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Contributed Paper

Polarization Sensitive Optical Coherence Tomography for Materials Characterization

Kunakorn Palawong, Somchai Sonsupap, Santi Maensiri and Panomsak Meemon*
School of Physics, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand.
* Author for correspondence; e-mail: panomsak@sut.ac.th

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ABSTRACT

Polarization sensitive optical coherence tomography (PS-OCT) is an extension of optical coherence tomography (OCT), which is a technique of non-contact and non-destructive 3D imaging. PS-OCT can provide cross-sectional image of not only the inner structure of a sample but also its birefringence properties, such as phase retardation and crystal axis orientation. In this paper, the implementation of our custom-designed PS-OCT system is descripted. The developed PS-OCT system has been designed for characterization and investigation of the birefringence properties of fibrous materials. Examples of the application of the developed PS-OCT for characterizing the birefringence of a cover slide glass, a multi-layered plastic tape, and a thin film of fibrous materials fabricated by electrospinning technique are presented. The experimental results verified that the implemented PS-OCT system can differentiate between isotropic and anisotropic media.

Keywords: polarization sensitive optical coherence tomography, PS-OCT, characterization of anisotropic materials, birefringence imaging, phase retardation imaging

1. INTRODUCTION

Optical Coherence Tomography (OCT) is an optical imaging technique that can capture a depth cross-sectional image similar with ultrasound imaging but at the resolution close to optical microscopy. It is capable of high resolution depth-resolved imaging of microstructure by measuring the depth location and amount of light back reflected from beneath the sample surface by using the low-coherence interferometry [1]. Furthermore, using the principle of interference of broadband light beams in spectral domain, a high speed OCT imaging has been developed, so called frequency domain OCT (FD-OCT), which allows for real time imaging and three dimensional (3D) imaging [2]. Over years, to extend the use of the conventional OCT for characterizing functional properties of samples, many extensions of OCT, such as Doppler OCT [3-5], Polarization sensitive OCT [6-8], spectroscopic OCT , and OCT elastography [9, 10], have been developed.

Polarization sensitive OCT (PS-OCT) provides depth-resolved information of the induced changes in the polarization state of light reflected from sample of interest such as biological samples. An accumulated phase difference between vertical and horizontal components when propagating through the birefringence sample leads to a total phase retardation similar to that observed in birefringence crystal material. The first PS-OCT was introduced by Hee et al in 1992 [6]. After that, a simplify derivation and first 2D-birefringence images of biological samples were presented by de Boer in 1997 [8]. Implementation of polarization sensitive OCT (PS-OCT) requires capturing of at least two spectra per one depth scan, e.g. one to detect a vertical polarized interference spectrum and the other to detect horizontal polarized interference spectrum. This can be achieved by either sequential detection or simultaneous detection of two spectra. Sequential detection scheme uses only one spectrometer, which allow for low cost design of the system at the expense of longer acquisition time [11]. Simultaneous detection or parallel detection captures two or more spectra simultaneously, which allow for high speed PS-OCT. However, a conventional setup of simultaneous detection requires at least two spectrometers, which leads to more complicate optical alignment and higher cost as compared with the sequential detection [12].

In this work, we have designed and built a spectrometer-based PS-OCT system that can simultaneously capture two spectra by using a single spectrometer setup. The optical setup of the spectrometer is explained. The implemented system was used to produce 2D images and phase retardation maps of three different samples that were a glass plate (i.e. isotropic medium), a multi-layered plastic tape (i.e. stress induced birefringence medium), and an electro-spun fibrous material (i.e. a birefringence medium). The developed PS-OCT system has been designed for characterization and investigation of the birefringence properties of fibrous materials.

2. MATERIALS AND METHODS

PS-OCT system has been designed and developed in our laboratory at Suranaree University of Technology. The implemented PS-OCT system is based on a free-space Michelson interferometry as shown in Figure 1. The light source is a Super-Luminescent Emitting Diode (SLED) (Exalos, EXS0880-070-10-0204131), having a central wavelength of 882.5 nm and a full width at half maximum (FWHM) spectral bandwidth of 70.9 nm. The light from the light source was converted to vertical linear polarization by polarization beam splitter cube (Thorlabs, CCM1-PBS252). The vertical linear polarization light beam was split by power ratio of 50:50 to reference and sample parts by using a non-polarizing beam splitter cube (Thorlabs, CM1-BS014).

In the reference path, the light was passed through a quarter wave plate (Thorlabs, WPQ10ME-830), whose optical axis oriented at 22.5 degrees relative with the vertical axis of the system, which changed the vertical linear polarization of the input beam to a circular polarization. The light beam was focused on the reference mirror by focusing lens 35 mm (Thorlabs, AC254-035-B-ML). The light was then reflected at the reference mirror and pass the same quarter wave plate again that converts the circular polarization beam to a linear polarization at 45 degrees. This creates identical reference wave fields for vertical and horizontal polarization components at the detector.

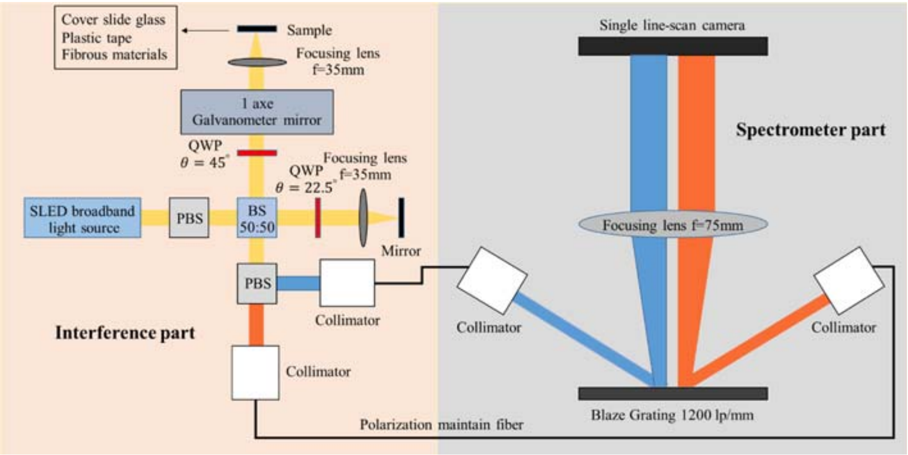

Figure 1. The schematic of PS-OCT based on the free-space Michelson interferometry (BS = beam splitter, PBS = polarization beam splitter, QWP = quarter wave plate).

In the sample path, the light was changed from vertical linear polarization to circular polarization by placing a quarter wave plate (Thorlabs, WPQ10ME-830) with its optical axis oriented at 45 degree. The light beam was then incident on a galvanometer mirror (Thorlabs, GVS012) to produce a transverse scanning of the light beam and then was focused on the sample by a focusing lens of 35 mm focal length (Thorlabs, AC254-035-B-ML). While propagating inside the sample, the polarization of the light beam will be altered by anisotropic property of the sample. Light reflected from the sample was then collected by the same lens and delivered back to the beam splitter cube.

The light back scattering from both reference and sample paths are recombined and interfered at the non-polarizing beam splitter. The interfered beam was then split to orthogonal component vertical polarization and horizontal polarization by polarization beam splitter cube (Thorlabs, CCM1-PBS252). The two polarized interfered light beams were delivered to a spectrometer by polarization maintain fibers (Thorlabs, P3-780PM-FC-1) as shown in Figure 1.

The spectrometer consisted of a blaze grating with 1200 line-pairs/mm (Thorlabs, GR25-1208), a focusing lens of 75 mm focal length (Thorlabs, AC508-075-B-ML), and a single line-scan CMOS sensor (Basler, Sprint spL4096-70km).

Figure 2 shows a photograph of the implemented system. Cover slide glasses, transparent plastic tapes, and fibrous material were used to verify the capability of the detection of phase retardation by the implemented PS-OCT system. The cover slide glass is isotropic medium and hence was expected to cause zero phase retardation. The plastic tape and fibrous material are both birefringence medium and hence was expected to cause some phase retardation. The fibrous material was prepared by electro-spinning technique, which used PVP solution as sample to spin.

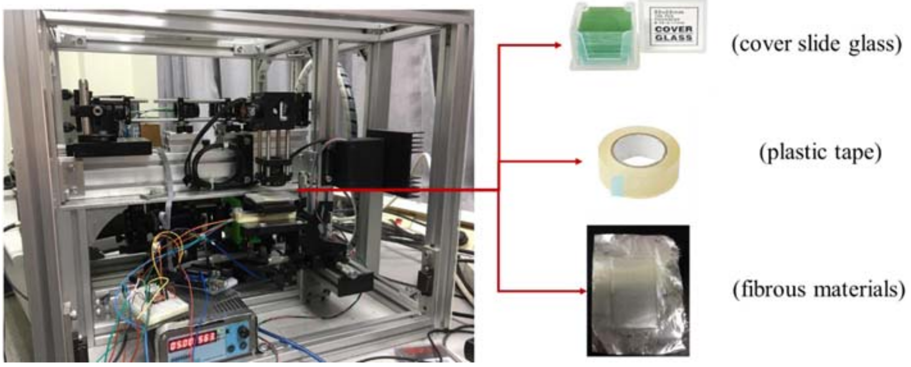

Figure 2. A photograph of the developed PS-OCT system and three samples for verification of birefringence mapping.

3. RESULTS AND DISCUSSION

The performance of the implemented PS-OCT with dual beam spectrometer was verified. As a result, for both polarization components, the axial resolutions were measured to be about 8 µm and the penetration depths were about 1 mm. The system was optimized and capable of 2D cross-sectional image and phase retardation maps of the birefringence samples as shown in figure 3. The interference spectrum of two orthogonal components were Fourier transformed to obtain depth profiles of the sample. In addition, if the sample under tested is a birefringence sample, i.e. the effective refractive index is depended on the polarization of the incident light beam, the phase relation between the vertical and horizontal polarized light beams will be altered, a so called ‘phase retardation’. In this configuration of the PS-OCT system, the amount of phase retardation can be computed from the ratio of the amplitude of two orthogonal components, i.e. vertical and horizontal polarizations, as Figure 3 (a) and (d) are intensity map and phase retardation map of the double layered cover slide glass; (b) and (e) are intensity map and phase retardation map of the double layered plastic tape; (c) and (f) are intensity map and phase retardation map of the thin film of electro-spun fibrous material.

Figure 3 (a-c) show cross-sectional intensity maps, which represent reflectivity of the sample at each depth and transverse location, of a double layered cover slide glass plate, a double layered plastic tape, and a thin film of electro-spun fibrous material, respectively. The intensity map can be used to observe depth cross-sectional structures of the samples, such as thickness, porosity, and density. Figure (d-f) shows phase retardation maps, which represent cumulative phase retardation of the sample at each depth and transverse location of a double layered cover slide glass plate, a double layered plastic tape, and a thin film of electro-spun fibrous material, respectively. The phase retardation maps reveal the birefringence properties and structure of the samples. As shown in Figure 3 (d), the phase retardation image of the cover slide glass, which is an isotropic medium, was used as a controlled sample. The phase retardation map of isotropic medium is expected to be zero. However, there is still some red dots in the retardation map, which was caused by the phase error of the background noise that need to be further improved through the optimization of the optical alignment of the spectrometer. In the cases of the plastic tape and the electro-spun fibrous materials, the phase retardations were clearly observed. The strong phase retardation could be observed at the bottom most layer of the plastic tape.

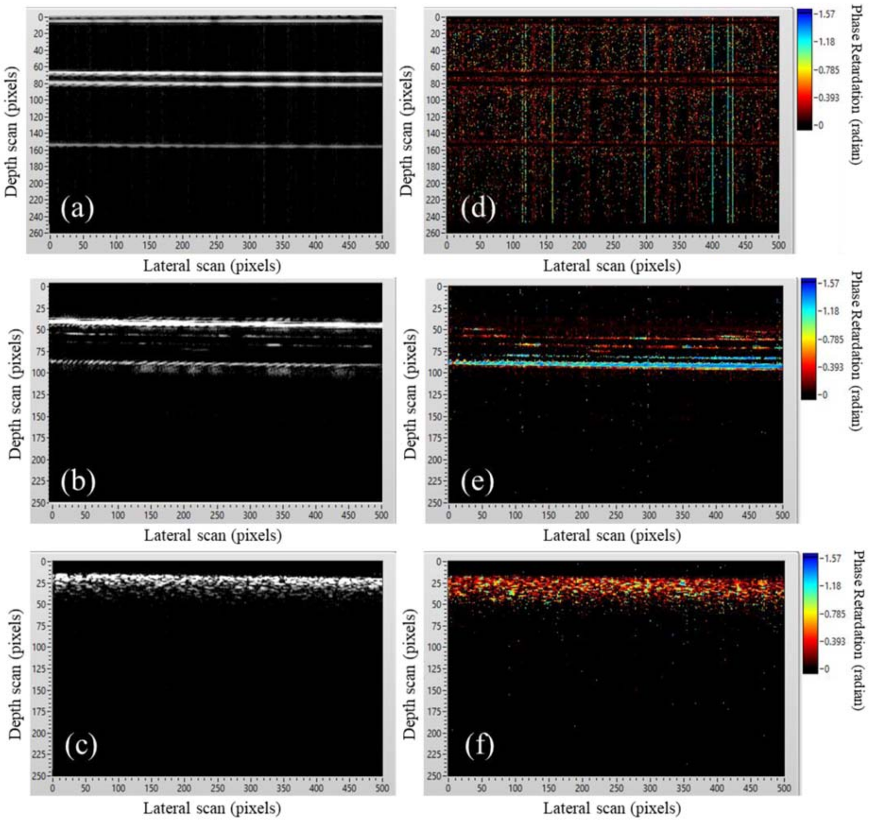

Figure 3. (a) and (d) are intensity map and phase retardation map of the double layered cover slide glass; (b) and (e) are intensity map and phase retardation map of the double layered plastic tape; (c) and (f) are intensity map and phase retardation map of the thin film of electro-spun fibrous material.

4. CONCLUSION

We have designed and implemented a high-speed PS-OCT system that can be used to characterize the birefringence contrast of anisotropic materials. The system was designed to simultaneously detect vertical and horizontal polarized interference spectra by using single setup of a spectrometer to optimize the detection speed and cost performance of the system. We have verified that the implemented system can provide high contrast of birefringence property of the sample that can be used to differentiate isotropic and anisotropic media. The implemented PS-OCT system could be a useful metrology tool for controlling birefringence properties of electro-spun fibrous materials. The fabrication of a thin film of electro-spun fibrous materials with precision control of its birefringence properties could be used to develop a high precision polarization controlling waveplates. As part of future work, we will verify the detection sensitivity of the system to birefringence materials. Furthermore, 3D birefringence maps of fibrous materials will be implemented and verified.

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