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Publisher's version / Version de l'éditeur:
https://doi.org/10.1117/12.2612382
Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XXVI, Proceedings of SPIE, 2022-03-07

Simple and robust calibration procedure for passive quadrature demultiplexing in full-range swept-source OCT

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Introduction

Standard optical coherence tomography (OCT) relies on the measurement of the real component of the complex interference signal. As such it suffers from the well know "complex conjugate" or "mirror artifact", which prevents imaging on both sides of zero-delay (ZD). Measuring the complex interference signal resolves this ambiguity and allows imaging on both sides of ZD. Passive demultiplexing uses optical circuits to enable simultaneous measurement of both the real and imaginary components of the complex interference signal. However, to achieve high (>60 dB) extinction of the mirror peak, this requires extremely precise and stable measurements.

We propose a method to measure and correct both spectral/ chromatic and frequency response/ RF-errors from mirror measurements performed directly on the full OCT system.

System

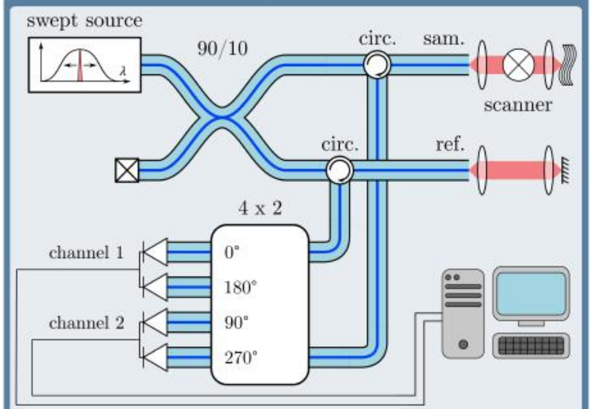

Figure 1 : Schematic representation of a full-range OCT system using a 2x4 optical hybrid (COH24, Kylia). The optical hybrid utilizes free-space polarization optics to produce 4 outputs each phase shifted by $\pi/2$. Outputs with π phase offset are measured using balanced detectors on 2 separate channels and digitized with a DAQ card.

References

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[2] Choma, M. A., et al. (2003). Instantaneous quadrature low coherence interferometry with 3x3 fiber optic couplers. OSA Trends in Optics and Photonics Series, 88(22), 2178–2182.

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Theory & Method

1. Chromatic errors

The complex interference signal can be reconstructed from the real and imaginary components following Eq. (1). However, these signals must be perfectly matched in amplitude and maintain a phase offset of $\pi/2$ at all wavelengths.

$$\tilde{S} = S_I + i \cdot S_Q \tag{1}$$

When wavelength-dependent variations in phase ($\Delta\varphi_k$) or amplitude (β_k) exist in the signals S_I and S_{II}, the corrected imaginary signal (S_Q) is found using Eq. (2) provided these wavelength-dependent variations are precisely known [1,2].

$$S_Q = \frac{\beta_k \cdot S_{II}'' - \cos\Delta\phi_k \cdot S_I'}{\sin\Delta\phi_k} \tag{2}$$

We show that the amplitude and phase characteristics of the demodulation circuit in both channels can be described by an arbitrary phasor multiplying the interference signal ($I_S(k)$), as described in Eq. (3).

$$\begin{aligned} \tilde{S}_I(k) &= A_I(k)e^{i\Omega_I(k)} \cdot \tilde{I}_S(k) \\ \tilde{S}_{II}(k) &= A_{II}(k)e^{i\Omega_{II}(k)} \cdot \tilde{I}_S(k) \end{aligned} \tag{3}$$

2. RF-errors

RF-errors refer to depth-dependent errors originating from temporal delays between the signals or differences in the frequency response of the two channels [3]. When expressed in the Fourier domain (i.e., in frequency- or z-space), the measured signal ($\tilde{S}_I'$) is the product of the optical signal ($\tilde{S}_I$) in Eq. (3) with the transfer functions of the various components ($\widetilde{H}_i(z)$). These contributions can be summarized into a single phasor:

$$\begin{aligned} F\{\tilde{S}_I'\} &= F\{\tilde{S}_I\} \cdot \widetilde{H}_1(z) \cdot \widetilde{H}_2(z) \cdot \ldots = F\{\tilde{S}_I\} \cdot \alpha_I(z)e^{i\omega_I(z)} \\ F\{\tilde{S}_{II}'\} &= F\{\tilde{S}_{II}\} \cdot \widetilde{H}_3(z) \cdot \widetilde{H}_4(z) \cdot \ldots = F\{\tilde{S}_{II}\} \cdot \alpha_{II}(z)e^{i\omega_{II}(z)} \end{aligned} \tag{4}$$

For mirror measurements with a narrow peak in the Fourier domain, the approximation given in Eq. (5) holds, where Δz refers to the position of the mirror.

$$\begin{aligned} \tilde{S}_I' &= \tilde{S}_I \cdot \alpha_I(\Delta z)e^{i\omega_I(\Delta z)} \\ \tilde{S}_{II}' &= \tilde{S}_{II} \cdot \alpha_{II}(\Delta z)e^{i\omega_{II}(\Delta z)} \end{aligned} \tag{5}$$

3. Method

We demonstrate that the phase and amplitude differences between the two channels, caused by chromatic and RF errors, are captured by parameters $\beta(k,z)$ and $\Delta\varphi(k,z)$, described in Eqs. (6). These parameters can be deduced from mirror measurements and used to reconstruct an ideal imaginary signal.

$$\begin{aligned} \beta(k,z) &= \frac{\|\tilde{S}_I'\|}{\|\tilde{S}_{II}'\|} = \underbrace{\frac{A_I(k)}{A_{II}(k)}}_{\beta_k} \cdot \underbrace{\frac{\alpha_I(z)}{\alpha_{II}(z)}}_{\beta_z} \\ \Delta\phi(k,z) &= \measuredangle\tilde{S}_{II}' - \measuredangle\tilde{S}_I' = \underbrace{[\Omega_{II}(k) - \Omega_I(k)]}_{\Delta\phi_k} + \underbrace{[\omega_{II}(z) - \omega_I(z)]}_{\Delta\phi_z} \end{aligned} \tag{6}$$

The phase and amplitude of mirror measurements at different axial locations can be extracted using the Hilbert Transform. In order to reconstruct the quadrature signal using Eq. (2) the RF variations must first be corrected using Eq. (7).

$$S_{II}'' = \mathcal{R}\left\{F^{-1}\left\{F\{\tilde{S}_{II}'\} \cdot \beta_z \cdot e^{-i\Delta\phi_z}\right\}\right\} \tag{7}$$

It is important to note that after the calibration vectors are defined, processing the measured signal to reconstruct the complex one only requires Eqs. (2) & (7) and comes at little additional computational cost compared to standard processing.

Results

The proposed method was first tested on simple A-line measurements. Coherent averaging of 512 A-lines was implemented to lower the noise floor to enable measurement of high mirror artifact extinction. Excellent extinctions (>60 dB) were achieved on the majority of the imaging range.

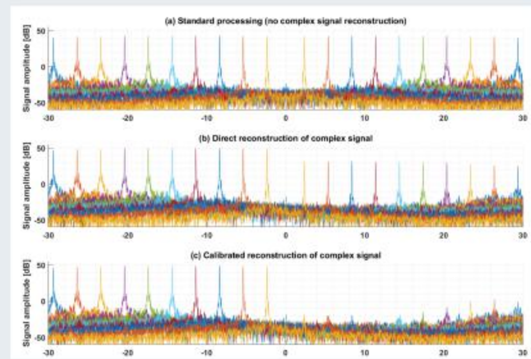

Figure 2: Processed A-lines. From top to bottom: standard OCT processing, direct reconstruction of complex signal from measured signals, calibrated reconstruction of complex signal with proposed method.

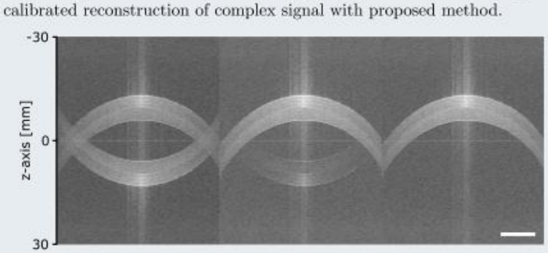

Figure 3: Image of tape roll. From left to right: standard OCT processing, direct reconstruction of complex signal from measured signals, calibrated reconstruction of complex signal with proposed method.

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