High-Speed Polarization Sensitive Optical Coherence Tomography for Retinal Diagnostics

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ABSTRACT

We report design and construction of an FPGA-based high-speed swept-source polarization-sensitive optical coherence tomography (SS-PS-OCT) system for clinical retinal imaging. Clinical application of the SS-PS-OCT system is accurate measurement and display of thickness, phase retardation and birefringence maps of the retinal nerve fiber layer (RNFL) in human subjects for early detection of glaucoma. The FPGA-based SS-PS-OCT system provides three incident polarization states on the eye and uses a bulk-optic polarization sensitive balanced detection module to record two orthogonal interference fringe signals. Interference fringe signals and relative phase retardation between two orthogonal polarization states are used to obtain Stokes vectors of light returning from each RNFL depth. We implement a Levenberg-Marquardt algorithm on a Field Programmable Gate Array (FPGA) to compute accurate phase retardation and birefringence maps. For each retinal scan, a three-state Levenberg-Marquardt nonlinear algorithm is applied to 360 clusters each consisting of 100 A-scans to determine accurate maps of phase retardation and birefringence in less than 1 second after patient measurement allowing real-time clinical imaging-a speedup of more than 300 times over previous implementations. We report application of the FPGA-based SS-PS-OCT system for real-time clinical imaging of patients enrolled in a clinical study at the Eye Institute of Austin and Duke Eye Center.

Keywords: SS-PS-OCT, thickness, phase, birefringence, RNFL, glaucoma, Levenberg-Marquardt, FPGA

1. INTRODUCTION

Optical coherence tomography (OCT) is a non-invasive optical imaging technique\textsuperscript{1} widely applied in ophthalmology, cardiology, and dermatology. OCT is capable of recording cross-sectional images of a tissue with high resolution (a few microns) at higher-than-video rates. Polarization-sensitive OCT (PS-OCT)\textsuperscript{2–7} adds polarization sensitivity to OCT and may be utilized to detect and characterize fibrous tissue by measuring changes in depth-resolved polarization state of reflected light. With appropriate processing algorithms, anisotropic tissue properties including birefringence, diattenuation, and optic axis orientation can be determined and provide diagnostic information regarding a tissue’s fibrous structure, orientation, and refractive index. A clinical application of PS-OCT is detection of changes in birefringence and phase retardation in the retinal nerve fiber layer (RNFL) for early detection of glaucoma\textsuperscript{8,9}.

Polarization state of light returning from the RNFL can be represented by depth-resolved Stokes vectors on the Poincaré sphere\textsuperscript{10}. In absence of diattenuation, the Stokes vector trajectory for light returning from the RNFL traces a circular arc. For three different incident polarization states, the three arcs rotate about a single optical-axis. In fibrous tissue such as the RNFL, birefringence and diattenuation share a common optical-axis. Geometry of the Stokes vector trajectory includes circular rotation about the optical-axis due to birefringence, with the rotation angle equal to double pass phase retardation; collapse of the Stokes vector trajectory towards the optical-axis corresponds to diattenuation. For each incident polarization state, we record 100 clustered A-scans of Stokes vector data points corresponding to light backscattered by the retina from a small region and apply a Levenberg-Marquardt nonlinear fitting algorithm to
determine accurate estimates of RNFL phase retardation, birefringence and optical-axis orientation. In the measurement we fit depth-resolved Stokes vector’s trajectory on Poincaré sphere to a parameterized curve which describes polarization state change of light in sample. Advantage of our technique is that by applying a three-state Levenberg-Marquardt nonlinear fitting algorithm, all clustered A-scans and incident polarization states are utilized simultaneously to calculate accurate estimates of the polarimetric properties of the RNFL, compared with competing techniques that use algebraic equations with start and end points and do not constrain the solution to have a common phase retardation, birefringence and optical-axis orientation. Motivation of this study is to reduce substantially processing and computational time so that phase retardation and birefringence maps can be displayed immediately following patient imaging.

2. METHODOLOGY

We designed and constructed a fiber-based swept-source PS-OCT system for human retinal nerve fiber layer (RNFL) imaging (Figure 1). The SS-PS-OCT system provides three incident polarization states and uses a bulk-optics polarization sensitive balanced detection module in which two detection channels record interference fringe signals in orthogonal polarization channels. A Santec swept-source laser is used for the system which provides a sweep frequency of 27kHz at 1064nm wavelength with a spectral range of 80nm. Polarization controller consists of a linear polarizer oriented horizontally and a phase modulator. The phase modulator is controlled by a high-voltage amplifier, and composed of two lithium niobate crystals oriented at 90 degrees to cancel intrinsic dispersion of the birefringence. The optical axis of the phase modulator is oriented at 45 degrees with respect to the linear polarizer. The polarization controller will provide three polarization states at 0 degree, 120 degree and -120 degree on the QV plane of the Poincaré sphere. The sample arm is composed of a patient interface which delivers the light onto the cornea as well as a line scanning laser ophthalmoscope (LSLO). A glass rod is used as the dispersion compensator in reference arm. A Mach-Zehnder interferometer (MZI) is used as the sampling clock to ensure sampling of the signal in linear wavenumber space. MZI is connected to an external circuit board to quadruple the sampling rate.

![Figure 1. Schematic of fiber-based swept-source polarization-sensitive OCT system.](http://proceedings.spiedigitallibrary.org/)
Interference fringe signals and relative phase retardation of these two orthogonal linear polarization states are used to obtain Stokes vectors of light returning from each RNFL depth. In each cluster of A-scans, we trace depth-resolved Stokes vector trajectory, apply a three-state Levenberg-Marquardt nonlinear fitting algorithm to determine optical-axis orientation, phase retardation, and birefringence. A typical fit of the three arcs on the Poincaré sphere (Figure 2) correspond to three incident polarization states in which all three arcs rotate around a common axis; the rotation angle represents the double pass phase retardation of light propagating through and backscattering from the retinal nerve fiber layer (RNFL). A retinal cluster ring scan consists of 10 concentric rings about the optic nerve head with diameters ranging from 2.0mm-5.0mm, and each ring contains 36 clusters of 100 A-lines corresponding to an angular separation of 10 degrees. For the three incident polarization states, we apply a three-state Levenberg-Marquardt fitting algorithm for 360 clusters. When implemented on a personal computer, the Levenberg-Marquardt algorithm requires 300-600 seconds of run time to generate RNFL phase retardation and birefringence maps.

Figure 2. Depth-resolved Stokes vector Levenberg-Marquardt nonlinear fitting on Poincaré sphere for one cluster corresponding to three incident polarization states. Each arc represents the fitted trajectory of one incident polarization state.

For clinical application of SS-PS-OCT for retinal imaging, birefringence and phase retardation maps must be generated within 1 minute after patient imaging. We implement the three-state Levenberg-Marquardt algorithm on National Instrument’s (NI) Field-Programmable Gate Array (FPGA) chip. The FPGA-based PS-OCT system includes an NI 8354 quadcore controller, a PXIe-1082 chassis, and PXIe-7965R FlexRIO board which uses a XilinxTM VirtexTM 5 SX95T FPGA. The FGPAgs are able to execute parallel tasks at the hardware level.

Figure 3 is a digital photograph of the SS-PS-OCT clinical system. The measurements were recorded from patients enrolled in a clinical study at the Eye Institute of Austin (EIA) and the Duke Eye Center. Patients were carefully selected, inclusion criteria for the study included: age between 40 and 80, visual acuity score of 20/40 or better, spherical refraction with ±5 diopters and cylinder refraction with ±3 diopters. Patient measurement protocol was: 1. PS-OCT measurement, 2. GDx nerve fiber analyzer, 3. Optovue OCT test, 4. Visual field test and eye exam.
3. RESULTS

80 subjects were enrolled in this study, including normal subjects, glaucoma suspects, and glaucoma patients (Table 1). In addition to SS-PS-OCT data, GDx and Optovue OCT data were also recorded.

Table 1. Patients enrollment in clinical study

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Glaucoma patient</th>
<th>Glaucoma suspect</th>
<th>Normal control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye Institute of Austin</td>
<td>9</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>Duke Eye Center</td>
<td>16</td>
<td>2</td>
<td>19</td>
</tr>
</tbody>
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The FPGA-based high-speed SS-PS-OCT system using a three-state Levenberg-Marquardt algorithm speeds computational time 300-600 fold with respect to previous implementations on a personal computing system. With the FPGA-based high-speed SS-PS-OCT system, phase retardation and birefringence maps are displayed in less than 1 second making the system suitable for real-time clinical imaging. A typical SS-PS-OCT data set obtained from one subject includes ten intensity cluster ring scan images (figure 4), cluster ring scan thickness map, cumulative phase retardation map and birefringence map with blood vessels superposed (figure 5).
Figure 4. Retina cluster ring scan intensity image with retinal segmentation

Figure 5. (a) Cluster thickness map (μm); (b) Phase retardation map (degree); (c) Birefringence map (degree/μm).
4. CONCLUSION

Application of SS-PS-OCT for early diagnosis of glaucoma requires computation of accurate phase retardation and birefringence maps to detect changes that may be associated with disease progression. Further study is required to analyze the patients’ data in clinical study and investigate the prognosis value of phase retardation and birefringence maps. An FPGA-based high-speed SS-PS-OCT instrument for retinal diagnostics has been designed and constructed. The instrument uses a three-state Levenberg-Marquardt non-linear algorithm implemented on an FPGA to compute and display accurate phase retardation and birefringence maps in less than 1 second making the system suitable for clinical imaging. The FPGA-based high-speed SS-PS-OCT provides a 300-600 fold speedup compared to previous implementations on a personal computing system.

5. REFERENCES