Polarization-sensitive plug-in optical module for a Fourier-domain optical coherence tomography system

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ABSTRACT

In this manuscript we communicate a theoretical study on a plug-in optical module to be used within a Fourier-domain optical coherence tomography system (FD-OCT). The module can be inserted between the object under investigation and any single-mode fiber based FD-OCT imaging instrument, enabling the latter to carry out polarization measurements on the former. Similarly to our previous communication[1] this is an active module which requires two sequential steps to perform a polarization measurement. Alternating between the two steps is achieved by changing the value of the retardance produced by two electro-optic polarization modulators, which together behave as a polarization state rotator. By combining the rotation of the polarization state with a projection against a linear polarizer it is possible to ensure that the polarization measurements are free from any undesirable polarization effects caused by the birefringence in the collecting fiber and diattenuation in the fiber-based couplers employed in the system. Unlike our previous work, though, this module adopts an in-line configuration, employing a Faraday rotator to ensure a non-reciprocal behavior between the forward and backward propagation paths.

The module design also allows higher imaging rates due to the use of fast electro-optic modulators. Simulations have been carried out accounting for the chromatic effects of the polarization components, in order to evaluate the theoretical performance of the module.

Keywords: polarization-sensitive OCT, polarimetry, fiber-based system

1. INTRODUCTION

Spectrometer-based OCT methods have been extensively used over the past decade to image translucent structures.[2] Polarization-sensitive optical coherence tomography (PS-OCT) methods emerged as early as 1992,[3] evolving from bulk-based to more compact fiber-based designs. These systems are useful in medical OCT applications due to the link between polarization properties and the health state of biological tissues. In non-destructive testing, PS-OCT also provides birefringence information, which is useful in assessing the mechanical properties of the structures evaluated.

Due to their versatility, easy alignment, compact size and the need for single spatial mode selection, fiber-based systems are used in OCT practice.[4] However, external factors (such as temperature and mechanical stress) affect the birefringence of single-mode fibers (SMFs) used in OCT systems, inducing disturbances[5] to the measured polarization.

One way to avoid the influence of these external factors and their corresponding disturbances is to perform the polarization selection before the collecting fiber, which was firstly demonstrated by Roth et al. in 2001.[7] Our recently reported approach,[1] summarized in Figure 1 (a), follows the same philosophy,

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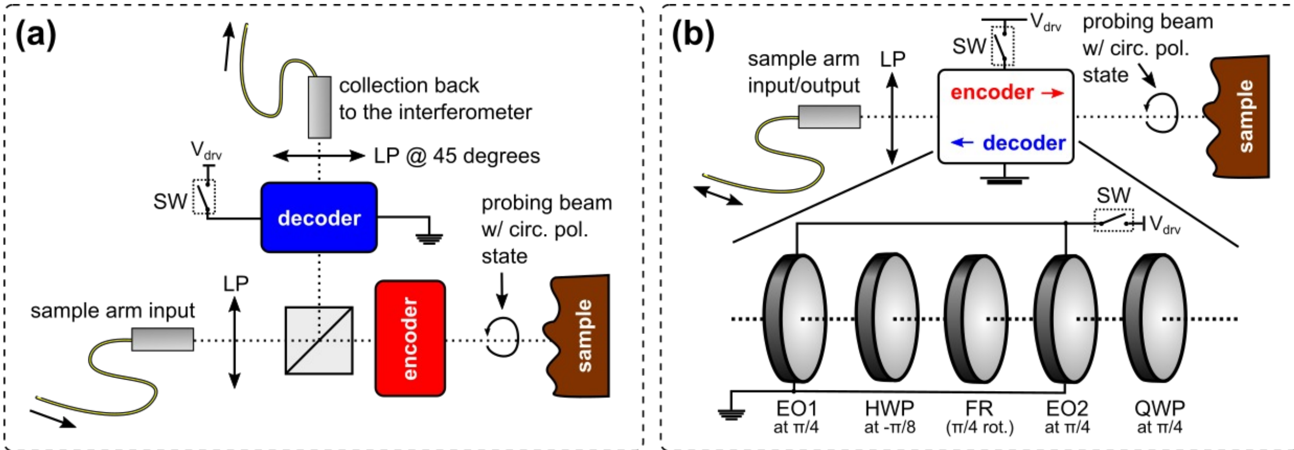

Figure 1. Comparison between **(a)** our initial PS-OCT system[1] and **(b)** the newly proposed plug-in PS-OCT optical module.[6] **SW:** switch toggling between the two states of the polarization states encoder/decoder; **LP:** linear polarizer; **EO1-2:** electro-optic polarization modulators; **HWP:** half-wave plate; **FR:** Faraday rotator; **QWP:** quarter-wave plate. The complete module description is presented in Rivet *et al.*[6]

while also ensuring a circular polarization state in the imaging beam, which minimizes the number of measurements required for a full characterization of polarization.

This approach has, however, a few drawbacks, most notably the split-path design due to the need to employ a bulk beam-splitter to physically separate the two paths (input and output), thus enabling a non-reciprocal behavior on the sample arm. Having such a design meant that the system is not a plug-in PS-OCT module in the true sense of the word, i.e. the supporting OCT system needs to be specifically modified in order to accommodate the PS-OCT system. Additionally, the system uses a liquid crystal rotator as the polarization rotator element, which reduces the speed of the system considerably, rendering it unusable for *in-vivo* imaging.

2. DESCRIPTION OF THE OPTICAL MODULE

To address these issues, a new design was proposed in a follow-up publication,[6] which is summarized in Figure 1 (b) and its operation principles detailed in Figures 2-3. Similarly to our previous work, the system employs a two-step sequential procedure in order to carry the polarization measurements, using active polarization elements. However, there are two major differences from our previously reported work: (1) the polarization state rotation is carried out by two electro-optic polarization modulators (represented as EO1 and EO2 in Figures 1(b), 2 and 3), enabling higher acquisition rates and (2) the design is completely in-line (input and output share the same fiber), which allow this design to be a plug-in PSOCT module (i.e., without having to modify the supporting FD-OCT system). This is achieved by employing a Faraday rotator (represented as FR in in Figures 1(b), 2 and 3) to break the reciprocal behaviour of the remaining polarization components of the module, allowing it to behave as a polarization state encoder when illuminating the sample and as a polarization state decoder when retrieving the back-reflected signal.

In Figure 2 the operation of the OM is detailed for the forward propagation of the beam (the illuminating beam). In order to perform the polarization characterization with the least amount of measurements, the polarization state of the probing beam incident on the sample should be circular; this means that the Jones matrix corresponding to the forward propagation inside the optical core (grey box in Figure 2) must be equal to unity irrespective of the values of ϕ_{EO} introduced by EO1 and EO2,

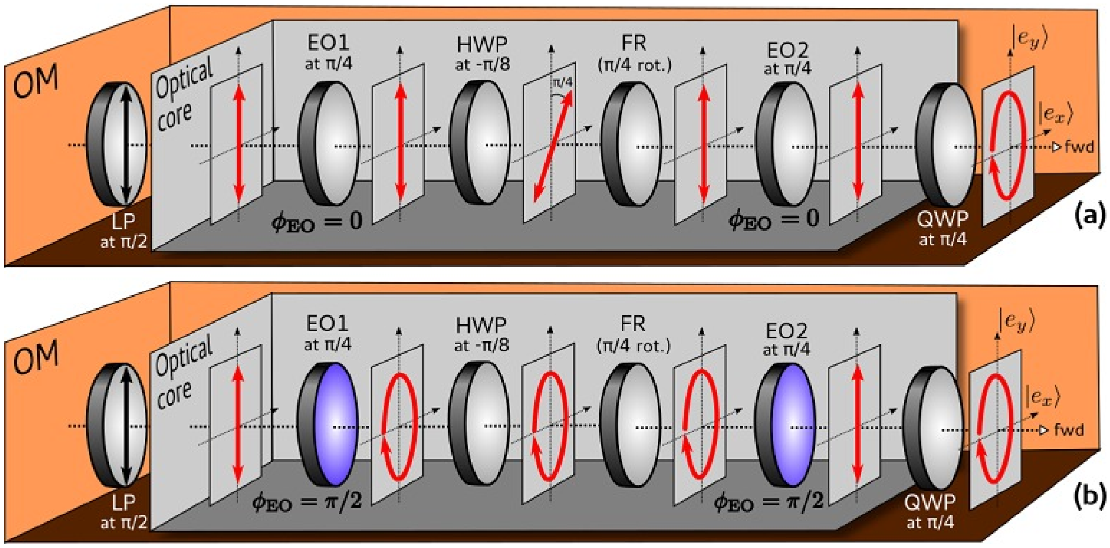

Figure 2. Orientation of the polarization states in the OM for the two states ($\phi_{EO} = 0$ **(a)** and $\phi_{EO} = \pi/2$ **(b)**) of the EO modulators (EO1 and EO2) considering forward propagation (left to right). Irrespective of the value ϕ_{EO} corresponding to the retardance of the two EO modulators, the output polarization state is always circular. (from Rivet *et al.*[6])

with the quarter-wave plate QWP turning the polarization state from linear to circular before the beam reaches the sample.

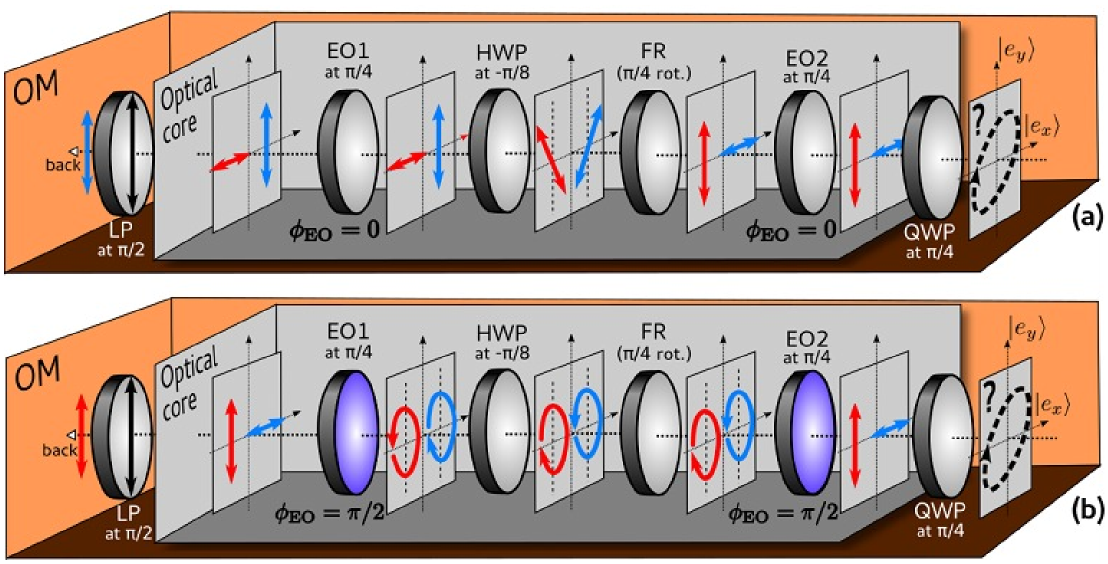

Figure 3. Orientation of the polarization states in the OM for the two states ($\phi_{EO} = 0$ **(a)** and $\phi_{EO} = \pi/2$ **(b)**) of the EO modulators (EO1 and EO2) considering backward propagation (right to left). The probing beam returns from the sample with an unknown polarization state, composed of two linear orthogonal components (represented as red and blue in the diagram) (from Rivet *et al.*[6])

Figure 3 schematically represents the operation of the OM for backward propagation (i.e., light returning from the sample). In the same way as in our previously reported work,[1] the module carries out the polarization measurement before the light is re-injected into the fiber leading back to the interferometer; as before, this is done sequentially. Figures 3(a) and 3(b) depict the two states of the EO modulators within the OM ($\phi_{EO} = 0$ and $\phi_{EO} = \pi/2$); each of them ensures that only one of the orthogonal polarization components from the light returning from the sample (represented as red and blue lines) reaches the fiber at any given time.

By taking the ratio of the intensities measured for the two states of the EO modulators it is possible to measure the retardance of the sample; moreover, since the actual measurement takes place before the light is re-injected into the fiber leading back to the interferometer, it renders it immune to any fiber and coupler-based disturbances.

However, due to the sequential operation involved, the full polarization characterization of the sample cannot be directly achieved, since the orientation of the optical axis relies on the phase information that may be affected by interferometer noise altering the phase during the time required to shift from one state of the EO modulator to the other. Having higher switching rates in the EO modulators allows the phase measurement to be more tolerant to fiber fluctuations (employing the shallowest surface of the sample as a phase reference), therefore overcoming this issue. A comprehensive analysis has been presented in our recent publication.[6]

3. VALIDATION OF THE CONCEPT AND ITS LIMITATIONS

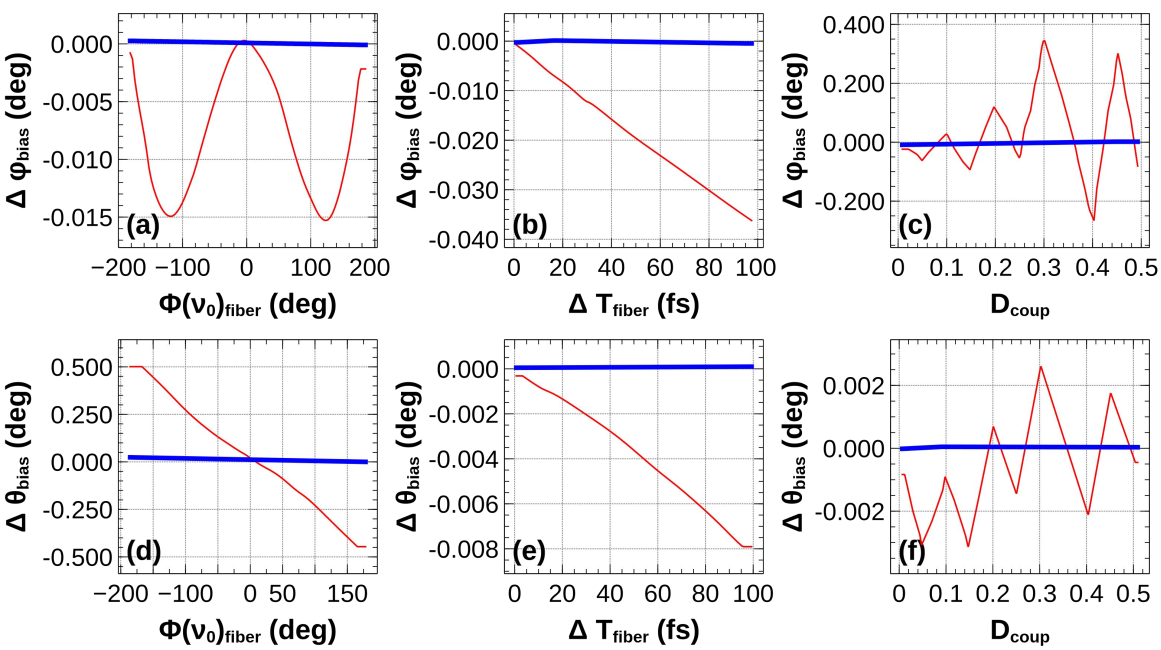

Figure 4. Simulation results for the working bias of the optical module in the measurement of the phase retardance φ (top row) and the orientation of the optical axis θ (bottom row), as described in Rivet *et al.*[6] Thick blue curves: no change in the fiber/coupler properties (fiber birefringence $\phi(\nu_0)_{fiber}$, fiber polarization mode dispersion ΔT_{fiber} and coupler diattenuation D_{coup}) between the two measurements necessary for the full polarization characterization; thin red curves: a change of 1% is applied to each of the parameters between the two measurements necessary for the full polarization characterization.

In order to validate the performance of the device and evaluate the intrinsic errors of the method (by estimating its working bias), simulations have been carried out. These have been thoroughly described in[6] and the main results have been reproduced in Figure 4. The collecting fiber and coupler (partially represented in Figure 1(b) as sample arm input/output) have been modeled as a product of different Jones matrices which account for the chromatic birefringence $\phi(\nu_0)_{fiber}$ and polarization mode dispersion ΔT_{fiber} of the fiber, as well as the diattenuation D_{coup} in the coupler. For a broad range of values for these three parameters, two situations were considered: (1) each of the three parameters remained constant during the two states of the EO modulators, necessary to perform the polarization measurement (represented in Figure 4 as thick blue lines); and (2) each of the three parameters changed by 1% during the change of state of the EO modulators (represented in Figure 4 as thin red lines). While the former case depicts a complete flat response throughout the whole range of values, a slight bias is observed on the latter case.

The simulations carried out to generate the results depicted in Figure 4 do not take into account any chromatic behavior from the elements used in the OM, namely the EO modulators and the Faraday rotator, which are known to exhibit a considerable chromatic response.

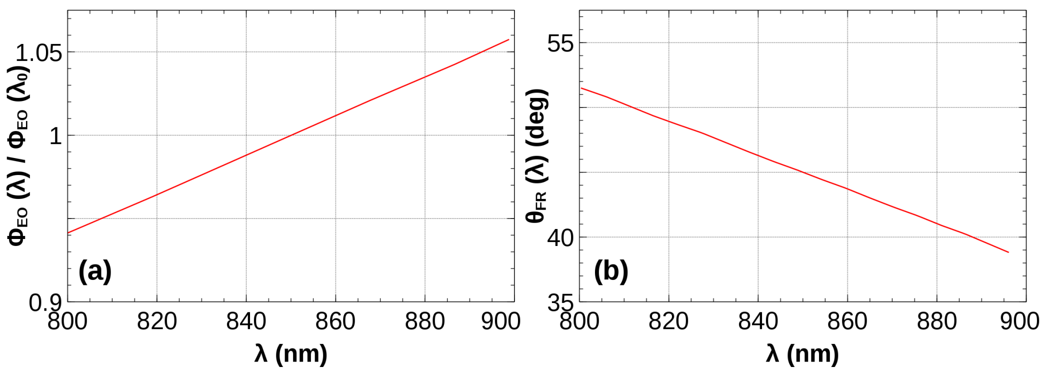

Figure 5. Chromatic response of the EO polarization modulators **(a)** and the Faraday rotator **(b)**. (adapted from Rivet *et al.*[6])

In order to study the impact of the elements present in the OM on the accuracy of the polarization measurements carried out by the OM, we have modeled the chromatic response of the EO polarization modulators and the Faraday rotator as linear curves, with the expected performance for each element centered at the central wavelength of the optical source considered (850 nm). These curves are represented in Figure 5(a) and 5(b).

Taking these responses into consideration, the measurement bias on both the retardance and axis orientation has been numerically simulated for different sample retardances φ_{sample} and axis orientations θ_{sample}. These biases are respectively shown in Figures 6(a) and 6(b) for two separate source spectrum full-width at half maxima (FWHM): thick (blue) lines represent a FWHM of 50 nm, whereas thin (red) lines represent a FWHM of 100 nm. It is now quite evident that the biases caused by the chromatic response of the components used far outweigh the biases shown in Figure 4, where the collecting fiber has been disturbed during the two-step measurement procedure. It is also clear that larger optical bandwidths yield larger measurement biases on both retardance and axis orientation. However, large optical bandwidths are essential to ensure good axial resolution in OCT systems.

Therefore, a compromise has always to be made between PS-OCT performance (impacting the accuracy of the retardance and axis orientation measurements) and optical bandwidth (impacting the axial resolution of the OCT system).

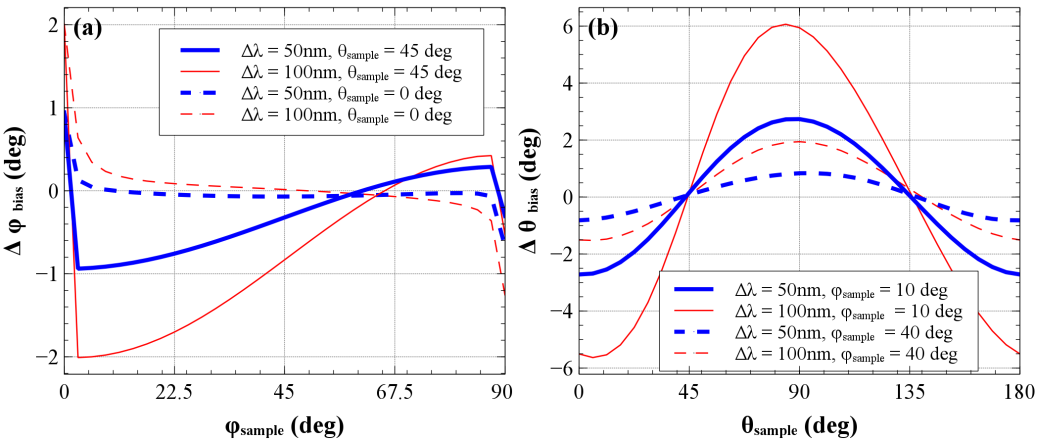

Figure 6. Measurement of the bias on the retardance φ_{sample} (a) and on the orientation angle θ_{sample} (b) of a linear retarder. Thin (red) curves: the FWHM of the source spectrum is equal to 100 nm. Thick (blue) curves: the FWHM of the source spectrum is equal to 50 nm. Solid lines in (a): sample oriented at 45 degrees. Dashed lines in (a): sample oriented at 0 degrees. Solid lines in (b): sample retardance equal to 10 degrees. Dashed lines in (b): sample retardance equal to 40 degrees. (adapted from Rivet *et al.*[6])

4. CONCLUSIONS

The module presented can then be used to add the polarization-sensitive capability to any existing fiber-based OCT system without requiring extensive modifications or calibration procedures. Since it is based on the same principle as the previously reported set-up,[1] it is insensitive to disturbances on the polarization properties of the collecting fiber and coupler which would otherwise impact the polarization measurements. Unlike the previously reported set-up, though, this module allows for higher imaging rates, while allowing it to be a true plug-in module, not requiring any modifications to be made to the supporting OCT system.

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