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Invited Paper

Noise Analysis of Interference Waveform with Real Envelope for Swept Source Optical Coherence Tomography

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Abstract. This paper describes a noise analysis including an interference waveform's envelope for a swept source optical coherence tomography. A quality of a tomographic image depends on a signal-to-noise ratio (SNR) of a point spread function (PSF). We analyzed an influence of a noise in the interference waveform with an ideal envelope on the PSF in previous work. However, a measured interference waveform in experiment has a real envelope. We try to incorporate the real envelope to the interference waveform by amplitude modulation. It is found that the SNR of the PSF with the ideal envelope is overestimated in comparison to that with the real envelope.

1. Introduction

A swept source optical coherence tomography (SS-OCT) system is a technique for obtaining a tomographic image with higher spatial resolution and shorter acquisition time compared with a time domain OCT system and a spectral domain OCT system. An SS-OCT system using a $KTa_{1-X}Nb_XO_3$ (KTN) deflector has especially shorter acquisition time in the SS-OCT system [1]. A quality of the image depends on a signal-to-noise ratio (SNR) of a point spread function (PSF) [2]. The PSF is given by the spectrum of an interference waveform.

We study an influence of a noise in the interference waveform on the PSF's SNR. The interference waveform with a constant amplitude was used in previous work [3]. We call the constant amplitude an ideal envelope. However, a measured interference waveform in experiment has a non-constant amplitude. We call the non-constant amplitude a real envelope. We try to incorporate the real envelope to the interference waveform by amplitude modulation between the real envelope and a simulated interference waveform with ideal envelope.

2. Interference Waveform with Ideal Envelope

Figure 1 shows a wavelength swept using a KTN deflector. The KTN swept light source uses Littman-Metcalf optics with a grating and mirror. A wavenumber $k(t)$ [3] of an optical output from the KTN swept light source and a maximum deflection angle Ψ_0 [3] of the light at the KTN crystal are given by

$$k(t) = \frac{2\pi}{\lambda_0 + \frac{1}{mN}\left(\sin\left(\alpha + \Psi_0 \sin(2\pi f_{\mathrm{DRV}} t)\right) - \sin(\alpha)\right)}, \qquad (1)$$

$$\Psi_0 = \sin^{-1}\left(\frac{mN\Delta\lambda}{2\cos(\alpha)}\right). \tag{2}$$

Here, t is time, λ_0 (=1.06 μm) is a center wavelength, m (=1) is a diffracting order, N (=600 line/mm) is a grating constant, α (=60°) is an angle of the grating, f_{DRV} (=200 kHz) is a frequency of an applied voltage, and $\Delta\lambda$ (=100 nm) is a sweep range of the wavelength. The simulated interference waveform with the ideal envelope is given by

$$\frac{V(t)}{V_0} = \cos\left(2zk(t)\right). \tag{3}$$

Here, $V(t)$ is normalized by a peak-to-peak voltage V_0 of the interference waveform. $2z$ is an optical path difference between a reference light and sample light, and z correspond to the depth of a device under test relative to an incident surface. An interference waveform with a voltage noise V_{VN} and jitter t_{J} is given by

$$\frac{V(t)}{V_0} = \frac{V_{\mathrm{VN}}}{V_0} + \cos\left(2zk\left(t + t_{\mathrm{J}}\right)\right). \tag{4}$$

We assumed that the V_{VN} and t_{J} obey the Gaussian distribution. The V_{VN} and t_{J} are given by

$$V_{\mathrm{VN}} = \Delta V Q, \tag{5}$$
$$t_{\mathrm{J}} = \Delta t Q'. \tag{6}$$

Here, ΔV is a standard deviation of the voltage noise, and Δt is a standard deviation of the jitter. Q and Q' are random number according to the Gaussian distribution based on a Box-Muller method.

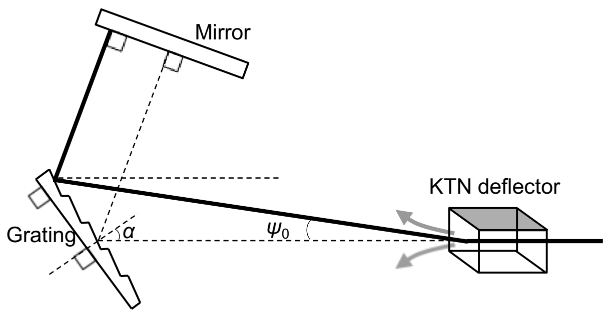

Fig. 1. Wavelength swept using KTN deflector.

3. Interference Waveform with Real Envelope

We try to incorporate the real envelope to the interference waveform by amplitude modulation between the real envelope and the simulated interference waveform with the ideal envelope. Figure 2 shows a flow of generating the interference waveform with the real envelope. Figure 2 (a) shows the measured interference waveform in experiment. We assumed that an upper envelope corresponds to a lower envelope. The real envelope of the measured interference waveform is given by using the Hilbert transform and is shown in Fig. 2 (b). Figure 2 (c) shows the simulated interference waveform with the ideal envelope given by Eq. (3). We obtain the interference waveform with the real envelope by amplitude modulation of the simulated interference waveform and real envelope. Figure 2 (d) shows the interference waveform with the real envelope. Since the wavenumber is not precisely reproduced by Eq. (1), a wave density of the interference waveform is different between the measured interference waveform shown in Fig. 2 (a) and the interference waveform with the real envelope shown in Fig. 2 (d).

The PSF is obtained by a signal processing with a rescaling [4] and fast Fourier transform. A Blackman window function and 0-padding technique are used for high SNR and spatial resolution after the rescaling. We simulate the voltage noise and jitter dependence on the SNR. The trial number is 50 in each noise. These PSFs are averaged, and the SNR of the averaged PSF is evaluated. The SNR is given by

$$SNR\ [dB] = 10\log_{10}\frac{P_{\mathrm{AVE\_S}}}{P_{\mathrm{AVE\_N}}}. \tag{7}$$

Here, $P_{\mathrm{AVE\_S}}$ and $P_{\mathrm{AVE\_N}}$ are the averaged PSF's electrical signal power and electrical noise power, respectively.

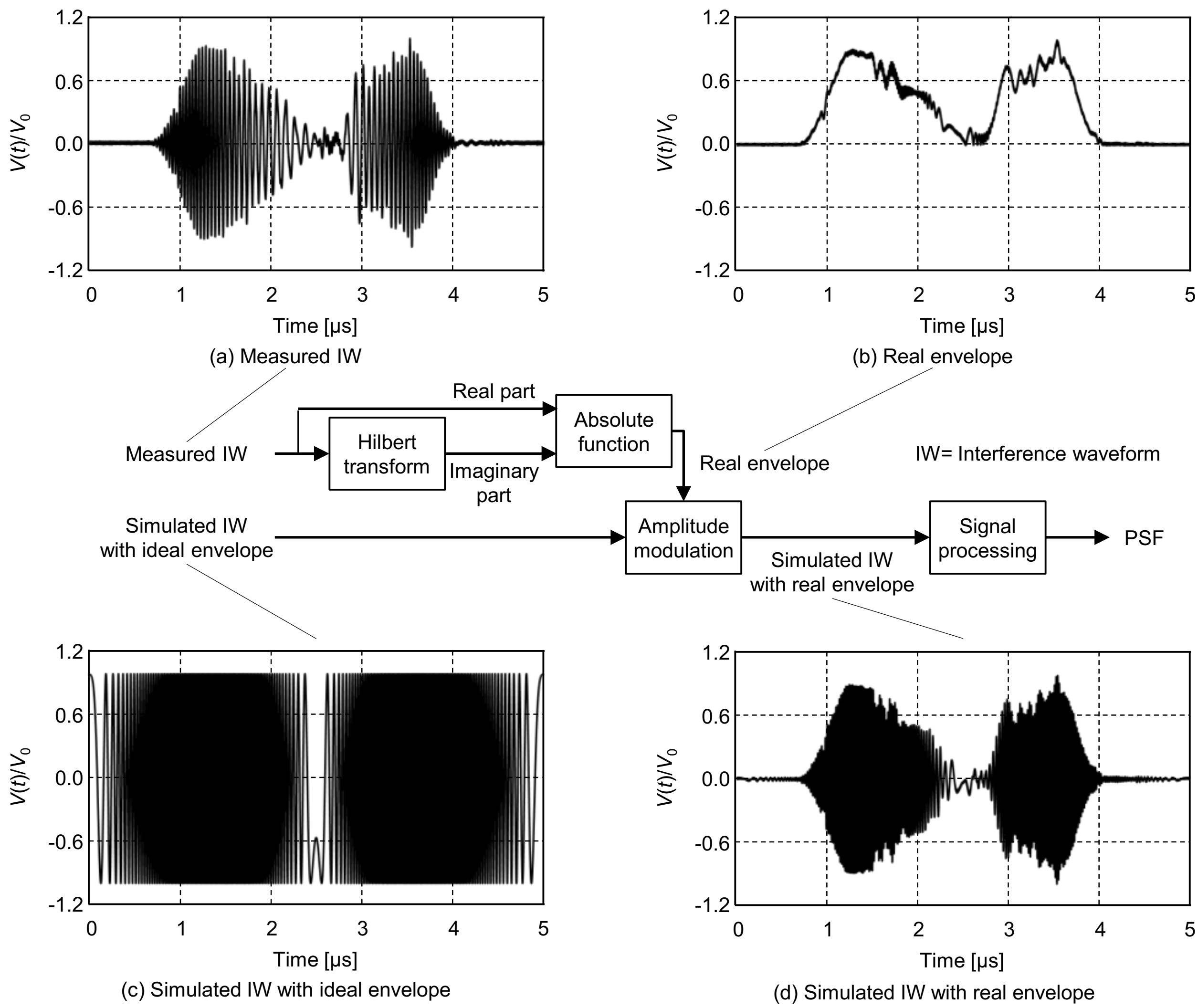

Fig. 2. Generation of interference waveform with real envelope.

4. Simulation Results

Figure 2 shows the jitter dependence on the PSF's SNR with a typical voltage noise V_{VN}/V_0 of 0.01 [5]. The plotted marks (□ and ○) are the simulation results with the ideal envelope and that with the real envelope, respectively. The broken line denotes -20 dB/decade characteristics. It is found that the SNR of the PSF with the ideal envelope is overestimated in comparison to that with the real envelope in the jitter region of < 0.2 ns. The interference waveform with the real envelope should be considered for a precise noise simulation.

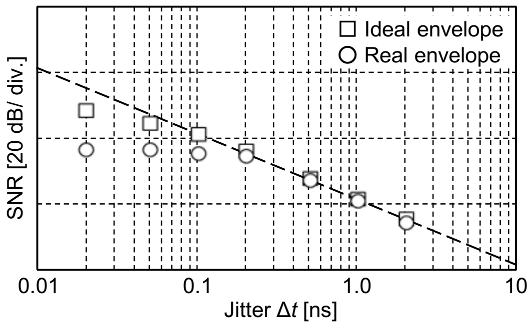

Fig. 2. Influence of envelope's difference on SNR.

5. Conclusion

We studied a noise analysis including an interference waveform's envelope for a swept source coherence tomography. A quality of a tomographic image depends on a signal-to-noise ratio (SNR) of a point spread function (PSF). We try to incorporate a real envelope to an interference waveform by amplitude modulation between the real envelope and a simulated interference waveform with ideal envelope. It is found that the SNR of the PSF with the ideal envelope is overestimated in comparison to that with the real envelope. The interference waveform with the real envelope is needed for a precise noise simulation.

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