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Periodic reference subtraction method for efficient background fixed pattern noise removal in Fourier domain optical coherence tomography

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A B S T R A C T

We have demonstrated an efficient scheme of automatically removing fixed pattern noise in Fourier domain optical coherence tomography by using a periodic reference spectrum subtraction method. By periodically acquiring the reference spectra using a separate light absorber placed to the right of the scan lens, we were able to adaptively compensate the background fixed pattern due to the spectral intensity variation of the source. The adaptive removal of fixed pattern noise was effectively performed by controlling the reference spectrum acquisition rate (R). A seawater pearl was used for a test sample under an intentional abrupt source power change to validate the proposed method. Based on this method, it is possible to perform immediate cold start scanning because it is not necessary for a stabilization period of the light source, as well as a manual process of reference spectrum acquisition for obtaining clear image under unstable environment.

1. Introduction

Optical coherence tomography (OCT) is an optical imaging technique which has received considerable attention because OCT can provide a high-resolution cross-sectional image of samples [1–3]. OCT commonly uses near-infrared broadband light as a low coherence source that can penetrate into the sample in comparison with a sonogram. OCT, however, has been limited to subsurface area imaging due to the inherent scattering properties of near-infrared light in the sample so that most applications have been focused on demonstrating imaging areas in ophthalmology [4–7], dermatology [8–11], and cardiology [12,13]. Recently, Fourier domain OCT (FD-OCT) has become a mainstream OCT scheme because of higher imaging speed and better sensitivity than time domain OCT (TD-OCT) by skipping the practical depth-scanning mechanism and by directly extracting the depth information from the modulated envelope of the spectrum by signal processing [14–17].

In spite of providing various attractive features, the FD-OCT scheme has the following artifacts: complex conjugate, fixed-pattern, auto-correlation, and cross-correlation. From the so-called fixed patter artifact, multi-line horizontal fixed-patterns significantly deteriorate acquired image results. Basically there are two kinds of methods that have been typically used in the FD-OCT system to alleviate the fixed-pattern noise: by simply subtracting the real reference spectrum captured in the absence of a specimen, and a signal processing approach using the acquired overall data [18,19]. In the former case, additional signal processing is not required for resolving the fixed pattern noise resulting in a fast and effective performance in the FD-OCT system with use of a highly stable light source. However, in this case based on a reference spectrum, subtraction is neither always convenient nor effective if the light source shows moderate changes in the source spectral intensity profile. For an endoscopic FD-OCT [20,21], fiber bending can cause a significant optical power fluctuation which gives rise to a severe fixed pattern noise in the produced cross-sectional image.

In the latter method based on signal processing using the obtained B-scan data matrices, a mean- and median-line can be used for subtraction purposes instead of using the really measured spectrum in the former case mentioned above [19]. This way of compensation can also be applied to a source showing a gradual power variation. However, it requires an additional processing for the mean and/or median line calculation followed by a sequential subtraction in a whole two-dimensional B-scan image, which results in a much slower performance than a simple Fourier transform process. Therefore, the processing speed and accommodation of the source showing a gradual or moderate change in the source emitting intensity spectrum should be overcome in order to efficiently cancel out the fixed-pattern noise.

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In this work, we proposed a periodic reference spectrum subtraction in the FD-OCT system in which the reference signal was periodically renewed to effectively cancel the fixed pattern noise owing to the variation in the source spectrum profile. A light absorber has been introduced to reacquire the reference spectrum during the B-scanning process without additional signal processing, such as mean or median calculation to remove the background artifact in the overall image. The effect of the reference acquisition rate has been investigated under an intentional reference spectrum fluctuation during lateral scanning for validation of the effectiveness of our proposed method.

2. Reference spectrum fluctuation in the FD-OCT

The FD-OCT system uses low coherence interferometry that consists of an interferometer (Michelson interferometer), broadband light source, spectrometer, reference mirror, and sample stage. In the reference arm, a silver-coated mirror is placed for reflecting the reference beam to an interferometer, and a two-dimensional scanner is used for B-scan imaging in a sample arm. Back-reflected light from the sample interferes with the reference light in the interferometer and the depth information is encoded by optical frequency in time. The signal in frequency (k)-domain received from the spectrometer, $I_{SI}(k)$, is given below and includes DC light intensity back-reflected from the reference mirror, $I_R(k)$, and sample, $I_S(k)$ [16].

$$I_{SI}(k) = I_R(k) + I_S(k) + 2\sqrt{I_R(k)}\sqrt{I_S(k)} \times \cos[\phi_S(k) - \phi_R(k) - 2\pi k\tau] \quad (1)$$

The last term in Eq. (1) is an interference term that contains depth information, and is decoded by taking the inverse Fourier transform of $I_{SI}(k)$. However, because of the DC intensity terms, $I_R(k)$ and $I_S(k)$, there are stationary horizontal high-intensity lines in the corresponding result image near the zero delay line, the so-called fixed pattern noise. We have neglected the $I_S(k)$ term because this DC light intensity back-reflected from the sample is relatively small in general compared to the DC reference term, $I_R(k)$.

Accordingly, a reference spectrum subtraction method has been applied for rejecting the fixed pattern noise by measuring the spectrum of back-reflected light from the reference mirror without any sample before the experiments [22]. Thus, this method can remove the fixed pattern noise in an effective manner. However, optical power can be changed by temperature variation of light source controlled by constant current driving mode, and also spectrum shape can be changed by super-luminescent diode (SLD) pumping wavelength variation and phase instability. To observe the profile changes, we measured the spectrum of the source for an hour. SLD has a 1310 nm center wavelength with a 14 mW optical power at 800 mA, and we used a commercial spectrometer (details for the experiment will be provided in the next chapter). Fig. 1(a) indicates the SLD spectrum changes for a 1-hour measurement, and the spectrum has changed by 1.18%. Fig. 1(b) shows the same experimental result after having a 1-hour SLD temperature stabilization period and the spectrum experienced a change of 0.47%. These changes seem to be meaningless, but the spectrum can be modified by approximately 6% when we used a silver-coated mirror as a sample with our FD-OCT setting. Thus, these become significant (8%–20%) for spectrum fluctuations in the image processing standpoint. In Fig. 2, the measured spectrum (solid line) and optical power difference (dotted line) are shown in the case of silver-coated mirror sample at a 300 μm axial distance apart from the zero delay line. The maximum optical difference was 4.7%, which was <6%, because of the signal loss by depth and tilted angle of the sample surface to the beam direction.

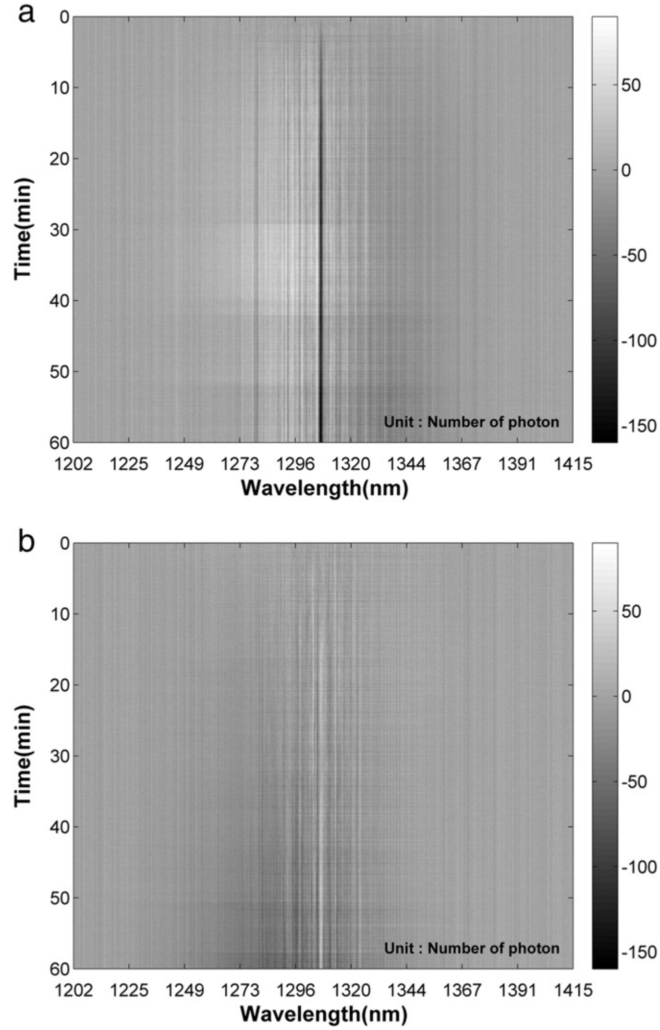

Fig. 1. SLD spectrum changes for 1-hour (a) after power on, and (b) after a 1-hour stabilization.

The spectral change or the deviation from the initial reference spectrum, $g_{d,n}(w)$, can be calculated by the following Eq. (2) that subtracted the initially obtained spectrum, $g_1(w)$, from the current spectrum $g_n(w)$.

$$g_{d,n}(w) = g_n(w) - g_1(w) \quad (2)$$

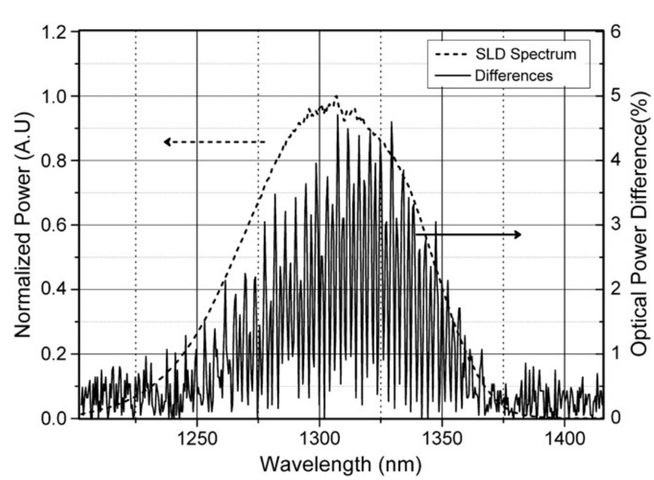

Fig. 2. Received SLD spectrum from the spectrometer (solid line) and optical power differences (dotted line) when a silver-coated mirror is used as a sample.