mm x 25 mm. After passing through the multiplexed grating, two incident beams take slightly different path each other. Thus, two polarization beams can be arrived at different line pixels each other (about 200um spacing) because each incident angle of two polarization channel beams has small difference. The center-to-center spacing between lines is 112um. The different incidence angle does not result in critical change of spectrometer performance that was verified by commercial software ZEMAX. The maximum line rate of three-line camera is 9.2 kHz. The image data can be transferred into personal computer via a high speed frame grabber board with camera rink type (Horizon Link, i2S). Fig. 3 shows the schematic diagram of the designed spectrometer by the commercial software ZEMAX. The camera lens is composed of a commercial NIR achromatic doublet lenses (Edmunds) and two designed singlet lens. Two collimated beams are made an angle of about 60 degrees with regard to the multiplexed transmission grating. The total length from the grating to CCD pixel except the grating is about 142 mm. The effective focal length of the optical system in spectrometer is about 120 mm.

Fig.4 shows the plot of root-mean-square (RMS) wave front error versus wavelength, the value is much lower than the diffraction limited 0.07. The shorter the wavelength the smaller the airy disc size due to diffraction. The tissue sample is illuminated by the circular polarized beam; the inteferometric signals are detected by two channels of the polarization-sensitive detectors, respectively. These two signals are formularized as follows:

$$I_H(z) = A_H(z)\exp[i\phi_H(z)],\ \ I_V(z) = A_V(z)[i\phi_V(z)] \quad (1.1)$$

From these analytic signals, the reflectivity, retardation, and cumulative fast axis orientation can be expressed by these formulas.

$$R(z) \propto A_H(z)^2 + A_V(z)^2 \qquad (1.2)$$

$$\delta(z) = \tan^{-1}\left[\frac{A_V(z)}{A_H(z)}\right] \qquad (1.3)$$

$$\theta = \frac{180^o - \Delta\phi}{2}(\Delta\phi = \phi_V - \phi_{VH})$$

The unambiguous ranges are 90^o for δ and 180^o for θ $[2, 4-7]$.

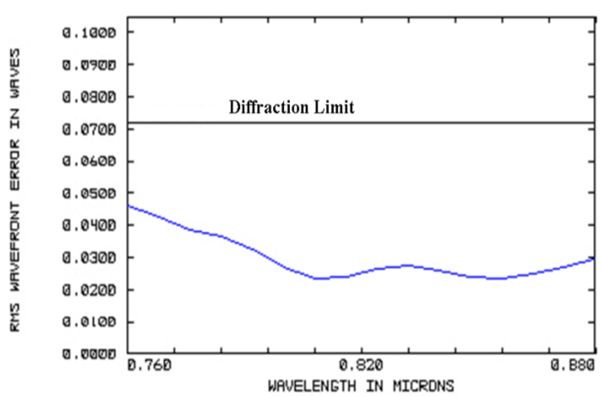


Figure 4. Root-mean-square wave front errors vs. wavelength. The wavelength of laser source ranges between 760nm and 880nm.

3. IMPLEMENTAION

The polarization sensitive imaging proposed here is implemented by using spectral domain optical coherence tomography system on the anti-vibration table, as illustrated in Fig 5.

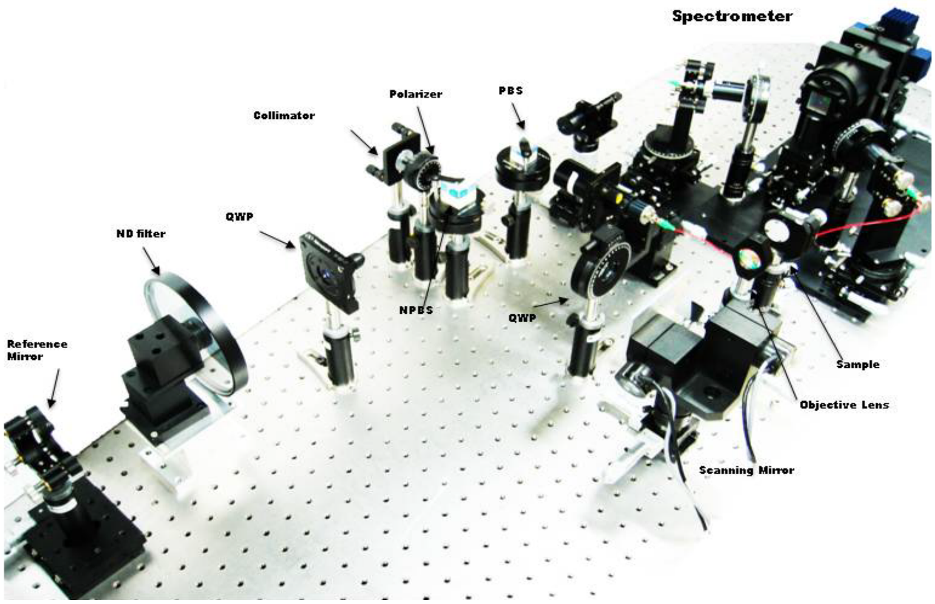


Figure 5. Photograph of the implemented SD PS-OCT system

The sample is placed onto the precision manual stage and moved on this stage. Figure 6 shows a photograph of a spectrometer manufactured to detect interference signals. The components of the spectrometer were precisely placed onto multi-axis translation and rotation precision stages driven by micrometer screws, to exactly position of every component. The camera lenses were precisely aligned by positioning each kinematically, thus reducing the total wave-front aberration. The positioning of three-element air-spaced camera lens in two cells is determined by locating two spacers between the lenses.

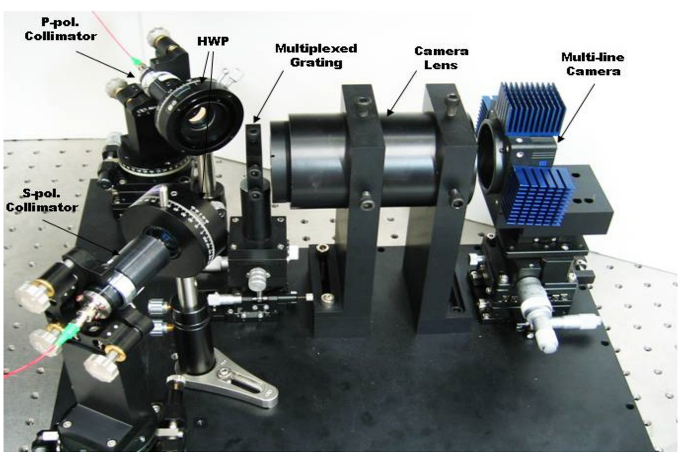
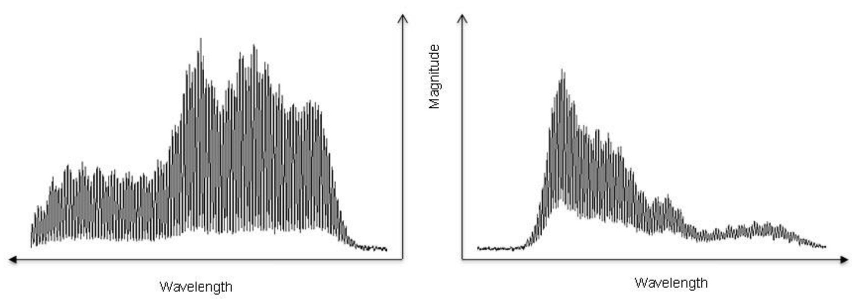


Figure 6. Implementation of the single camera spectrometer.

4. EXPERIMENTS

The interference spectra detected by the multi-line CCD camera is processed as follows. Axial scan spectra have DC and autocorrelation noises after Fourier transformation, resulting in degradation of the final image quality. Thus, the ensemble average of all axial scan results was subtracted from each axial scan result before Fourier transformation. The axial scan results acquired on the line CCD were evenly sampled in wavelength domain, thus becoming evenly sampled by linear interpolation and re-sampling in the wave-number domain. Also, by using an iterative numerical process that sharpens each image, the dispersion mismatch between the sample arm and the reference arm was compensated to obtain the optimal axial resolution corresponding to the bandwidth of the laser source. One axial scan time corresponding to the camera exposure period was 110 . The 2D image data were acquired at a rate of about 17 frames per second by the high-speed frame grabber with a camera link type. Fig 7 shows the one dimensional raw data of the interference intensity of the mirror sample which has different reflectivity according to polarization state. The CCD pixel sequence between P-polarized and S-polarized channel is reverse due to different incident angle against grating surface.



(a) P-polarized interference channel (b) S-polarized interference channel

Figure7. Raw interference signals of sample mirror

5. CONCLUSION

In this paper, we present novel polarization-sensitive spectral domain optical coherence tomography based on single camera detection. The system does not have any limitation of the camera full imaging speed and maximum depth range determined by the spectrometer resolution. The single camera spectrometer is composed of a custom-made multiplexed grating, three-element designed camera lenses and a three-line CCD camera. Because two orthogonal polarization channel beams from two beam collimators have slightly different incident angle on the multiplexed grating, they are separately measured by different line of multi-line CCD camera each other. Simple signal acquisition for polarization sensitive imaging of various tissues was performed by the proposed SD PS-OCT system until now.

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