Complex artifact suppression using vestigial sideband filter in Fourier-domain optical coherence tomography

Hyun-Woo Jeong, Jae-Guyn Lim, Hyung-Jin Kim, Wonzoo Chung, and Beop-Min Kim

Department of Biomicrosystem Engineering, Korea University, Jeongneung 3-dong, Seongbuk-ku, Seoul 136-703, South Korea
Department of Biomedical Engineering, Korea University, Jeongneung 3-dong, Seongbuk-ku, Seoul 136-703, South Korea
Samsung Advanced Institute of Technology, Nongseo-dong, Giheung-ku, Yongin 446-712, South Korea
Department of Radio Communication Engineering, Korea University, Anam-Dong, Seongbuk-ku, Seoul 136-713, South Korea

Received August 9, 2012; revised September 21, 2012; accepted October 16, 2012; posted October 22, 2012 (Doc. ID 174081); published November 22, 2012

In order to achieve computationally efficient mirror image rejection during the off-pivot, full-range approach in spectral-domain optical coherence tomography, we used a vestigial sideband (VSB) filter in place of a Hilbert transform. The appropriate choice of the VSB filter parameters enabled almost complete removal of one sideband with much reduced computational load. To determine the optimal filter parameters, we acquired images of the infrared card and analyzed the mirror suppression ratio of the card surface. Comparison between images obtained using the two filters revealed that the computational load is reduced by 52.4 ± 0.17% when using the VSB filter as it requires a much shorter truncation length. Finally, we present the anterior segment images of a human volunteer’s eye processed using the VSB filter. © 2012 Optical Society of America

OCIS codes: 170.3010, 170.4500.

Optical coherence tomography (OCT) is a powerful imaging modality that enables high-resolution in vivo cross-sectional imaging of biological samples [1]. Recently, Fourier-domain OCT (FD-OCT) has attracted considerable attention due to the improved sensitivity and higher image acquisition speed than those of a conventional time-domain implementation [2,3].

In FD-OCT, the detected spectral density is a real-valued function, and its Fourier transform is Hermitian. Hence, the depth-resolved information has a complex artifact that is symmetrical with respect to the zero-delay depth. If the entire imaging depth is to be used, for instance, when imaging the entire anterior segment of the human eye, the mirror image must be removed to obtain unambiguous images. Furthermore, it is highly desirable that the zero-delay position is included within a sample since sensitivity around this position is the highest.

Over the past few years, several complex artifact removal techniques, referred to as full-range complex (FRC) methods, have been suggested [4-12]. One such widely accepted approach involves phase modulation induced by the off-pivot illumination on the galvanometer, which does not require additional devices [10-12]. In this method, the acquired two-dimensional spectral data are Hilbert transformed to yield complex signals along the B-scan direction. Then, the desired depth-resolved images without the mirror term can be reconstructed via Fourier transformation for each A-scan.

Since the ideal Hilbert transform requires an infinite filter length in the time domain, it is necessary to truncate the filter. However, this truncation introduces distortion to the reconstructed image and is directly proportional to the computational load. Thus, it is essential to use the minimum truncation length with acceptable image distortion.

In this Letter, we propose an alternative full-range algorithm using a vestigial sideband (VSB) filter instead of a Hilbert transform for the off-pivot illumination approach, which can improve both the mirror suppression efficiency and computational load.

The VSB filter, the generalized version of the Hilbert transform, realizes a faster decay in the time domain (~1/t^n, n ≥ 2) than that obtained in the case of the Hilbert transform (~1/t), at the cost of the narrowed bandwidth of the filter. We consider a VSB filter with a raised cosine shape in the frequency domain in [-π, π] with respect to a given constant called the “roll-off” factor, R(0 ≤ R ≤ 1). The filter function is expressed as

\[
H(\omega) = \begin{cases} 
0 & |\omega| > \frac{\pi}{2}R \\
\frac{1}{2} \left[ 1 + \cos \left( \frac{\omega}{\pi} - \frac{\pi}{2} \right) \right] & \frac{\pi}{2}R < |\omega| < \frac{\pi}{2}(2 - R) \\
\frac{1}{2} \left[ 1 + \text{sgn}(R - \frac{1}{2}) \cos \left( \frac{\omega}{\pi} - \frac{\pi}{2} \right) \right] & 0 < |\omega| < \frac{\pi}{2}R \\
\frac{\pi}{2}(R - 2) < |\omega| < -\frac{\pi}{2}R \\ \frac{\pi}{2}(2 - R) < |\omega| \end{cases}
\]

and is illustrated in Fig. 1.

The bandwidth of this filter is given as π(1 - R). Therefore, as R approaches 0, H(\omega) becomes the Hilbert transform.
transform, and as \( R \) approaches 1, the bandwidth of the filter becomes 0. An inverse discrete time Fourier transform yields the following discrete time domain coefficient:

\[
h(k) = \frac{\sin(\pi k/2)}{\pi k/2} \cdot \frac{\cos(\pi Rk/2)}{1 - R^2k^2} \cdot e^{j\phi}.
\]

(2)

Note that \( h(k) \) decays at the rate of \( 1/R^2k^2 \), which indicates that the filter distortion (deviation from the ideal filter), due to truncation, diminishes as \( R \) increases. Hence, there exists a trade-off determined by \( R \) between the minimum truncation length \( [N \text{ in Eq. (3)}] \) introducing acceptable filter distortion in time domain, and the bandwidth in frequency domain. Furthermore, \( h(k) \) has an additional property that \( \text{Re}[h(k)] = \delta(k) \) and \( h(2k) = 0 \), \( k = 1, 2, \ldots \) that enables the following computational simplification where \( x(n) \) is the spectral interference data corresponding to the \( n \)th B-scan position at each wave number:

\[
y(n) = h(n) \ast x(n) = x(n) + \sum_{k=0}^{N} \text{Im}[h(2k - 1)] \times [x(n - 2k - 1) - x(n + 2k + 1)].
\]

(3)

Figure 2 shows the simulation results for the frequency response of the Hilbert transform \([R = 0 \text{ in Eq. (2)}] \) and the VSB filters \([R \neq 0 \text{ in Eq. (2)}] \) as a function of truncation length \((N)\) for 1500 A-scan lines. In the case of the Hilbert transform, the imaginary part in spatial domain is suppressed only gradually for large truncation lengths \((N)\). The residual of one sideband exists even if \( N \) is as large as 9, as shown in Fig. 2(a). On the other hand, in the case of the VSB filter, one sideband is almost completely removed, even for a low truncation length as shown in Fig. 2(b). In this case, the \( R \) factor has been determined via the iterative simulation process so that the filter distortion, due to truncation, becomes minimized at each \( N \).

As stated earlier, increasing the \( R \) factor decreases the bandwidth of the filter, which may introduce distortion in the final image. Therefore, to minimize the computational load and image distortion, optimal values of \( N \) and \( R \) have to be determined.

A spectral-domain OCT (SD-OCT) system was used to estimate the optimal filter parameters \((N, R)\). We used a broadband superluminescent diode (SLD; Superlum Ltd., Ireland) with a center wavelength of 830 nm, (FWHM, \( \Delta \lambda \)) of 64 nm, and output power of 25 mW. This SLD can provide a theoretical axial resolution of 4.7 \( \mu \)m in air. The spectrometer consists of a transmission grating (1,800 lines/mm; Wasatch Photonics, USA), an achromatic doublet lens \((f = 75 \text{ mm}; \text{Thorlabs, USA})\), and a line-scan camera (spL2048-140k; Basler AG, Germany) with 2048 pixels and a maximum line rate of 70 kHz. The imaging depth (\(~20\text{ dB}\)) of our SD-OCT was measured to be \(~3.0 \text{ mm}\) in air, which can be doubled using the FRC techniques. The measured axial resolution was \(~6.7 \mu \text{m}\) in air and 4.9 \( \mu \text{m}\) in tissues, which was limited due to the Nyquist sampling theorem for the depth range of \(~3 \text{ mm}\) [13].

The probe beam was aligned to be incident on the off-pivot position of a galvanometer that results in a phase shift in the spatial domain. The beam power was \(~1.2 \text{ mW}\) for the anterior segment imaging, which meets the safety requirements set by the American National Standards Institute Z136.1. The sensitivity was measured to be \(~92 \text{ dB}\) with an exposure time of 12 \( \mu \text{s}\) near the zero-delay position.

Figure 3 shows the images of an IR card (Thorlabs, USA) on the entire complex range, unprocessed [Fig. 3(a)] and processed by the full-range algorithm with \( R = 0 \) [Figs. 3(b)–3(d)] and \( R \neq 0 \) [Figs. 3(e)–3(g)]. When \( R \neq 0 \), we set the \( R \) factor to make one sideband become almost zero for each truncation length \((N)\) via simulation results. Both real and mirror images were placed just off the zero-delay position. The incidence angle of the probe beam was adjusted so that the surface reflectivity

![Fig. 2. (Color online) Simulation of (a) Hilbert transform \((R = 0)\) and (b) VSB filter \((R \neq 0)\) with truncation lengths \((N)\) of 3, 5, 7, and 9.](image)

![Fig. 3. (Color online) IR card images (a) with and without the mirror artifact using the filter with \( R = 0 \) (Hilbert transform) and with \( R = 0.3 \) (VSB filter) at the truncation length \((N)\) of (e) 5, (f) 7, and (g) 9. Each image has 1130(axial) \times 1800(lateral) pixels with a lateral scan range of 12.5 mm.](image)
becomes almost maximized, which was necessary because the highly reflecting surfaces could contribute the most in deteriorating the image quality after mirror noise suppression. As seen from all the images, the mirror artifacts were greatly suppressed as compared to the original image in Fig. 3(a). When \( R = 0 \) (Hilbert transform), even if the mirror artifacts for the highly reflecting top surfaces are still observable in all the images, the artifacts become further suppressed as \( N \) becomes larger [Figs. 3(b)–3(d)]. However, as the roll-factor \( R \) is adjusted to be 0.3 (VSB filter), the images show barely observable artifacts even with \( N = 5 \) [Figs. 3(e)–3(g)].

To quantify the mirror suppression efficiency, the suppression ratio (dB) was measured as a function of truncation length (\( N \)) from the images of the IR card surface that originally displayed the peak sensitivity of 27 dB. The suppression ratio was defined as the difference of the peak sensitivities between the mirror and the real signals in an axial profile averaged with 5 A-lines [red box region in Fig. 3(b)]. As shown in Fig. 4, the suppression ratio for the filters with the predetermined \( R \) factors (\( R = 0.5 \) in the \( N = 3 \), \( R = 0.3 \) in others) are approximately 24 dB, starting from a small \( N (N = 3) \). However, the Hilbert filter (\( R = 0 \)) shows gradual improvement as \( N \) is increased; with a suppression ratio of 23.3 dB even at \( N = 13 \), which is still slightly worse than that (23.7 dB) of the filter with \( R = 0.5 \) at \( N = 3 \). These results are consistent with the simulation results, which show the almost complete removal of the mirror term when using the filter with a proper \( R \) factor of \( N \geq 3 \). However, using a larger \( R \) factor does not ensure better filter performance when \( N < 5 \), since the bandwidth of the filter becomes narrowed significantly, which may induce the real signal loss and the reduced mirror suppression. As a result, we propose that a truncation length (\( N \)) of 5 with an \( R \) factor of 0.3 may be the optimal value for the VSB.

We compared the computation times for the IR card images using the Hilbert transform filter with the minimum \( N \) of 13 and the VSB filter with \( R = 0.3 \) at the minimum \( N \) of 5. They were measured to be \( \sim 390.5 \) ms and \( \sim 185.2 \) ms, respectively, by using the Visual C++ 2008 software on a 2.66 GHz Intel Core i7 CPU 920. Trials with five different images revealed the computational load is reduced by 52.4 − 0.17% when using the proposed filter.

Figure 5 shows the anterior segment images of a human eye with and without the mirror artifact [Figs. 5(a) and 5(b)], processed using the VSB filter. The mirror image is suppressed, and microstructures of the anterior segment are visualized. We can also see the artifacts (red arrows) induced by the camera readout noise and the sample motion near the zero-delay zone [10, 11].

In summary, we demonstrated that mirror artifacts in the FD-OCT images could be more effectively suppressed using the VSB filter during the off-pivot, full-range approach. The optimal filter parameters, including the roll-off factor (\( R \)) and the truncation length (\( N \)), were proposed. The VSB filter affords a significantly reduced computational load without degradation of the real image. Considering that three-dimensional imaging and real-time display are important issues in recent OCT technologies, we believe that the use of the VSB filter may serve as a useful technique.

This project was supported by a grant from the Korean Health Technology R&D Project, Ministry for Health, Welfare & Family Affairs (A102024), and a grant from the Industrial Strategic Technology Development Program (10040121) funded by the Ministry of Knowledge Economy (MKE, Korea).

\* These authors contributed equally to this work.

### References