Optics Communications 410 (2018) 222–227

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Two-harmonic complex spectral-domain optical coherence tomography using achromatic sinusoidal phase modulation

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ARTICLE INFO

Keywords:
Complex spectral-domain optical coherence tomography
Two-harmonic method
Achromatic sinusoidal phase modulation
Digital lock-in technique

ABSTRACT

We resolve the complex conjugate ambiguity in spectral-domain optical coherence tomography (SD-OCT) by using achromatic two-harmonic method. Unlike previous researches, the optical phase of the fiber interferometer is modulated by an achromatic phase shifter based on an optical delay line. The achromatic phase modulation leads to a wavelength-independent scaling coefficient for the two harmonics. Dividing the mean absolute value of the first harmonic by that of the second harmonic in a B-scan interferogram directly gives the scaling coefficient. It greatly simplifies the determination of the magnitude ratio between the two harmonics without the need of third harmonic and cumbersome iterative calculations. The inverse fast Fourier transform of the complex-valued interferogram constructed with the scaling coefficient, first and second harmonics yields a full-range OCT image. Experimental results confirm the effectiveness of the proposed achromatic two-harmonic technique for suppressing the mirror artifacts in SD-OCT images.

1. Introduction

Fourier-domain optical coherence tomography (FD-OCT) is currently widely applied to clinical diagnosis and industrial inspection because of its superior sensitivity and speed relative to time-domain detection [1–3]. Spectral-domain OCT (SD-OCT) [4] and swept-source OCT (SS-OCT) [5] are the well-known representatives of FD-OCT. However, SD-OCT has made tremendous gains in market acceptance due to the maturity and reliability of superluminescent diodes (SLDs) and line cameras [6,7]. Complex conjugate ambiguity is an inherent obstruction of SD-OCT arising from the Fourier transform of a real-valued spectral interferogram. The true object is obscured by its mirror image, or conjugate artifact, with respect to the plane of zero optical path difference (OPD). Therefore, only half the imaging depth range of conventional SD-OCT is valid. The ambiguity problem can be effectively resolved by using a complex-valued spectral interferogram as the input of the inverse Fourier transform [8].

The probe beam in complex SD-OCT is laterally scanned on the sample to obtain a cross-sectional tomographic image. Temporal [8–11] and spatial [12–16] phase-shifting methods have been developed to measure the interferometric phase for retrieving the complex-valued interference spectrums. The spatial method has a tremendous speed advantage over the temporal method because only single phase-shifted A-scan signal is acquired at each lateral position. Most previous approaches of spatial phase-shifting method introduce a constant phase shift into adjacent A-scans with a spatial carrier generated by linear phase modulation. Lining up these sequential A-scan signals yields a B-scan interferogram, which is a 2D position–wavenumber (x–k) data. Using the technique of fast-Fourier-transform (FFT)-based fringe-pattern analysis can convert the real-valued x–k data into a complex-valued x–k interferogram [12,17]. The intensive computations of multiple FFTs in complex SD-OCT can be accelerated significantly by using graphics processing units [18]. Real time quadrature projection complex FDOCT [19] acquires multiple phase-shifted interferograms simultaneously at each transverse position to overcome the depth degeneracy. The FDOCT can be operated at a high A-line rate but the complexity of the system limits its practical use. In addition to a 3×3 fiber interferometer, two or more spectrometers are required for SDOCT.

Linear phase modulation is commonly performed with a piezo translating mirror but its short travel range limits the lateral width of SD-OCT images. Beam-offset scanning method can conquer the limitation without using additional phase shifters [13]. However, the phase shifts depend on k and the scanning beam has a non-zero diameter which deteriorate the performance of complex SD-OCT. Sinusoidal phase modulation is another alternative for generating spatial carriers [14–16]. The piezo mirror in sinusoidal phase modulation vibrates continuously with an amplitude much smaller than that in linear phase modulation.

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https://doi.org/10.1016/j.optcom.2017.10.020
Received 25 August 2017; Received in revised form 6 October 2017; Accepted 11 October 2017
0030-4018/

Complex SD-OCT with sinusoidal phase modulation is also named two-harmonic technology [12] because the first and second harmonic of an acquired B-san interferogram carry the real and imaginary parts of the complex-valued interference spectrum, respectively. The magnitude ratio of the first to the second harmonics, or the so-called scaling coefficient, must be known before reconstructing the complex-valued interference spectrum. The scaling coefficient is a function of k in conventional two-harmonic complex SD-OCT using chromatic phase shifter (CPS). The most important step in determining the k-dependent scaling coefficients is the decision of the modulation amplitude a_{m0} at the central wavelength of the light source. Vakhtin et al. adjusted a_{m0} iteratively to maximize the complex conjugate rejection ratio [14,15]. Wang et al. needed an additional harmonic, third harmonic, and changed a_{m0} repeatedly to minimize the least square error between the measured and theoretical ratios of first harmonic to third harmonic [16]. Once a_{m0} was decided then a set of scaling coefficients for different k were calculated with the theory of two-harmonic complex SD-OCT.

In this paper, we present a simple and efficient method to avoid the cumbersome iterations and the extraction of third harmonic. The optical phase is modulated by an achromatic phase shifter (APS) which is based on a frequency-domain optical delay line (FDODL), broadly used in high-speed TD-OCT [20]. The FDODL is always kept at zero group delay while the optical phase is modulated by tilting a mirror [21,22]. The achromatic sinusoidal phase modulation enables a single scaling coefficient for all k. The scaling coefficient is directly determined by dividing the mean absolute value of first harmonic to that of second harmonic. This paper reports the principle, configuration, and performance of the proposed achromatic two-harmonic complex SD-OCT.

2. Principles

Fig. 1 shows a two-harmonic complex SD-OCT system using a sinusoidally modulated APS. A fiber coupler divides the output of a SLD into two beams of equal power. One enters the reference arm and the other goes into the measurement arm. The optical phase of the reference beam is modulated by the APS which has been described in detail elsewhere [21,22]. The APS comprises a transmission grating G_1 with a period of p_g, a lens L_1 with a focal length of l_{f1} and a piezo-tilting mirror. The grating and tilting mirror are placed in the front and back focal planes of L_1, respectively. In order to operate the APS in achromatic region, the pivot of the tilting mirror is laterally displaced from the optical axis by a distance s_o:

$$s_o = \frac{\lambda_0 l_{f1}}{p_g} \tag{1}$$

where λ_0 is the central wavelength of the SLD. When the piezo mirror is tilted by an angle θ, the optical phase of the reference beam is shifted by ϕ. This k-independent phase shift can be expressed as

$$\phi = \frac{4\pi l_{f1}}{p_g}\theta. \tag{2}$$

Driving the piezo mirror with a sinusoidal signal at a frequency of f_m introduces a phase modulation $\phi(t) = a_m \sin(2\pi f_m t)$ where a_m is the amplitude and independent of wavelength. A galvano mirror laterally scans the measurement beam in the x direction across the sample at a constant speed. During OCT imaging, the achromatic phase modulation and lateral beam scanning are performed simultaneously. The light beams reflected from the sample and reference mirror are recombined at the fiber coupler again. A reflection grating G_2 disperses the return light waves and a lens L_3 focuses the dispersed light waves on a line camera.

For simplicity of explanation, the sample is chosen as a planar reflector placed at z_o, and the zero OPD plane of the interferometer is located at the origin of z axis. The recorded B-scan time–wavenumber $(t-k)$ interferogram $I_R(t,k)$ can be expressed as

$$I_R(t,k) = A(k) + B(k)\cos\left[2kz_o + a_m \sin\left(2\pi f_m t\right)\right] \tag{3}$$

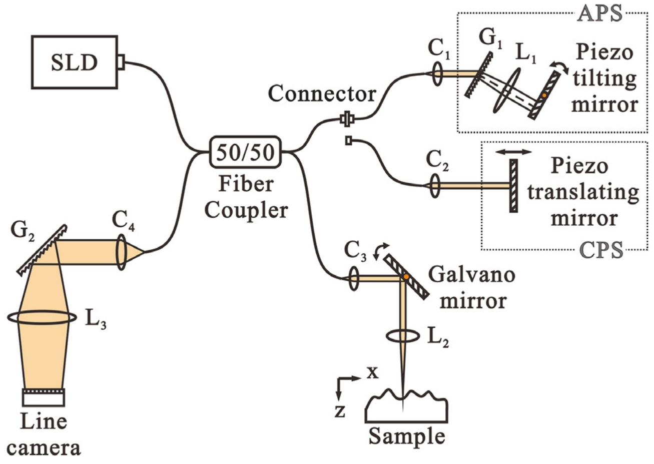

Fig. 1. Two-harmonic complex SD-OCT system using achromatic sinusoidal phase modulation.

where $A(k)$ is the DC term and $B(k)$ is the amplitude of the cross-correlation (or interference) term. The interference term can further be expanded into a series of harmonics weighted with Bessel functions of the first kind. Rearranging Eq. (3) yields

$$\begin{aligned} I_R(t,k) = {} & A(k) + B(k)\cos\left(2kz_o\right) J_0\left(a_m\right) \\ & +2B(k)\cos\left(2kz_o\right) \times \sum_{n=1}^{\infty} J_{2n}\left(a_m\right)\cos\left[(2n)\left(2\pi f_m t\right)\right] \\ & -2B(k)\sin\left(2kz_o\right) \times \sum_{n=0}^{\infty} J_{2n+1}\left(a_m\right)\sin\left[(2n+1)\left(2\pi f_m t\right)\right] \end{aligned} \tag{4}$$

where J_n is the nth order Bessel function. The full-range SD-OCT needs a complex-valued B-scan interferogram $I_C(t,k)$ rather than real-valued $I_R(t,k)$. Eq. (4) indicates that even and odd harmonics carry the real and imaginary parts of $I_C(t,k)$, respectively. Considering the signal strength, we extract the first (H_1) and second (H_2) harmonics from $I_R(t,k)$ by using digital lock-in demodulation technique. The demodulated first and second harmonics are given by

$$H_1(k) = -2B(k)\sin\left(2kz_o\right) J_1\left(a_m\right) \tag{5}$$

$$H_2(k) = +2B(k)\cos\left(2kz_o\right) J_2\left(a_m\right). \tag{6}$$

The complex-valued interferogram can be obtained by means of $I_C(t,k) = \beta H_2(k) - iH_1(k)$. Due to the unbalance in the magnitude of H_1 and H_2, the second harmonic needs to be multiplied by a scaling coefficient,

$$\beta = \frac{J_1\left(a_m\right)}{J_2\left(a_m\right)}. \tag{7}$$

The β is a constant over the whole spectrum because a_m is independent of k by using an APS. Since the measurement beam is scanned laterally at a constant speed v_s during OCT imaging, t can be replaced with x/v_s. Applying inverse FFT to $I_C(x,k)$ from the k domain to the z domain yields a full range OCT image:

$$f(x,z) = 2J_1\left(a_m\right) B(k)\,\delta\left(z - z_o\right) \tag{8}$$

where $\delta(z)$ is the delta function. Eq. (8) indicates that only the planar reflector at z_o is left and mirror artifact as well as DC term are removed in the OCT image. Fig. 2 depicts the signal processing procedure for the proposed achromatic two-harmonic complex SD-OCT.

Previous CPS-based two-harmonic studies, commonly a mirror attached to a piezo translator, cause the dependence of β on k. Consequently, the determination of β becomes complicated and inefficient [14–16]. These studies all used a flat mirror as the sample to determine β. Once a_{m0} was precisely decided, a set of β coefficients for different k was calculated by using $a_m(k) = a_{m0}k/k_0$ and