Electronically Controlled Optical Sampling Terahertz Time-Domain Spectroscopy

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***Abstract*—We present high-speed terahertz time-domain spectroscopy based on electronically controlled optical sampling (ECOPS). The time delay between the two laser pulses is demonstrated to be rapidly swept at a scan rate of 1 kHz on a time delay window of 77 ps. It is shown that a measurement time is shortened by a factor of 50 by using ECOPS compared to asynchronous optical sampling.**

I. Introduction

For the purpose of rapid data acquisition and high spectral resolution, asynchronous optical sampling (ASOPS) method has been applied to terahertz time-domain spectroscopy (THz-TDS). Electronically controlled optical sampling (ECOPS) method has recently been proposed as another approach for high-speed measurement [1]. In this paper, we report on experimental demonstration of ECOPS for high-speed THz-TDS. It is shown that a THz pulse can be exactly measured by ECOPS as done by ASOPS and a measurement time is shortened by a factor of 50 by using ECOPS compared to ASOPS.

II. Experimental Method And Results

Fig. 1 illustrates our experimental setup for ECOPS THz-TDS. We employ two Ti:Sapphire femtosecond (fs) lasers synchronized at a 100 MHz repetition frequency. By modulating an external offset voltage applied to the locking electronics for one of the lasers, the time delay can be repetitively scanned to measure a terahertz (THz) time-domain waveform.

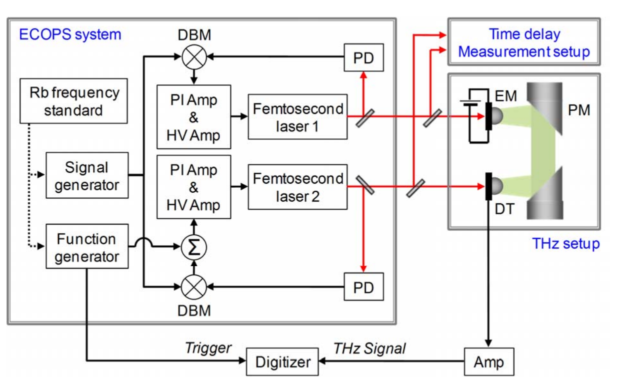

Fig. 1. Illustration of the experimental setup for ECOPS THz-TDS. DBM: double-balanced mixer, PI Amp: proportional-integral amplifier, HV Amp: high-voltage amplifier, PD: photodetector, EM: THz emitter, DT: THz detector, PM: off-axis parabolic mirror, Amp: preamplifier.

Temporal variation of the time delay made by the ECOPS system can be measured using the time delay measurement setup depicted in Fig. 2(a). Optical pulse trains from the two fs lasers are detected by photodetectors, respectively. Amplifiers and 100 MHz low-pass filters filter out the 100 MHz fundamental components from the output signals of the photodetectors. The phase difference signal of the fundamental components, output from a 1.9 MHz low-pass filter following a double-balanced mixer, is acquired by the digitizer triggered by the sync signal of the function generator. The signal ($V(t)$) measured from the time delay measurement setup is related to the phase difference ($\Delta\phi(t)$) by $V(t) = A_0 \cos\Delta\phi(t)$, where A_0 is a coefficient depending on measurement conditions. Fig. 2(b) shows $V(t)$ measured from the time delay measurement setup when the time delay is swept at a 1 kHz scan rate by the ECOPS system. The temporal variation of the time delay ($\tau(t)$) can be determined from $V(t)$ by

$$\tau(t) = \frac{\Delta\phi(t)}{2\pi f} = \frac{1}{2\pi f}\cos^{-1}\left(\frac{V(t)}{A_0}\right), \tag{1}$$

where f is the repetition frequency of 100 MHz here, as plotted in Fig. 2(b).

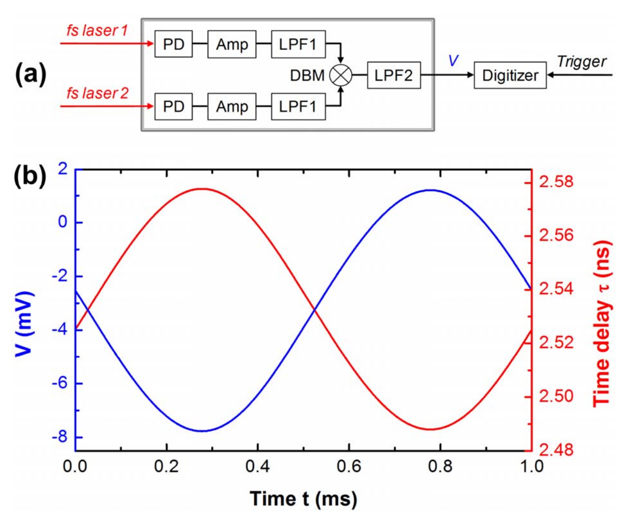

Fig. 2. (a) Schematic diagram of the time delay measurement setup. LPF1: 100 MHz low-pass filter, LPF2: 1.9 MHz low-pass filter. (b) Signal (blue line) measured from the time delay measurement setup and temporal variation of the time delay (red line) determined from the signal by Eq. (1) when the time delay is swept at a scan rate of 1 kHz by the ECOPS system.

The time scale of a THz temporal waveform measured by ECOPS is calibrated using the time delay measured in such a way as described above. A typical THz waveform measured by ECOPS is plotted against the time delay in Fig. 3(a). The scan rate was set to 1 kHz and the time delay window of 77 ps was obtained. For comparison, a THz waveform measured by

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ASOPS is also displayed in Fig. 3(a). For ASOPS, the laser repetition frequencies were stabilized at 100 MHz and 100 MHz - 20 Hz by using reference signals of a dielectric resonator oscillator and the signal generator, respectively [2]. All the measurement conditions else were the same with those of ECOPS. The THz waveforms measured by ECOPS and ASOPS were obtained by averaging 1,000 consecutive traces acquired during 1 and 50 seconds, respectively. The THz waveform measured by ASOPS is displayed with an offset on a part of the entire 10 ns time delay window. As shown in Fig. 3(a), the THz waveform by ECOPS agrees well with that by ASOPS.

To obtain a THz spectrum by fast Fourier transform (FFT) of a time-domain data measured by ECOPS, the time-domain data should be interpolated since the time delay step is not regular. Fig. 3(b) shows the THz amplitude spectrum obtained by FFT after interpolation of the time-domain data by ECOPS shown in Fig. 3(a), together with that by ASOPS. The spectral shapes of the spectra are almost identical. Also, the frequencies of absorption lines of water vapor agree well in the spectra by ECOPS and ASOPS. Therefore, ECOPS is confirmed to exactly measure a THz pulse like ASOPS.

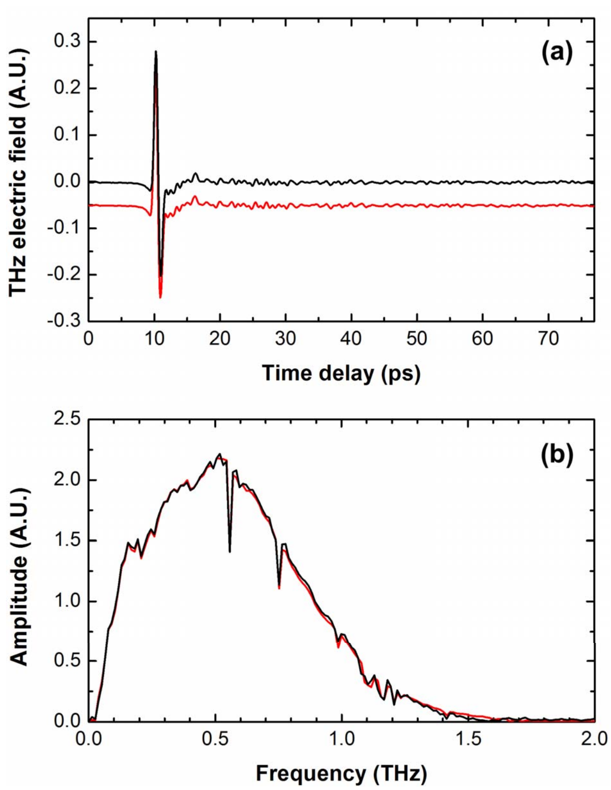

Fig. 3. (a) Typical THz temporal waveforms measured by ECOPS and ASOPS. (b) THz amplitude spectra obtained by FFT of the waveforms in (a). The black and red lines indicate the results of ECOPS and ASOPS, respectively.

To compare the measurement speeds of ECOPS and ASOPS, we investigated signal-to-noise ratios (SNR) of THz temporal waveforms measured by ECOPS and ASOPS with varying the number of averaged traces under the same measurement condition as in Fig. 3. For ASOPS, a scan rate given by a laser repetition frequency difference was set to 20 Hz, which led to the maximum SNR for a fixed measurement time [2]. Fig. 4 shows the SNR versus the measurement time when 1, 10, 100, and 1,000 traces are acquired and averaged. The lines are fits of the results to $Y=\alpha * X^{\beta}$. The noise levels are close to the shot noise limit since β is 0.49 for both the ECOPS and ASOPS. Fig. 4 clearly shows that the measurement speed of ECOPS is 50 times higher than that of ASOPS.

For ASOPS THz-TDS, a high laser repetition frequency has an advantage for high-speed scanning as a scan rate can be even higher with a higher repetition frequency [3]. However, pump and probe pulse energies are higher with a lower repetition frequency. Consequently, a low repetition frequency is advantageous in view of a measurement time needed to reach a desired SNR. Fig. 4 shows that the ECOPS THz-TDS demonstrated here enables much more rapid measurement than even the ASOPS THz-TDS with a low repetition frequency of 100 MHz.

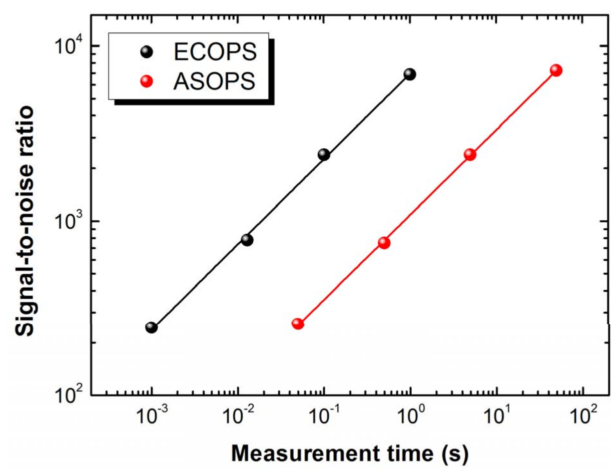

Fig. 4. SNR versus measurement time for THz pulse measurements using ECOPS and ASOPS. The black and red dots indicate the results of ECOPS and ASOPS. The lines are fits of the results to $Y=\alpha * X^{\beta}$.

III. Conclusion

In conclusion, we have demonstrated high-speed THz-TDS based on ECOPS. It was confirmed that ECOPS could exactly measure a THz pulse as ASOPS could. A measurement time was also shown to be reduced by a factor of 50 by using ECOPS compared with ASOPS. In terms of a measurement time taken to reach a desired SNR, ECOPS THz-TDS is the most rapid method of various ones for THz-TDS at this time to our knowledge.

References

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