High-speed terahertz time-domain spectroscopy based on electronically controlled optical sampling

Youngchan Kim and Dae-Su Yee*

Center for Safety Measurement, Korea Research Institute of Standards and Science, Daejeon 305-340, Korea
**Corresponding author: dsyee@kriss.re.kr*

Received August 25, 2010; revised October 4, 2010; accepted October 10, 2010;
posted October 13, 2010 (Doc. ID 133920); published November 1, 2010

We demonstrate high-speed terahertz (THz) time-domain spectroscopy based on electronically controlled optical sampling (ECOPS). The ECOPS system utilizes two synchronized Ti:sapphire femtosecond lasers with a 100 MHz repetition frequency. 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 by using an external offset voltage applied to a locking electronics. It is shown that a THz pulse can be exactly measured by ECOPS, as is done by asynchronous optical sampling (ASOPS), and the measurement time is shortened by a factor of 50 by using ECOPS compared with ASOPS in the case of employing 100 MHz repetition-rate lasers. © 2010 Optical Society of America

OCIS codes: 300.6495, 300.6270, 300.6190, 120.6200.

Recently, the asynchronous optical sampling (ASOPS) technique, which employs two femtosecond (fs) lasers with slightly different repetition frequencies without a mechanical delay line, has been applied to terahertz time-domain spectroscopy (THz-TDS) to achieve rapid data acquisition and high spectral resolution [1,2]. ASOPS always scans the time delay over an entire time delay window determined by laser repetition frequency. For example, an ASOPS system using 100 MHz repetition-rate fs lasers has a fixed time delay window of 10 ns. Unless high frequency resolution is needed, a time delay window of only several tens of picoseconds is commonly enough to investigate a material response in the THz spectral range. In this case, more than 99% of the data acquisition time is unnecessary. Thus, there is room to enhance the measurement speed by avoiding the unnecessary time delay scanning.

For high-speed measurement, we apply the electronically controlled optical sampling (ECOPS) technique to THz-TDS. In the ECOPS technique, two synchronized fs lasers produce pump and probe optical pulses, and modulation of the cavity length of one of the lasers via a piezoelectric transducer (PZT) serves to sweep the probe pulse against the pump pulse in a precisely controlled manner [3]. The ECOPS technique has been recently applied to optical coherence tomography [4]. The main advantage of the ECOPS technique is that the temporal scan range, as well as the scan frequency, can be electronically adjusted. With a narrowed temporal scan range, the scan frequency can be raised and, consequently, the measurement time can be shortened. In this Letter, we demonstrate high-speed THz-TDS based on ECOPS using two synchronized Ti:sapphire fs lasers with a 100 MHz repetition frequency.

Figure 1 illustrates our experimental setup for ECOPS THz-TDS. Two synchronized fs lasers emit pump and probe optical pulses used for THz wave generation and detection. The fs lasers have a center wavelength of 800 nm and pulse durations of 10 and 20 fs, respectively. For synchronization, the tenth harmonics of the repetition frequencies of the two lasers are separately phase locked to the 1 GHz common output of a signal generator. The phase error signal output from a double-balanced mixer (DBM) is supplied via a proportional-integral amplifier (PI Amp) and a high-voltage amplifier (HV Amp) to a PZT to which a cavity mirror is attached. The two laser repetition frequencies are synchronized at 100 MHz by controlling the cavity lengths via the PZTs. Then, the phase difference between the pump and probe pulses can be controlled by an external offset voltage applied to the locking electronics for one of the lasers, as shown in Fig. 1. Thus, the time delay between the pump and probe pulses can be repetitively scanned at the modulation frequency of the external offset voltage. The scan rate and time delay window can be adjusted by the modulation frequency and amplitude of the external offset voltage. The signal generator and the function generator supplying the external offset voltage are referenced to a Rb frequency standard. We use two low-temperature-grown GaAs photoconductive antennas as a THz emitter (EM) and detector (DT). The pump pulses are incident on the biased EM to generate THz pulses, which are guided into the DT by using two off-axis parabolic mirrors (PMs). Then, the probe pulses are used to optically sample the THz pulses incident upon the DT. The photocurrent output from the DT, which represents the magnitude of the electric field of the THz pulses, is amplified by a

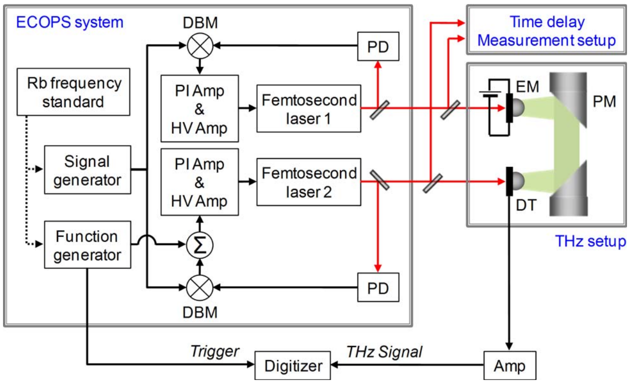

Fig. 1. (Color online) Schematic diagram of the experimental setup for ECOPS THz-TDS.

0146-9592/10/223715-03$15.00/0

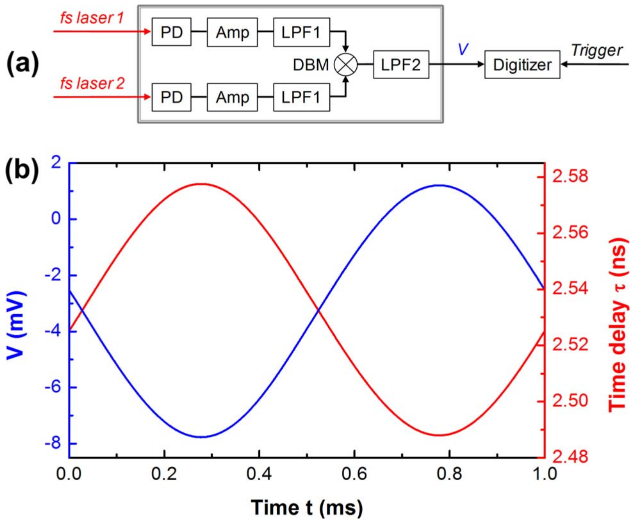

Fig. 2. (Color online) (a) Schematic diagram of the time delay measurement setup. (b) Signal (blue curve) measured from the time delay measurement setup and temporal variation of the time delay (red curve) determined from the signal by Eq. (1).

variable-gain preamplifier (Amp) and then is acquired by a 24-bit flexible resolution digitizer triggered by the sync signal of the function generator.

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 (PDs). Amplifiers and 100 MHz low-pass filters (LPF1s) filter out the 100 MHz fundamental components from the output signal of the PDs. The phase difference signal of the fundamental components, output from a 1.9 MHz low-pass filter (LPF2) following a DBM, 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. Figure 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

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

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

To evaluate the time delay resolution due to the relative timing jitter between the two fs lasers, we performed an optical cross-correlation measurement under the same condition of the ECOPS system as in Fig. 2(b) [5]. The cross-correlation signal was measured using an oscilloscope triggered by the sync signal of the function generator. A single scan trace of the cross-correlation signal was measured to have an FWHM of 25 fs. An average over 1000 scans of the cross-correlation signal resulted in a FWHM of 67 fs, which represents the time delay resolution due to the timing jitter.

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). Here, we set the scan rate to 1 kHz and obtained a time delay window of 77 ps, corresponding to a spectral resolution of 13 GHz. The gain and bandwidth of the preamplifier was set to 10^7 and 220 kHz, respectively, and the data were acquired at a sampling rate of 2 megasamples per second, yielding a mean time delay step of ~100 fs. For comparison, a THz waveform measured by 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 [5]. All the other measurement conditions were the same as those of ECOPS. The THz waveforms measured by ECOPS and ASOPS were obtained by averaging 1000 consecutive traces acquired over a duration of 1 or 50 s, 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 obtained by ECOPS is in good agreement with that obtained by ASOPS.

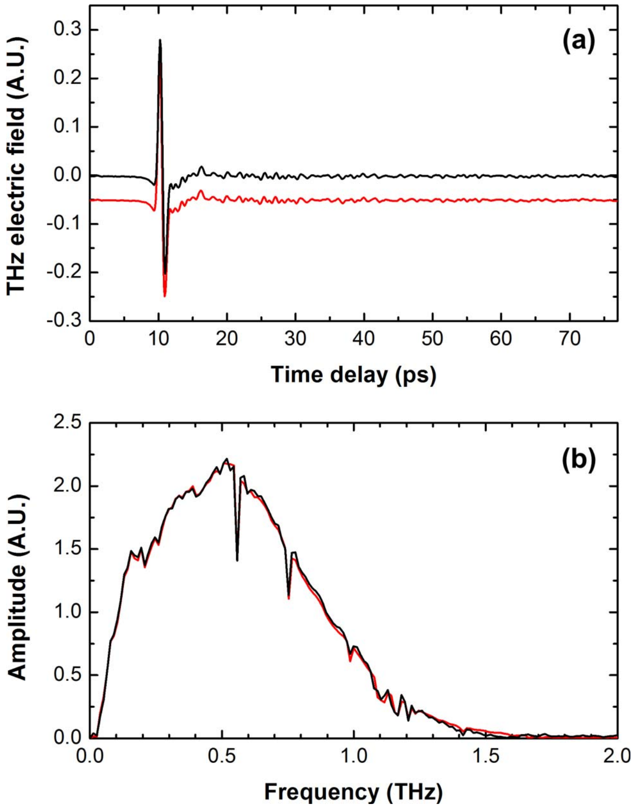

Fig. 3. (Color online) (a) Typical THz temporal waveforms measured by ECOPS and ASOPS and (b) their THz amplitude spectra. The black and red curves indicate ECOPS and ASOPS results, respectively. The ASOPS result is offset down for clarity in (a).

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 because the time delay step varies between 58 and 137 fs. Figure 3(b) shows the THz amplitude spectrum obtained by FFT after interpolation of the time-domain data obtained by ECOPS shown in Fig. 3(a), together with that obtained by ASOPS. The spectra have almost identical shapes and a spectral bandwidth of approximately 1.5 THz. We made sure that the spectral bandwidth was limited by the photoconductive antennas used for THz wave generation and detection [6], and thus it could be extended by altering the THz wave generation and detection methods [7]. Also, the frequencies of the 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.

To compare the measurement speeds of ECOPS and ASOPS, we investigated signal-to-noise ratios (SNRs) of THz temporal waveforms measured by ECOPS and ASOPS under the same measurement conditions as in Fig. 3 with varying the number of averaged traces. For ASOPS, a scan rate given by a laser repetition frequency difference was set to 20 Hz, which led to the maximum SNR at a given measurement time, while not reducing the THz spectral bandwidth with the preamplifier set to the 220 kHz bandwidth giving the highest gain and lowest noise [5]. The SNR was evaluated as the ratio of the peak-to-peak value of a THz temporal waveform to the standard deviation of a noise in the time domain. Figure 4 shows the SNR versus the measurement time when 1, 10, 100, and 1000 traces are acquired and averaged. The lines are fits of the results to $\mathrm{Y} = \alpha * \mathrm{X}^{\beta}$. The noise levels are close to the shot noise limit, because β is 0.49 for both the ECOPS and ASOPS. Figure 4 clearly shows that the measurement speed of ECOPS is 50 times higher than that of ASOPS.

Time delay window, SNR, measurement time, and spectral bandwidth should be considered in THz-TDS. In ECOPS THz-TDS, adjustable parameters include the gain and bandwidth of the preamplifier, the sampling rate of the digitizer, and the scan rate and time delay window set by the function generator. By adjusting the parameters, we tried to maximize a time delay window and minimize a measurement time taken to reach a desired SNR with maintaining the maximum spectral bandwidth. It was found that the measurement condition of Fig. 3 was optimal with a limitation of the scan rate due to the use of a PZT having a finite bandwidth. The measurement time can be reduced with a shorter time delay window, or the time delay window can be extended with a longer measurement time.

For ASOPS THz-TDS, a high laser repetition frequency has an advantage for high-speed scanning as the scan rate can be even higher with a higher repetition frequency [2]. However, an ASOPS THz-TDS system using low-repetition-rate lasers has the advantages of the high laser pulse energy and the high gain and low noise of a low-bandwidth preamplifier. Consequently, a low repetition frequency is advantageous to ASOPS THz-TDS in view of the measurement time needed to reach a desired SNR. Figure 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.

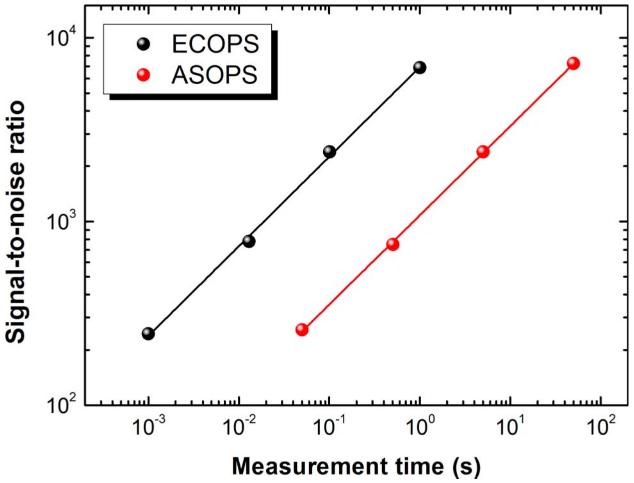

Fig. 4. (Color online) SNR versus measurement time for THz pulse measurements using ECOPS and ASOPS.

In conclusion, we have demonstrated high-speed THz-TDS based on ECOPS. It was confirmed that ECOPS could exactly measure a THz pulse, as could ASOPS. The measurement time was also shown to be reduced by a factor of 50 by using ECOPS compared with ASOPS in the case of employing 100 MHz repetition-rate lasers. In terms of the measurement time taken to reach a desired SNR, ECOPS THz-TDS using 100 MHz or less repetition-rate lasers is the most rapid method among the various ones for THz-TDS at this time, to our knowledge. Potential applications for high-speed ECOPS THz-TDS include real-time monitoring or sensing based on THz spectra and rapid THz spectroscopic imaging.

This work was supported in part by the Industrial Strategic Technology Program of the Ministry of Knowledge Economy (KI001889) and in part by the Ministry of Education, Science, and Technology (MEST) through project KRISS-10011131.

References

1. T. Yasui, E. Saneyoshi, and T. Araki, Appl. Phys. Lett. **87**, 061101 (2005).
2. A. Bartels, A. Thoma, C. Janke, T. Dekorsy, A. Dreyhaupt, S. Winnerl, and M. Helm, Opt. Express **14**, 430 (2006).
3. F. Tauser, C. Rausch, J. H. Posthumus, and F. Lison, Proc. SPIE **6881**, 68810O (2008).
4. S. Kray, F. Spöler, T. Hellerer, and H. Kurz, Opt. Express **18**, 9976 (2010).
5. Y. Kim, D. S. Yee, M. Yi, and J. Ahn, J. Korean Phys. Soc. **56**, 255 (2010).
6. A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hudert, C. Janke, and T. Dekorsy, Rev. Sci. Instrum. **78**, 035107 (2007).
7. G. Klatt, R. Gebs, C. Janke, T. Dekorsy, and A. Bartels, Opt. Express **17**, 22847 (2009).