Master/slave polarization-sensitive optical coherence tomography for birefringence measurement of oocytes

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Abstract: This study evaluates the influence of polarization maintaining fiber temperature variations on axial resolution and birefringence distributions in polarization-sensitive swept-source optical coherence tomography based on complex master/slave interferometry protocol, and presents measurements of biological specimens, notably oocytes. © 2024 The Author(s)
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1. Introduction

A variety of technologies of polarization-sensitive optical coherence tomography (PS-OCT) has demonstrated the ability to visualize and measure depth-resolved birefringence. PS-OCT, combined with polarization depth encoding techniques that utilize either free-space [1] or fiber systems [2], can illuminate the sample with a minimum of two polarization states, irrespective of the precise polarization state of the incident light. In the context of robustness and compactness, the optical fiber-based polarization depth encoding technique, which employs polarization maintaining fiber (PMF), has been extensively researched for its potential applications in translational fields, particularly with respect to endoscopic OCT [2]. Furthermore, the Jones matrix method based on eigen decomposition developed by Park et al [3] effectively mitigates polarization instability in the fiber optics from the process of obtaining the retardation and depolarization.

Nevertheless, PS-OCT with fiber-based polarization depth encoding struggles to compensate the dispersion effects due to utilization of PMF in the object arm and single mode fiber in the reference arm. To address this issue, complex master/slave interferometry (CMSI) [4] was employed as a method that is tolerant to the dispersion imbalance and enables achievement of theoretical axial resolution without the introduction in the optics set-up of other dispersion compensating elements. Furthermore, CMSI facilitates the execution of depth-resolved, flexibly depth-range-variable OCT measurements within a simple configuration. Thus, the master/slave PS-OCT features are anticipated to significantly contribute to simplification of signal processing of axially multiplexed SS/PS-OCT systems. We applied such method to imaging of embryos and oocytes under 100 µm in height, manifesting birefringence in some of its constituents. However, an initial investigation employing a 20-meter PMF revealed that the axial resolution experienced degradation in response to temperature variations within the PMF. This degradation is likely attributable to the diminished dispersion compensation effect of the masks, which were fabricated by CMSI, resulting from alterations in the PMF length.

In consideration of the aforementioned challenges, this study has engineered a CMS PS-OCT system with a PMF of 5 meters in length. The objective of this research is to scrutinize the alterations in the birefringence distribution of polarization retardation and orientation as well as the axial resolution with peak position drift, which are quantifiable and susceptible to fluctuations in the temperature of the PMF. Furthermore, we present examples of birefringence measurements for several biological samples, including oocytes, and discuss the impact of PMF temperature variations.

2. Method

The experimental set-up employed the configuration of Wang et al [2] as shown in Fig.1. Light from a swept source (Axsun, central wavelength of 1360 nm) with a sweeping rate of 100 kHz was used. In the sample arm, a 5 m long PMF generated two orthogonal polarization waves separated from each other axially by approximately 1 mm. PMF was placed in a temperature controller (Thorlabs, PTC1, temperature range of 5-45 °C) to study thermal effects. The interference signal was divided into vertically polarized (V-channel) and horizontally polarized (H-channel) waves by PM couplers, and each was detected by balanced detectors (Thorlabs, PDB435C-AC with 350 MHz bandwidth). Each orthogonal polarization state signal is separated into a fast signal and a slow signal, yielding a total of four channels (H1, H2, V1, and V2). These signals are digitized by a high speed digitizer (Alazar ATS9360, 12-bit, 1.8 GS/s). The calibration was performed according to the procedure indicated in [2] using a calibration port prior to performing the measurements. To apply CMSI, using a mirror, 4 channelled spectra were acquired at 0.1 mm optical path difference (OPD) intervals, and two sets of 500 masks corresponding to H- and V-channels were calculated employing the CMSI algorithm described in [4]. The masks incorporate the tuning nonlinearity and dispersion effects. Therefore, the wavenumber integration of their product with the photodetected signal collected from the set-up using the sample leads to narrow A-scans, deprived from the tuning nonlinearity and dispersion distortions.

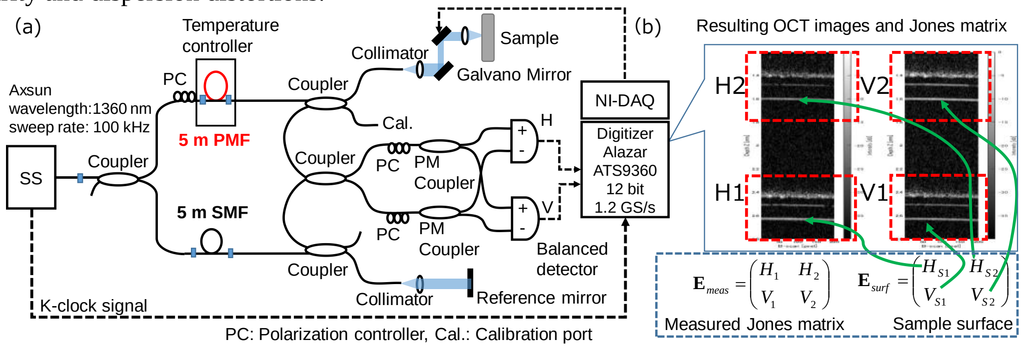

Fig. 1. Schematic of complex master/slave PS-OCT, (a) set-up, (b) OCT images and Jones matrices.

3. Results

In the experiment, a flat mirror was used as the sample to evaluate axial resolution, retardation and orientation. Fig. 2(a) shows the change in axial resolution (FWHM of the peaks) when the controller temperature is varied from 25°C to 45°C. The values were obtained as averages from 40,000 (200 × 200) A-scan signals. When k-clock was enabled, the alteration in resolution was minimal with no observable deterioration. The drift in the peak position, induced by a temperature change of 20°C, was approximately 0.9 mm. The mirror surface exhibited uniform retardation and orientation. As shown in Fig. 2(b), retardation remained close to zero (~0.2 rad), while orientation varied significantly with temperature. It is thought that orientation in our method, being a relative measure, is directly derived from $\mathbf{E}_{\mathbf{meas}}$, rendering it more susceptible to the influence of polarization fluctuations within the optical fiber from the PMF to the sample surface.

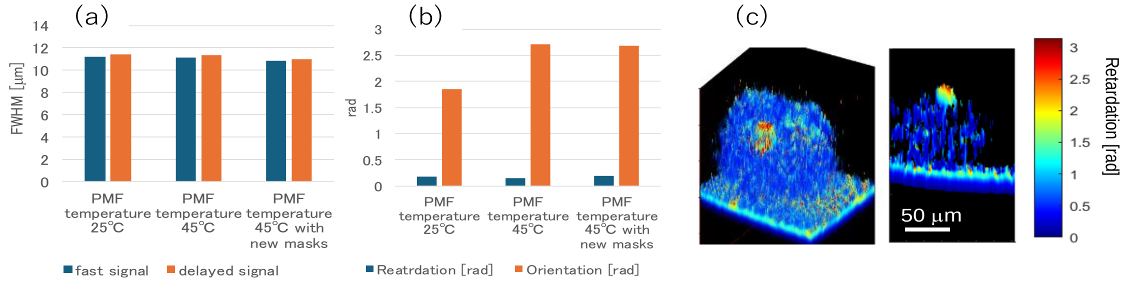

Fig. 2. Impact of PMF temperature changes on (a) axial resolutions, (b) retardations and orientations, and (c) volume and cross-section presentation of double-pass phase retardation distribution of a fixed oocyte.

Figure 2(c) illustrates the 3D retardation distribution along with its corresponding tomographic representation of the immobilized oocyte, as captured by our CMS PS-OCT system. A distinct birefringence distribution was discerned within the polar body region across multiple observations. This finding illustrate the potential of our system in revealing intricate birefringence of biological specimens.

4. Summary

A CMS PS-OCT introducing polarization depth encoding via a 5-meter PMF was assembled. Subsequently, an investigation was conducted to examine the impact of PMF temperature variations on the axial resolution and the resultant birefringence distribution. The study revealed that the resolution and retardation remained unaffected by temperature fluctuations, as long as masks are acquired and used for each temperature and that it was feasible to measure the birefringence of an oocyte. Methodologies for estimating orientation unaffected by fiber optic would require further discussion.

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