Jonas Golde*, Lars Kirsten and Edmund Koch

Polarization sensitive optical coherence tomography utilizing a buffered swept source laser

Abstract: We present an approach for polarization sensitive optical coherence tomography (PS-OCT) that solely requires a modification of the light source, a buffered swept source laser. For this purpose a single-mode fiber-based Fourier domain mode locked laser is extended by fourfold buffering with manual fiber polarization controllers to emit alternating sweep polarizations, while the polarization contrast calibration is realized by a high-speed polarimeter. As the introduced setup utilizes standard scanning and detection units, the proposed method is a promising way to enhance various swept source OCT systems by polarization sensitive imaging. Preliminary measurements of a human finger nail with different polarization contrasts demonstrate the feasibility of the concept.

Keywords: Polarization sensitive optical coherence tomography, swept source, buffering, Fourier domain mode locking

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1 Introduction

Optical coherence tomography (OCT) is a noninvasive high-resolution imaging technique for acquiring cross-sectional and volumetric images of near-surface tissues and materials. While conventional OCT detects the reflectivity of scattering layers, the measurement of polarization dependent effects in tissue, like birefringence and depolarization, requires an extended setup [1]. Several concepts have proved capability, but most common PS-OCT systems are characterized by a high complexity due to numerous additional components for polarization adjustment, maintenance and detection [2,3]. Since fast tunable lasers [4] are available, the temporally resolved detection of interference spectra for frequency domain imaging has become the preferred choice for high speed OCT concepts. Swept source OCT not only offers high temporal resolution but also toeholds for extension and adaption, e.g. buffering of the sweeps to achieve higher scanning rates [5].

We present an innovative method for PS-OCT entirely based on the modification of the light source, a swept source laser with a center wavelength of 1300 nm that does not require modification of the interferometer setup or detection unit of a standard OCT system to adapt polarization sensitive measurement. As it has been demonstrated [6], utilizing the buffering of a single-mode fiber-based Fourier domain mode locked (FDML) laser for the generation of two alternating polarization states is a simple approach to add a polarization contrast for imaging birefringent tissues. Due to the single-mode fiber's polarization mode dispersion, there are unpredictable constellations of vanishing contrast for certain incident light and specimen orientations in case of only two polarization states. We address this issue with a set of four polarization states and show in a preliminary examination of a human finger nail the possible distinction of optical axis orientations.

2 Methods and setup

To generate the sweeps for OCT imaging, a FDML laser is used, which is depicted in figure 1. A Fabry-Perot filter (FPF) and a booster optical amplifier (BOA) are connected with single-mode fibers as a resonator ring, whose round trip time matches the tuning frequency of the Fabry-Perot filter. The BOA initializes the laser activity and amplifies the light, which is transmitted by the FPF, while isolators guarantee

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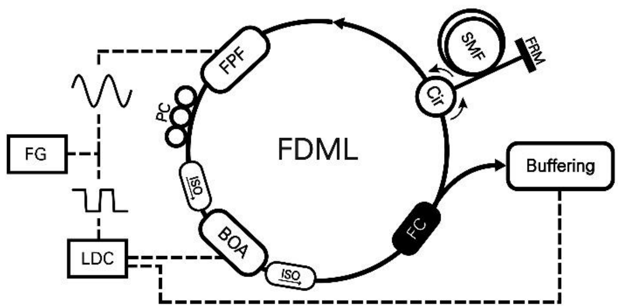

Figure 1: Fourier domain mode locked (FDML) laser setup with function generator (FG), laser diode controller (LDC), polarization control paddles (PC), Fabry-Perot filter (FPF), isolators (ISO), booster optical amplifier (BOA), circulator (Cir), Faraday rotating mirror (FRM), single-mode fiber (SMF) and fiber coupler (FC), which connects with the buffering unit.

unidirectional operation. That causes a continuous wavelength sweeping in the resonator ring due to the sinusoidal drive of a function generator. To suppress the backward sweep, an additional rectangular waveform is applied to the BOA via a laser diode controller. Polarization dependent losses in the BOA are minimized with polarization control paddles after the filter and the combination of a circulator (Cir) and Faraday rotating mirror (FRM) compensating polarization distortions in the main part of the fiber ring. The generated sweeps with a frequency of 60 kHz, a duty cycle of 25 % and a spectral range of 120 nm around a center wavelength of 1300 nm are coupled out with a fiber coupler (FC) and send to the buffering unit, which is illustrated in figure 2.

For monitoring the FDML laser output, 10 % of the light is coupled out at FC1. Analogous to the FDML BOA, the initial sweep is once more amplified, before the first copy is generated at the fiber coupler FC2. A circulator with a single-mode fiber spool and a FRM serve as a delay line, whose transit time corresponds to two times of the sweep length.

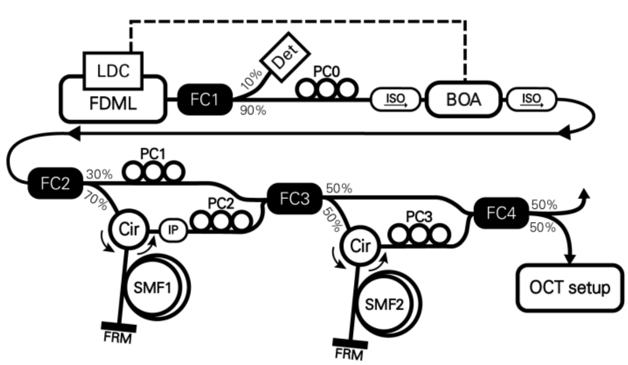

Figure 2: Buffering unit with laser diode controller (LDC) as a part of the FDML laser, polarization control paddles (PC), isolators (ISO), booster optical amplifier (BOA), circulator (Cir), inline polarizer (IP), Faraday rotating mirror (FRM), single-mode fibers (SMF) and fiber couplers (FC).

Although polarization distortion should again be minimized by the FRM, an inline polarizer ensures same linear polarization for the entire spectrum of the copied sweep.

Polarization control paddles PC1 and PC2 allow separate polarization state adjustment for both sweeps, before they merge at FC3 to be copied a second time. The following part equals the previous, expect of the inline polarizer, which is only used in the first buffering stage. The SMF2 spool's twin delay matches one sweep length, so that copies of the first two sweeps are inserted after those at FC4. The paddles PC3 eventually adjust the polarization of both created sweep copies with respect to the relation of the first sweep couple. Accordingly, four sweeps with three independent polarization states are realized. The thus formed signal of alternating polarizations propagates to the OCT setup, which has been previously published [6]. It consists of a modified Michelson interferometer with a scanning unit and detection modules with a Mach-Zehnder interferometer for wave number domain correction and balanced detectors connected with a digitizer. Alternatively, in place of the OCT systems' scanning head a self-made motorized polarimeter is connected, which is based on the rotating quarter-wave plate method [6,7]. It offers a sufficient sample rate to measure polarization change and uniformity within sweeps during the adjustment via polarization control paddles. While it is not possible to measure the exact incoming polarization in the scanning head, the angle between the sweep polarizations on the Poincaré sphere remains constant.

To achieve the optimal polarization contrast, a suitable combination of sweep polarizations is adjusted, which is a set of polarizations pairwise orthogonal on the Poincaré sphere, e.g. horizontal and vertical linearly, right- and left-hand circularly polarized. Eventually phase differences between the interference spectra of different sweeps are pairwise calculated and plotted.

3 Results and discussion

In a preliminary measurement, the finger nail of a volunteer was examined and sectional images orthogonal to the nail-cuticle transition are presented. As it is demonstrated in figure 3, the intended set of sweep polarizations was achieved within a variation of up to 15° on the Poincaré sphere at more than 95 % degree of polarization for all sweeps, while the original sweep 1 and its first copy sweep 3 show even less polarization dispersion than second copies sweep 2 and 4. Limitations are assumed to be mainly caused by slight wavelength dependent birefringence of circulators and fiber couplers while single-mode fiber influences can be

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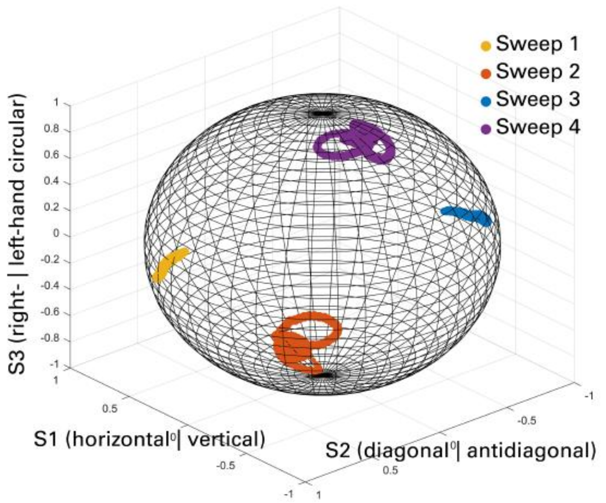

Figure 3: Poincaré sphere of normalized Stokes components, showing four separate sweep polarizations, whose ratio determines the achievable polarization contrast.

reduced by the usage of FRMs and proper polarization controller adjustment. Figure 4 shows first images with a sweep polarization depending contrast, which is exemplified in two regions. For sweep combination 1-3, which corresponds with an included angle of about 180° on the Poincaré sphere, region 1 shows a plain contrast, while it vanishes for combination 1-2 and is more faintly visible for 1-4. Hence, a recalculation of the fast optical axis orientation in the specimen should be possible with knowledge of the incident polarizations. Additionally, region 2 shows the case of overlapping layers with differing orientation as a phase difference occurs in the upper and lower half for combination 1-4, while for 1-2 there is only a contrast mid of this area. Due to the attenuation of the delaying fiber spools, sweeps 2 and 4 have a lower output power after passing SMF2, which results in a declined signal-to-noise ratio and a visible higher background noise for 1-2 and 1-4.

4 Conclusion

The demonstrated PS-OCT concept provides polarization sensitive imaging at a standard OCT setup, only by modifying the light source, a swept source laser. With further technical improvements and appropriate data handling, it can offer results comparable with conventional PC-OCT systems. Therefore, a calibration concept has to be developed, that allows the calculation of specimen's retardation and optical axis orientation values from the phase differences. Due to the minor requirements concerning scanning and detection, the concept is assumed to be suitable for the usage with manifold optics and applications.

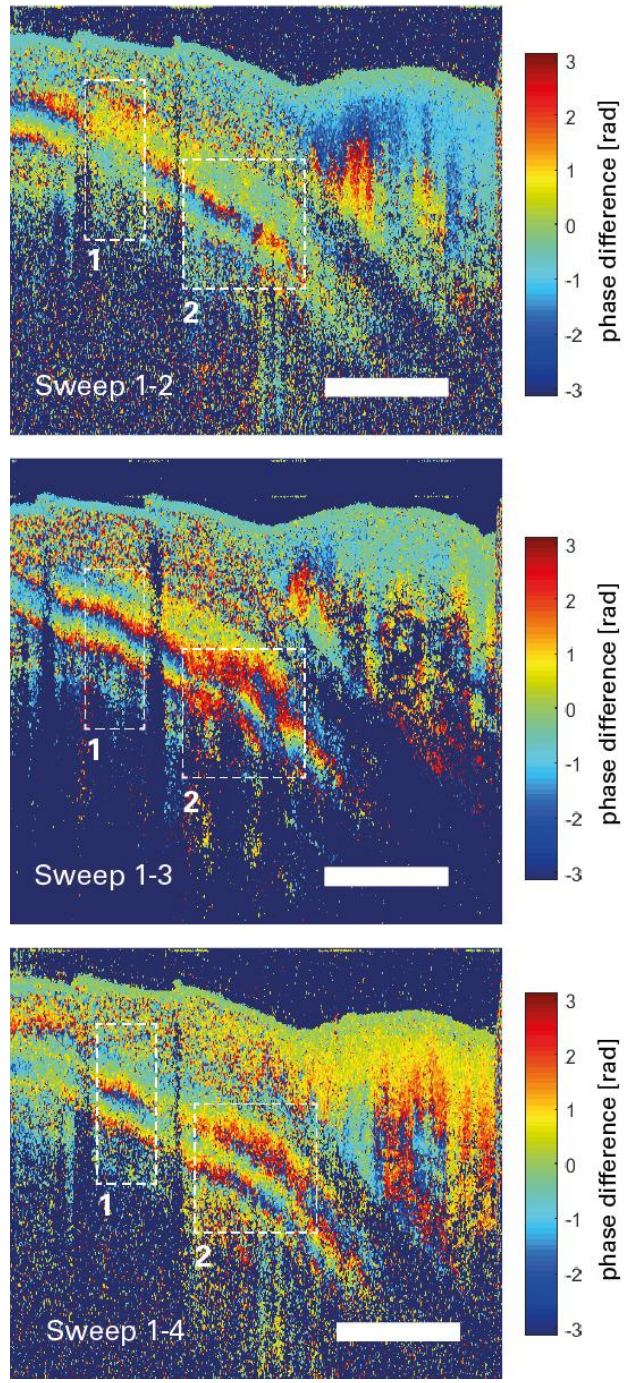

Figure 4: PS-OCT image of a human finger nail next to the cuticle. Polarization contrast for three different sweep combinations is displayed with a mask, setting pixel below the average intensity threshold at -π. Two concurrent regions are labeled in the images. The reference bar has a length of 1 mm.

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Author's Statement

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