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Invited Paper

Noise Simulation of Interference Waveform in Optical Coherence Tomography with Swept Light Source

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Abstract. This paper describes a noise simulation of a swept source optical coherence tomography (SS-OCT) with a $KTa_{1-x}Nb_xO_3$ electro-optic deflector. The SS-OCT system is a useful tool for observing a tomographic image that has high spatial resolution. The tomographic image is given by the point spread functions (PSFs) from an interference waveform, and the image fineness depends on the signal-to-noise ratio (SNR) of the PSF. The noise of the interference waveform is the voltage noise and the jitter. The noises are caused by the laser noise and the circuit noise and so on. We modeled the noises including voltage noise and jitter and developed a noise simulator that creates the interference waveform with the noises. The influence of the noise on the PSF's SNR was analyzed by using the noise simulator. We confirmed the noises degrade the SNR of the PSF, and also the influence of the jitter on the PSF's SNR is greater than that of the voltage noise.

1. Introduction

An SS-OCT system is a tool for obtaining a tomographic image with high spatial resolution. The SS-OCT with a KTN electro-optic deflector has a 200-kHz-wavelength sweep rate and short acquisition time [1]. A tomographic image is given by the PSFs from an interference waveform [2], and the image fineness depends on the PSF's SNR. Since the SNR is degraded by the noise caused by laser noise and circuit noise and so on, the relationship between the noises and the PSF's SNR is investigated by a noise simulator of the interference waveform.

2. SS-OCT with KTN Deflector

Figure 1 shows a configuration of the SS-OCT system with the KTN electro-optic deflector. The parameters in this system are summarized in Table 1.

A wave number $k(t)$ of an optical output is given by Eq. (1) [3].

$$k(t) = 1 \,/\, (1 \,/\, k_0 + (\sin(\alpha - aV_0 \sin(2\pi f t)) - \sin\alpha) \,/\, 2\pi m N) \tag{1}$$
$$(k_0 = 2\pi \,/\, \lambda_0, aV_0 = \sin^{-1}(mN\Delta\lambda \,/\, 2\cos\alpha))$$

Here, aV_0 is determined by the parameters of the KTN electro-optic deflector in accordance with the Littman-Metcalf resonator. The optical output is divided into two lights by a beam splitter. One is a reference light reflected by a mirror, and the other is a sample light reflected by the object. An optical interference waveform between the reference light and the sample light is converted into an electrical interference waveform by a balanced photo detector (BPD). The reference signal $E_R(t)$ and the sample signal $E_S(t)$ are given by Eqs. (2) and (3).

$$E_R(t) = E_{R0} e^{-j2k(t)l} \tag{2}$$

$$E_S(t) = \rho E_{R0} e^{-j2k(t)(l+z)} \tag{3}$$

Here, E_{R0} is an amplitude of the reference light. j is an imaginary unit, and l and z are the light propagation path lengths. ρ is a loss factor of the sample light against the reference light.

The interference waveform $i(t)$ between $E_R(t)$ and $E_S(t)$ without noise is given by Eq. (4).

$$i(t) = 2\rho {E_{R0}}^2 \cos(2zk(t)) \tag{4}$$
$$(A = 2\rho {E_{R0}}^2)$$

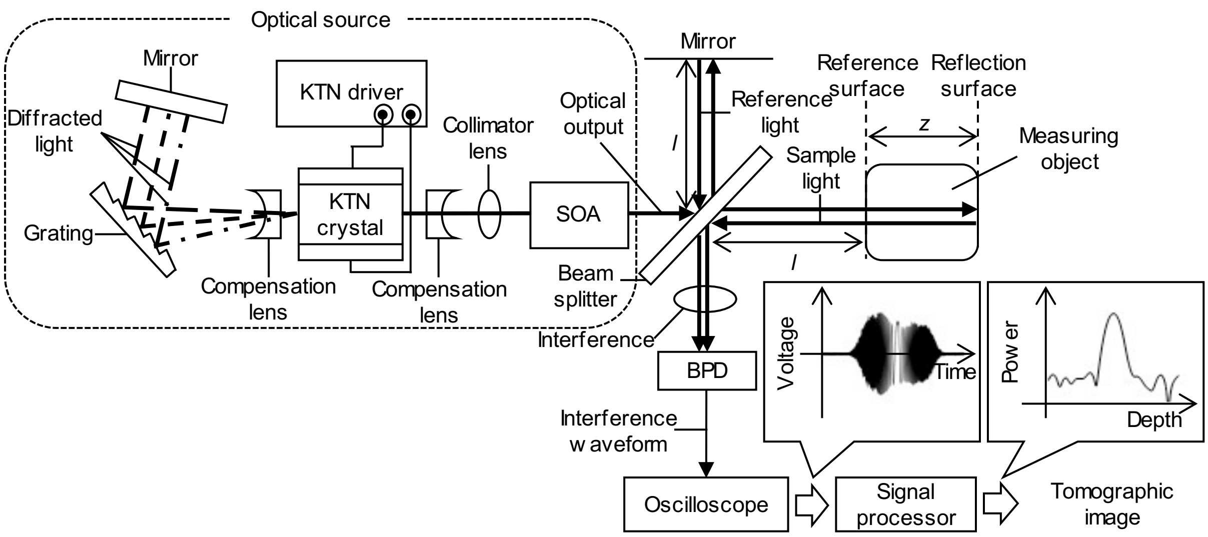

Fig. 1 Configuration of SS-OCT system with KTN electro-optic deflector.

Table 1. Parameters of SS-OCT system with KTN electro-optic deflector.

Path difference between reference light and sample light	$2z$	1.0 mm
Center wavelength of optical output	λ_0	1.06 μm
Wavelength sweep range	$\Delta\lambda$	100 nm
Diffracting order	m	1
Angle of grating	α	60 °
Frequency of KTN driver signal	f	200 kHz
Grating constant	N	600 line/mm
Amplitude of interference waveform	A	1 V

3. Noise Model in Interference Waveform

An interference waveform has two types of noise: voltage noise $V_{VN}(t)$ and jitter $t_j(t)$. The noises are caused by the laser noise and the circuit noise and so on. In this paper, we assume that the noises are white gauss noises. Figure 2 shows a typical measured interference waveform including the voltage noise and the jitter. Here, ΔV is voltage difference caused by the jitter.

The interference waveform $i(t)$ with noise is given by Eq. (5).

$$i(t) = V_{\mathrm{VN}}(t) + A\cos(2zk(t + t_{\mathrm{j}}(t))) \tag{5}$$

Here, $V_{\mathrm{VN}}(t)$ is the voltage noise, $t_{\mathrm{j}}(t)$ is the jitter. $V_{\mathrm{VN}}(t)$ and $t_{\mathrm{j}}(t)$ are given by Eq. (6) and (7).

$$V_{\mathrm{VN}}(t) = \sigma_{\mathrm{V}}\mathrm{Q} \tag{6}$$

$$t_{\mathrm{j}}(t) = \sigma_{\mathrm{J}}\mathrm{Q} \tag{7}$$

Here, σ_{V} is the standard deviation of the voltage noise normalized by the amplitude $\mathrm{A} = 2\rho E_{\mathrm{R0}}{}^2$ of the interference waveform. σ_{J} is the standard deviation of the jitter. Q is the random number in accordance with the Gaussian distribution given by a Box-Muller method. The random number Q is given by Eq. (8).

$$Q = \sqrt{-2\log X}\,\sin(2\pi Y)\ 0 \le X, Y \le 1 \tag{8}$$

Here, X and Y are uniform random numbers.

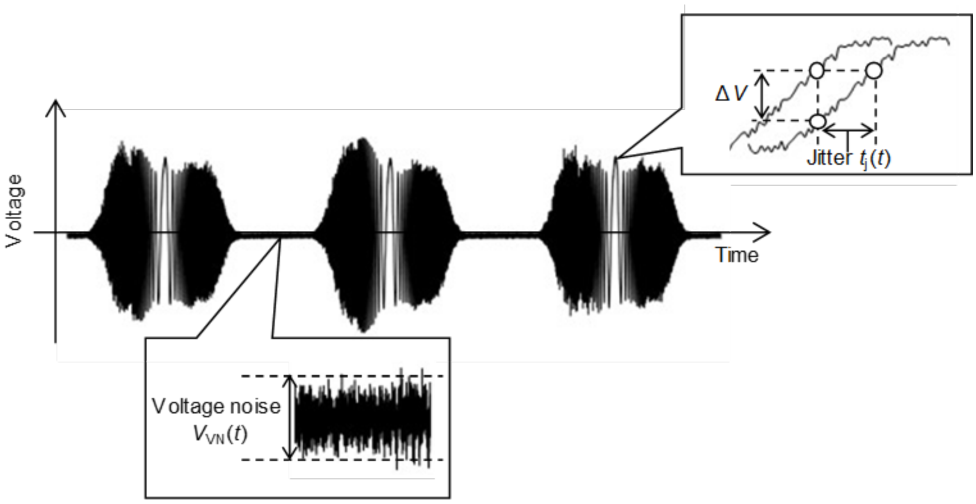

Fig. 2 Noise of interference waveform.

4. Simulation Results and Discussion

Figure 3 shows the simulated interference waveform without noise. The σ_{V} and σ_{J} are decided in accordance with the experimental results for an interference waveform [4]. Figure 4 shows the PSFs (a) without noise, (b) with voltage noise σ_{V} of 0.01, and (c) with jitter σ_{J} of 0.05 ns. The PSF's SNR with the voltage noise is 70 dB, and that with the jitter is 68 dB. The σ_{V} of 0.01 corresponds to 1% error for the amplitude A, and the jitter σ_{J} of 0.05 ns corresponds to 0.001% error for the interference waveform period. We found that influence of the jitter on the PSF's SNR is greater than that of the voltage noise.

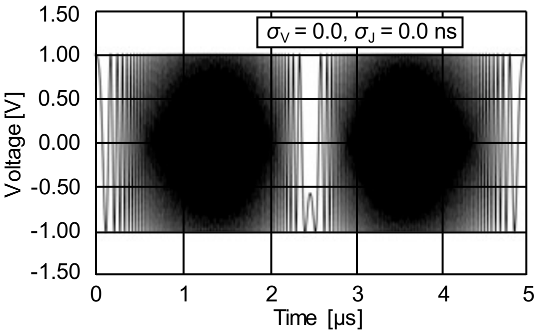

Fig. 3 Interference waveform without noise.

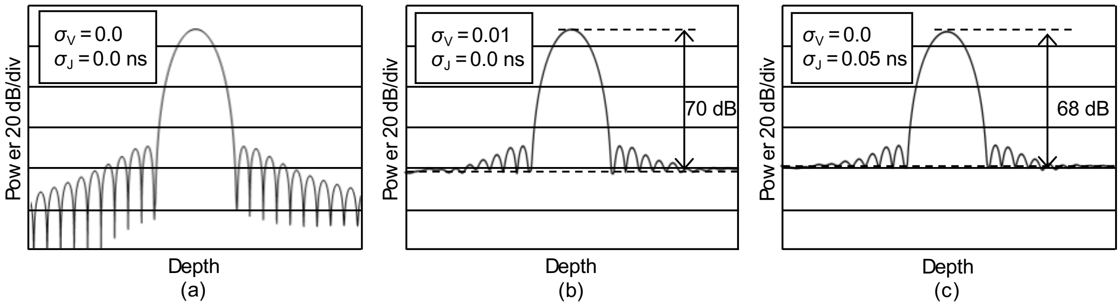

Fig. 4 PSFs of interference waveforms (a) without noise, (b) with voltage noise and (c) with jitter.

5. Conclusion

We developed a simulator of the interference waveform for SS-OCT with a KTN electro-optic deflector. We modeled the noise including voltage noise and jitter. It was found that the noise of the interference waveform degrades the PSF's SNR. We confirmed the influence of the jitter on the PSF's SNR is greater than that of the voltage noise. In this paper, we divided into two types of noise, but that can be divided further. For example, there are the drift noise and amplitude fluctuations. In the future, we will develop the noise simulator that creates the interference waveform containing a drift noise and amplitude fluctuation besides the noises included in this simulation.

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