Real-time quadrature projection complex conjugate resolved Fourier domain optical coherence tomography

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We present a novel algorithm for full-range imaging by suppression of the complex conjugate artifact in phase-shifting Fourier domain optical coherence tomography. This technique utilizes the projection of multiple phase-shifted interferograms onto an orthogonal basis set to reconstruct the complex interferogram. Full-range imaging with >30 dB suppression of the symmetric artifact is demonstrated using a 3 × 3 fiber coupler swept source OCT system, providing a depth range of 6.6 mm with -8 dB roll-off in sensitivity at the depth boundaries relative to DC. Real-time display of full-range images of the anterior segment of the human eye acquired in vivo at a line rate of 6.67 kHz are presented. © 2006 Optical Society of America

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Development of optical coherence tomography (OCT) in recent years has concentrated on Fourier domain (FD) techniques for high-speed cross-sectional imaging of biological tissue. In FDOCT, the locations of scatterers within a sample are obtained by Fourier transformation of real-valued spectral interferograms. The Fourier transform of the interferogram is Hermitian symmetric, introducing a complex conjugate artifact in which positive and negative distances are not resolved. In practice, this artifact may be avoided by locating the sample entirely within the positive or negative displacement range, thus utilizing only half the total imaging depth. Such one-sided imaging is suitable for thin objects, but imaging of extended objects is limited by the characteristic sensitivity roll-off due to the finite spectral resolution of FDOCT systems.

Full-range imaging, in which positive and negative distances are resolved, can be achieved by indirectly measuring the complex component of the interferometric OCT signal obtained by shifting the phase of the reference reflection in increments of 90°. Sequentially shifting the reference reflector phase has been demonstrated in spectrometer-based FDOCT but suffered from significant image corruption resulting from small (including chromatic) deviations in the actual phase shift or from small (subwavelength) sample motion between the phase-shifted acquisitions. Recently, the instantaneous acquisition of two phase-shifted signals was demonstrated using linearly polarized light. Complex signal reconstruction was limited by having only two phase-shifted signals and also by potential image corruption in birefringent samples. We have previously described methods to instantaneously acquire three phase-shifted interferograms using 3 × 3 fiber couplers for both spectrometer-based and swept source (SS) FDOCT systems. The performance of these systems was limited by the wavelength dependence of the splitting ratios of the couplers. A frequency-shifting approach to full-range imaging has also been presented in the literature but is not compatible with spectrometer-based systems.

All the phase-shifting FDOCT techniques described thus far suffer image corruption arising from miscalibration of the phase shifts and also from the wavelength dependence of the phase shifter. A least squares fitting algorithm has been presented in the literature to improve the suppression of symmetric artifacts by correcting for phase-shift irregularities and also by accounting for axial sample motion in between phase-shifted acquisitions. In this Letter, we present a novel algorithm for complex conjugate resolved FDOCT imaging by projecting phase-shifted signals onto an orthogonal basis set using Fourier decomposition. Quadrature projection processing is insensitive to miscalibrated phase shifts in 90° shift interferometry and requires only predetermined determination of the quadrant location for each phase shift in non-90° techniques.

The interferometric component of the detector signal in a phase-shifting FDOCT system can be written as

\[ s_n(k) = \sum m A_m \cos(2\Delta z_m k + \theta_m + \phi_m), \]

where \( \Delta z_m \), \( A_m \), and \( \theta_m \) represent the axial distance, the reflectance, and the relative phase of the \( m \)th scatterer in the sample, respectively, and \( \phi_m \) is an additional phase shift introduced for the \( n \)th phase-shifted acquisition. Three representative interferograms, \( s_n(k) \), phase shifted by nominally 120° are shown in Fig. 1a. Since the interferograms differ only by an external phase shift (corresponding to less than a wavelength), the Fourier transform of each signal, \( \hat{s}_n(z) = \text{FT}(s_n(k)) \), has the same intensity depth profile, but the phase at each corresponding depth differs by the induced phase shift, \( \phi_m \). The Fourier transformed signals, \( \hat{s}_n(z) \), can be represented vectorially in the complex plane by plotting the depth-resolved magnitude \( ||\hat{s}_n(z_m)|| \) at an angle \( \theta_m + \phi_m \), as illustrated in Fig. 1b (showing only a single reflector for clarity), with the possible values of \( \theta_m \) ranging from 0 to 2π.

The first step of quadrature projection processing
Fig. 1. Quadrature projection processing steps. The phase-shifted interferograms shown in a are Fourier transformed, and each depth location can be represented in the complex plane, b. Phase subtraction aligns the first signal onto the positive real axis, and the shifted signals are forced to the angle of the induced phase shift, c. The projections of each vector onto the real and imaginary axis are summed, taking the real and imaginary components of each scatterer by up to $\frac{\pi}{2}$, which is much smaller because the cosine and sine basis functions are orthogonal. Dependence of the projection with 90° phase-shifting techniques, only the projection along the desired axis is retained. A nonzero value of the perpendicular component represents a miscalibrated phase shift and/or sample drift. When quadrature projection is used with non-90° phase-shifting techniques, the real and imaginary components are of similar amplitude and both are retained. An estimate of each $\phi_n$ is required to predetermine which quadrature-projected components are aligned parallel or antiparallel to the axes, represented using $\delta_n^R = \pm 1$ and $\delta_n^I = \pm 1$. Since the sign of each $\delta_n$ is dependent only on the quadrant location of $\phi_n$, the quadrature-projection algorithm is insensitive to miscalibration or drift of the actual induced phase shift. The derived real and imaginary signals are thus determined using the relations $s^R_n = \sum_n \delta_n^R s_n^R$ and $s^I_n = \sum_n \delta_n^I s_n^I$, illustrated in Fig. 1d.

Lastly, the derived quadrature components $s^R_n$ and $s^I_n$ require scaling to account for unequal contributions to the real and imaginary quadrature components. The scaling coefficient is calculated using $\beta$, the ratio of the total energy in the derived real signal to that of the derived imaginary signal, given by $\beta = \frac{\int |s^R_n|^2 dz}{\int |s^I_n|^2 dz}^{1/2}$. The complex conjugate resolved A-scan is then obtained by directly adding the derived real component and the scaled imaginary component, $s(z) = s^R_n + \beta \cdot s^I_n$. The summation is illustrated in Fig. 1d, showing cancellation of the symmetric complex conjugate artifact peaks in $s^R(z)$ by the antisymmetric peaks in $s^I(z)$, resulting in the full-range depth profile $s(z)$.

Quadrature projection processing was demonstrated using the 3 × 3 Michelson-type interferometer illustrated in Fig. 2. The source was a fiber ring swept laser (Micron Optics) followed by a semiconductor optical amplifier (InPhenix), providing a FWHM bandwidth of 84 nm centered at 1310 nm, and an average power of >8 mW at the sample. The source was driven with a 3.33 kHz triangular wave, providing an effective 6.67 kHz line rate by processing both forward and backward sweeps. A calibration signal from a 2 × 2 fiber Michelson interferometer was used to resample the data channels using the nearest-neighbor algorithm presented by Huber et al. All four channels were digitized simultaneously at 10 MHz (NI PCI 6115), from four photodiode detectors (New Focus D1-3, Model 1817, and D4, Model 1617).

The optical power at the sample was reduced to 3.75 mW for ocular anterior segment imaging, and...
this value was also used to measure the system sensitivity. The complex conjugate suppression of 30 dB and resulting double-sided imaging depth of 6.6 mm are presented in Fig. 3. The system sensitivity, accounting for recoupling losses, was measured to be 103 dB near DC and decreased by 8 dB at the ends of the depth scan. The quadrature projection 3 × 3 OCT system was demonstrated for in vivo imaging of the ocular anterior segment of human volunteers with approval from the Institutional Review Board of Duke University Medical Center. Corruption of the complex conjugate resolved image due to sample motion was not observed since the phase-shifted interferograms from the 3 × 3 coupler were acquired simultaneously. Custom C++ code was written for efficient image processing on a standard desktop (Intel Pentium D 3.2 GHz) computer. The nearest-neighbor resampling and quadrature projection processing were performed and displayed in real time on 1024 point A-scans for 800 lines per frame at 6.7 frames/s. The complex conjugate resolved image is compared against the unresolved image (obtained by averaging the Fourier transformed detector outputs) in Fig. 4.

In conclusion, we have presented a novel algorithm for complex conjugate resolved FDOCT with arbitrarily spaced phase shifts. The algorithm was demonstrated using a 3 × 3 fiber interferometer but is generally applicable to other phase-shifting techniques.

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