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Dependence of Terahertz Electric Fields on Electric Bias and Modulation Frequency in Pulsed Terahertz Emissions from Electrically-Modulated Photoconductive Antenna Detected with Free-Space Electro-Optic Sampling

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We investigated the dependence of terahertz (THz) electric fields on electric bias and modulation frequency in the pulsed THz emissions from electrically modulated photoconductive antennas detected with free-space electro-optic sampling. The linear dependence of the THz electric field on the electric bias achieves distortion-free modulation of the THz pulse even for deep modulation. We confirmed that the signal-to-noise ratio in free-space electro-optic sampling of the THz pulse is strongly affected by the 1/f noise characteristics of the mode-locked laser, and is improved effectively by increasing the modulation frequency. The resulting signal-to-noise ratio was 4,900 in THz radiation power at 0.1 THz using an audio-frequency lock-in amplifier with a time constant of 1 ms and modulation frequency of 100 kHz. The proposed method will be a powerful tool for real-time or highly sensitive THz measurements. [DOI: 10.1143/JJAP.44.1777]

KEYWORDS: terahertz, photoconductive antenna, laser noise, amplitude modulation, free-space electro-optic sampling

1. Introduction

Recent advances in the area of coherent terahertz electromagnetic pulses (THz pulses) have opened the door for new schemes of nondestructive material tests,[1] biomedical measurements[2] and spectroscopy.[3] A typical setup for THz measurements, such as THz time-domain spectroscopy (THz-TDS) and THz imaging, employs a mode-locked Ti:Sapphire laser oscillator and a photoconductive (PC) antenna as the driving source and THz emitter (PC-THz emitter),[4] respectively. In the setup, a free-space electro-optic sampling (FSEOS) method is often applied to detect the THz signal.[5] The FSEOS scheme is attractive for the coherent detection of freely propagating THz pulses because of its ultrabroad detection bandwidth, high stability, ease of use, low probe power and real-time two-dimensional imaging capability.

However, the FSEOS method is much more sensitive to laser noise than conventional PC detection (using a PC antenna as the THz detector), because the FSEOS method detects a THz electric field in the form of very small changes in polarization (typically, 10^{-4}–10^{-5}) in the probe light, whereas the PC detection directly detects a photocurrent induced by the THz field. Consequently, the FSEOS method is not superior to PC detection with respect to signal-to-noise ratio (SNR) when the phase-sensitive lock-in detection with low-frequency ($\leq$ a few kHz) amplitude modulation (AM) is employed. In general, mode-locked lasers exhibit a high noise level in the audio frequency region (AF: <100 kHz), with a $\sim 1/f$ rolloff toward the radio frequency region (RF: >100 kHz).[6] In the FSEOS, such laser noise influence can be decreased by modulating the THz beam at the RF, resulting in an improved SNR with RF lock-in detection. On the other hand, the AF lock-in detection is usually applied to the PC detection because a poor noise characteristic of the RF region in a transimpedance preamplifier, following the PC antenna, makes RF modulation unattractive for PC detection. Hence, the RF-AM of the THz beam is crucial for FSEOS to achieve a SNR comparable to PC detection with AF modulation.[7] Such RF-AM can be achieved by modulating a pump light with an acousto-optic modulator (AOM) or an eletro-optic modulator (EOM). However, these modulators induce the following problems: (a) temporal broadening due to group velocity dispersion in a thick modulator crystal; (b) modulation distortion due to nonlinear response in the case of deep modulation; (c) free-space-propagating electromagnetic-induced noise from the high-power modulation driver; and (d) expensive and complicated apparatus. Furthermore, (e) spatial dispersion of the modulated laser beam causes another problem in the AOM method. When we attempt to compensate for (a) and (e), additional procedures such as temporal and spatial prechirping are required.[8] There is a need, therefore, for a new technique that can modulate the THz beam directly without the need for an AOM or EOM. Recently, the electric bias modulation of the PC-THz emitter is often been applied as another technique for high-frequency AM of the THz pulse,[9–11] and it has been implemented in commercially available system worldwide. The bias modulation technique is simple and does not require any special or expensive apparatus such as an AOM or EOM. Other advantages of this technique over AOM and EOM include no temporal/spatial broadening of the pump pulse and no electromagnetic-induced noise. However, the detailed investigations of the dependence of the pulsed THz emission on electric bias and modulation frequency for this technique are lacking.

Here, we evaluate the dependence of a THz electric field on the electric bias in a pulsed THz emission from an electrically modulated PC-THz emitter detected using the FSEOS method. We further investigate the dependence of modulation frequency on the SNR, and demonstrate an improved SNR based on the resultant frequency dependence. Furthermore, we show the feasibility of real-time THz measurements using a FSEOS setup with PC bias modulation.

2. Experimental Setup

Figure 1 shows a schematic diagram of the experimental setup. We used a typical THz-FSEOS setup comprising a

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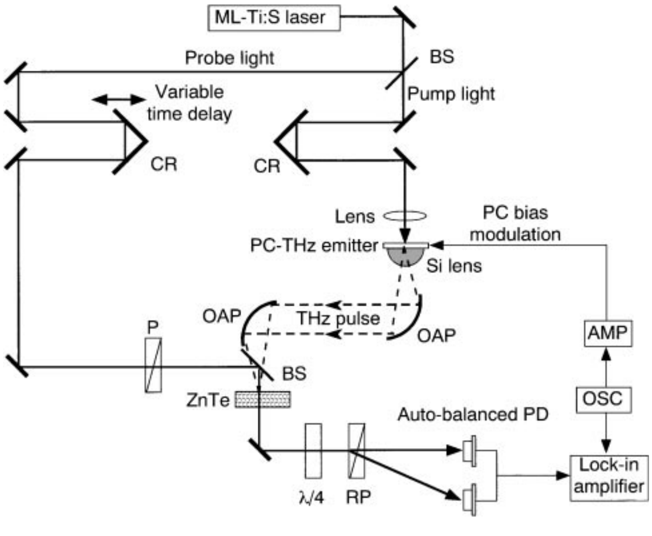

Fig. 1. Experimental setup. ML-Ti:S laser: mode-locked Ti:Sapphire laser, BS: beam splitter, CRs: corner reflectors, PC-THz emitter: photoconductive THz emitter, Si lens: silicon lens, OAP: off-axis parabolic mirror, P: polarizer, ZnTe: zinc telluride crystal, $\lambda/4$: quarter-wave plate, RP: Rochon prism, auto-balanced PD: auto-balanced photodetector, AMP: amplifier, OSC: oscillator.

mode-locked Ti:Sapphire laser oscillator, a PC antenna for THz generation (PC-THz emitter) and an electro-optic crystal for FSEOS. The laser is an 87 MHz Kerr-lens mode-locked Ti:Sapphire laser (Avesta Project, Ltd., TiF-Kit-100) pumped by a 5 W frequency-doubled Nd:YVO_4 laser (Showa Optronics, JUNO5000) running at 532 nm. The laser pulse has a duration of 80 fs and an average power of 300 mW at 808 nm. The PC antenna was fabricated on low-temperature-grown GaAs with a bowtie length of 1 mm and a 5 µm gap. A 1-mm-thick (110) ZnTe crystal was used as a THz sensor for FSEOS. The probe signal is detected with an auto-balanced photodetecor (New Focus Inc., 2007M, bandwidth = 125 kHz) after passing through a quarter-wave plate and a Rochon prism.

For electric bias modulation of the PC-THz emitter, we prepared an oscillator (OSC) and an amplifier (AMP). The electric bias of the PC-THz emitter was modulated in a unipolar sinusoidal wave with an appropriate offset (max. freq. = 1 MHz, max. amplitude = 30 V_{p-p}). The probe signal influenced by the modulated THz electric field was measured with a lock-in amplifier (NF Corporation, 5610B, bandwidth = 200 kHz) referred to the OSC.

3. Results

Two major methods are used for modulating a THz pulse from a PC-THz emitter: (1) modulation of the incident laser power, and (2) the modulation of electric bias voltage. Working from this viewpoint, we first investigated the effects of both the modulation methods on THz radiation. Figure 2(a) shows the dependence of the maximum THz electric field in the temporal domain on the PC electric bias. To evaluate the distortion of the temporal waveform of the THz pulse with an increase in the electric bias, we also show the dependence of THz amplitude at several different frequencies (0.25, 0.5, 0.75, 1, 1.25 and 1.5 THz) on electric bias, obtained by THz time-domain spectroscopy (THz-TDS), in Fig. 2(b). From these results, we confirm that the

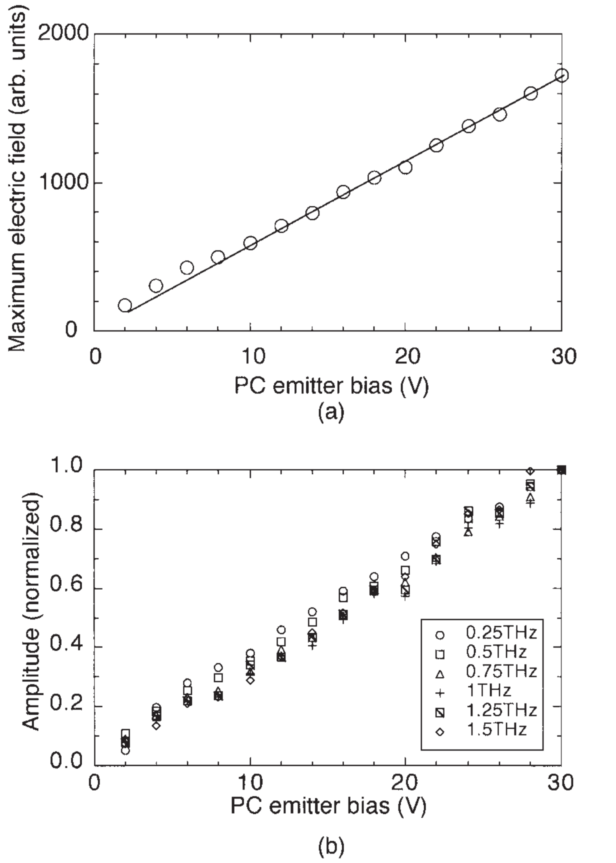

Fig. 2. Dependence of THz radiation on electric bias: (a) maximum THz electric field in temporal domain and (b) THz amplitude at several different frequencies in frequency domain. THz amplitude is normalized to its maximum at each frequency.

THz electric field and THz amplitude at each frequency increase almost proportionally with an increase in the bias voltage. Hence, we can adjust THz radiation without a marked waveform distortion using the bias voltage in the PC-THz emitter. The linear relationship between PC-THz emitter bias and THz radiation offers the possibility of distortion-free modulation of the THz pulse even when deep modulation is required. However, some distortion of the THz waveform (for example, perturbation on the negative part of the bipolar waveform) must be considered under the modulation of higher bias voltages because low-temperature–grown GaAs PC antennas indicate a tendency to increase response time with bias voltage.[12] We next investigated the dependence of (a) the maximum THz electric field and (b) the THz amplitude at several different frequencies (0.25, 0.5, 0.75, 1, 1.25 and 1.5 THz) on the pump power as shown in Fig. 3. The THz electric field and amplitude of the THz pulse increase with an increase in pump power but show a tendency toward saturation in the high-pump-power region. In general, the saturation effect is attributed to a screening of the bias field by excited photocarriers.[13] Furthermore, the absorption may start to saturate at the power levels under investigation. Such a nonlinear profile in pump power causes a secondary modulation distortion of the THz radiation when using an AOM or EOM.

The SNR in FSEOS is strongly affected by the noise characteristics of the mode-locked Ti:Sapphire laser, which

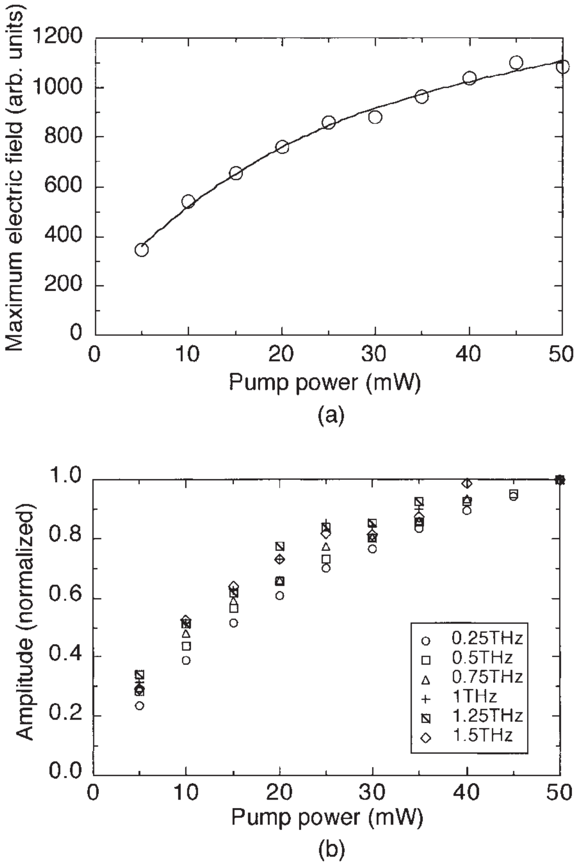

Fig. 3. Dependence of THz radiation on pump power: (a) maximum THz electric field in temporal domain and (b) THz amplitude at several different frequencies in frequency domain. THz amplitude is normalized to its maximum at each frequency.

is an essential component for generating and detecting the THz pulse. It is therefore necessary to determine an optimum modulation frequency from the viewpoint of laser noise characteristics; hence, we evaluated the noise characteristics of our laser. The laser pulse was detected with a Si-PIN photodiode (Hamamatsu, S5973, cutoff freq. = 1.5 GHz) and the resultant noise was determined with a spectrum analyzer (Agilent Technologies, 4395A, RBW = 1 Hz). Figure 4 shows the noise-power spectrum of our laser in the AF region between 0.1 and 100 kHz. The background,

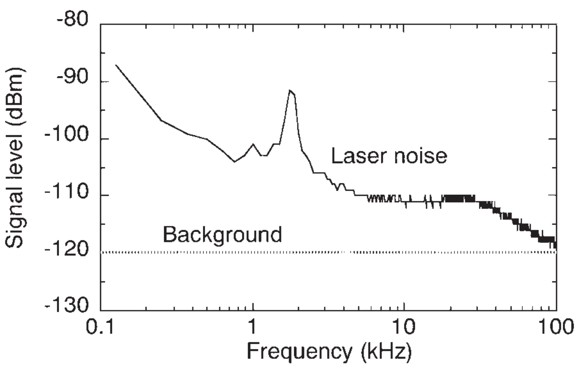

Fig. 4. Noise power spectrum of the mode-locked Ti:Sapphire laser. The background is the noise level of the spectrum analyzer and photodiode when the laser beam is blocked. The frequency resolution of the spectrum analyzer is 1 Hz.

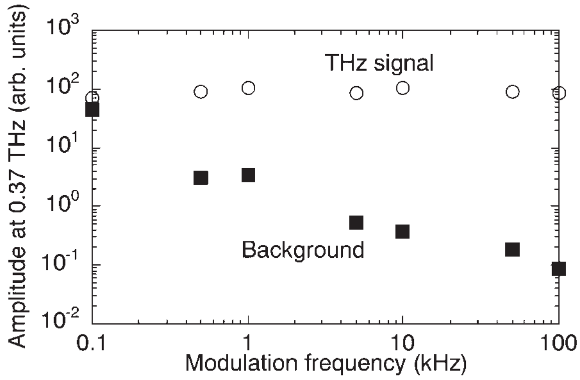

Fig. 5. Comparison of amplitude in the THz signal and background in FSEOS with respect to modulation frequency.

i.e., the instrumental noise of the spectrum analyzer and photodiode under no incidence of the laser beam, is approximately 120 dBm. As can be seen in Fig. 4, the laser noise spectrum shows $1/f$ characteristics with a peak at 2 kHz and becomes comparable to the background noise level at 100 kHz. This indicates that a modulation at 100 kHz yields a sufficient improvement in the laser noise characteristics. At a modulation of 100 kHz, laser noise is only 1% of that at 1 kHz.

We next investigated the relationship between modulation frequency and SNR in FSEOS. In the experiment, we applied a modulated voltage signal (amplitude = 20 $V_{p\text{-}p}$, offset = 10 V, and freq. = 100 Hz–100 kHz) to the PC-THz emitter as an electric bias at a fixed pump power (= 50 mW). A modulated voltage signal such as this is easily generated by a conventional audio-frequency amplifier (see Fig. 1), for which the price is much less than that of an AOM or EOM. Figure 5 compares the amplitudes of the THz signal and background at 0.37 THz (determined by the THz-TDS method) with respect to the modulation frequency. The time constant of the lock-in amplifier is 100 ms. The background corresponds to the signal level of the probe light when the THz beam is blocked. The background also conforms to a $1/f$ trend; while the signal level is almost constant over the modulation frequency range, such that the SNR improves with an increase in modulation frequency (for example, an SNR of 1,000 in the THz electric field at 100 kHz). The $1/f$ characteristic of the observed laser noise (see Fig. 4) strongly contributes to the SNR improvement in the high-frequency region. A 100-kHz modulation results in a practically sufficient improvement of SNR in FSEOS, although the bandwidth of the balanced photodetector (125 kHz) limits the range of the modulation frequency in this THz-TDS system. If the bandwidth of the signal detection system is markedly expanded, the upper limit of the possible modulation frequency is then determined by the frequency response characteristic, that is the RC time constant, of the PC-THz emitter and peripheral electronics such as the electric signal cable and connector. The RC time constant for the same type of PC antenna has been estimated to be approximately 0.2 ps.[14] Hence, the PC modulating method offers the possibility of RF modulation ($>$100 kHz) beyond the AF range ($<$100 kHz) if the capacitance of the peripheral electronics is negligible. Such RF modulation, however, is not practical because of the poor performance of

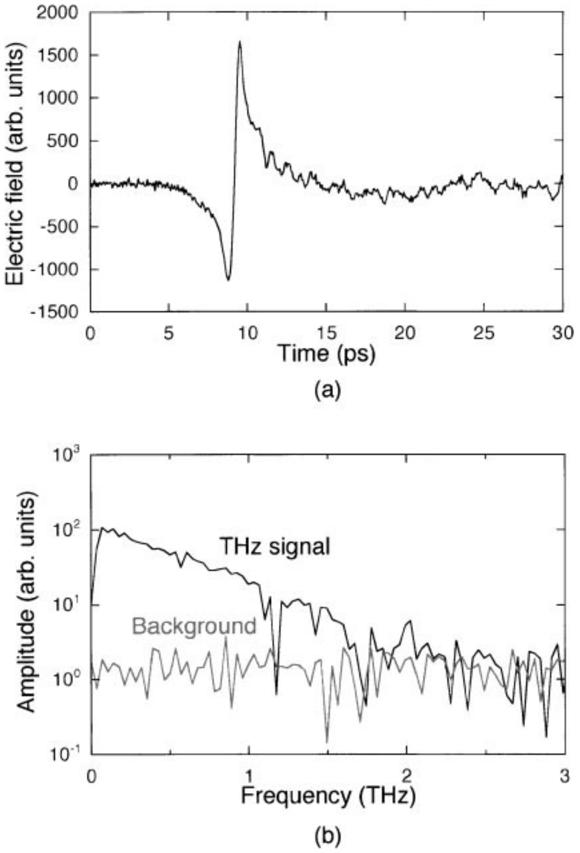

Fig. 6. (a) Temporal waveform of the THz pulse and (b) comparison of amplitude spectra in THz signal and background. The modulation frequency of the PC electric bias and the time constant of the lock-in amplifier are 100 kHz and 1 ms, respectively.

the current RF lock-in amplifiers and fast balanced photodetectors. For example, the internal noise level of RF lock-in amplifiers is approximately 100 times higher than that of AF lock-in amplifiers.[15] A similar improvement in SNR in FSEOS (see Fig. 5) can be achieved by the conventional EOM and AOM methods. It is important to emphasize, however, that the PC bias modulation method achieves these results with no temporal or spatial broadening of the pump pulse, no modulation distortion, no free-space-propagating electromagnetic-induced noise and, most importantly, no need for an expensive apparatus.

To evaluate the performance of the proposed modulation method in real-time THz measurements, we carried out rapid THz measurements using an AF lock-in amplifier with a time constant of 1 ms, in which a modulated voltage signal (amplitude $= 30\,V_{\text{p-p}}$, offset $= 15\,V$, and freq. $= 100\,\text{kHz}$) is applied to the PC-THz emitter bias. Figures 6(a) and 6(b) show the resulting temporal waveform and amplitude spectrum of THz pulse, respectively. For comparison, the background signal due to the instrumental noise is also shown in Fig. 6(b). From this result, we confirmed a SNR of approximately 70 in the THz electric field (4,900 in THz radiation power) at 0.1 THz for a single scan of the time delay. This result suggests the applicability of this technique to fast-delay-scan, single-pixel THz imaging.

4. Conclusions

We evaluated the dependence of THz electric field on electric bias and modulation frequency in the pulsed THz emission from electrically modulated PC-THz emitter detected using the FSEOS method. The linear dependence of the THz pulse on electric bias results in the distortion-free modulation of the THz pulse even when deep modulation is required. The SNR based on the FSEOS setup with PC bias modulation was effectively improved with an increase in modulation frequency, which is consistent with the $1/f$ noise characteristics of the actual mode-locked laser. The resultant SNR was 4,900 in THz radiation power at 0.1 THz using an AF lock-in amplifier with a time constant of 1 ms and a modulation frequency of 100 kHz. We evaluated the feasibility of real-time THz measurements based on the present setup. This technique is also useful for highly sensitive THz-TDS by combining the fast bias modulation and double-modulation techniques.[16]

Acknowledgement

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