FREQUENCY AND TIME DOMAIN MEASUREMENT OF COHERENT TRANSITION RADIATION

K. Kan#, J. Yang, T. Kondoh, M. Gohdo, I. Nozawa, Y. Yoshida†
The Institute of Scientific and Industrial Research (ISIR), Osaka University, Osaka 567-0047, Japan

Abstract

Ultrashort electron beams are essential for light sources and time-resolved measurements. Electron beams can emit terahertz (THz) pulses using coherent transition radiation (CTR). Michelson interferometer is one of candidates for analyzing the pulse width of an electron beam based on frequency-domain analysis. Recently, electron beam measurement using a photoconductive antenna (PCA) based on time-domain analysis has been investigated. In this paper, to improve beam diagnostics of ultrashort electron beam, investigation of characteristics of a PCA for generation and frequency and time-domain measurement of THz pulses was conducted.

INTRODUCTION

Short electron bunches with durations of picoseconds to femtoseconds are useful for generation of light in terahertz (THz) range [1]. Such electron beams are used in time-resolved studies of ultrafast phenomena and reactions, including ultrafast electron diffraction (UED) [2] and pulse radiolysis [3-5]. Electro-optic sampling [6], which is one of detection techniques of THz light pulse, is used in diagnostics of electron bunches. In EO samplings, the birefringence of EO crystals is induced by the beam electric field, and laser polarization corresponding to the longitudinal electron beam profile is detected [7, 8]. EO monitors based on the temporal decoding have revealed the Coulomb field of a root mean square (rms) width of 60 fs from femtosecond electron bunches [8]. Interferometers [9] have been also used for the detection of single mode or multimode THz pulses generated by electron bunches and slow-wave structures [10,11]. Smith-Purcell radiation, which uses metallic gratings, has also been analyzed by interferometers [12,13]. Coherent transition radiation (CTR), which is generated by electron bunches crossing a boundary between different media, has been measured by interferometers and grating-type spectrometers [14,15]. Photoconductive antennas (PCAs), which are composed of semi-insulating semiconductor with electrodes, are widely used for both generation and detection of THz pulses in THz time-domain spectroscopy [16-20]. PCAs could be good candidates for analyzing temporal electric field profiles of electron bunches due to the correlation between electric-field-induced current output and THz electric field strength [19]. THz pulses of CTR are radially polarized [21] due to the diverging electric fields from the beam center. Therefore, a PCA with radial polarization characteristics is considered to be useful for the measurement of THz pulse from an electron bunch. Recently, Winnerl et al. reported fabrication of a large- aperture PCA, and the radially polarized field pattern of focused THz pulses was measured [22]. Polarization components of radially polarized THz pulses from a similar PCA were also investigated using a wire grid polarizer [23]. Furthermore, time-domain measurement of CTR using the PCA [23] has been conducted [24]. The scheme is based on measurement of radially polarized THz pulses of CTR with a large-aperture PCA, which has radial polarization components. The combination of an interferometer and PCA will enable frequency and time-domain analysis of THz pulse of CTR. For improving the system of beam diagnostics of ultrashort electron beam, investigation of characteristics of PCA is essential for not only detection but generation.

In this paper, frequency and time-domain measurement of THz pulses from a PCA was conducted. Frequency of THz pulses from the PCA was changed by transmission through media. THz pulses through the media was measured by a Michelson interferometer, which detects THz pulses with frequency-domain information. And, time-domain information of THz pulses was analysed using transient transmission of THz pulses through a photoexcited semiconductor.

EXPERIMENTAL SETUP

Diagram and picture of the frequency and time-domain measurement of THz pulses from the PCA are shown in Fig. 1. In this study, the PCA was used for THz generation. The PCA was driven by a femtosecond laser (800 nm, <130 fs FWHM, <800 μJ/pulse, 1 kHz, Tsunami with Spitfire, Spectra-Physics) and DC bias voltage for electrodes of ≤50 V. According to a previous study, breaking voltage of ~100 V was estimated for 10 μm electrode gap, i.e., electric field of 100 kV/cm [23]. Figure 1 (a) shows diagram of measurement system. The PCA in the present study was fabricated on semi-insulating-GaAs substrate with dimension of 8.8 mm diameter and 0.6 mm thickness with 220 concentric gaps of 10 μm-wide electrodes, which was the same design of the previous report [23]. Figure 1 (b) shows paths for the laser and THz pulses in the measurement system. Figure 1 (c) shows the PCA with concentric electrodes set to a holder. DC bias voltage was supplied to the PCA through pads attached with silver paste.

#: koichi81@sanken.osaka-u.ac.jp
†: yoshida@sanken.osaka-u.ac.jp

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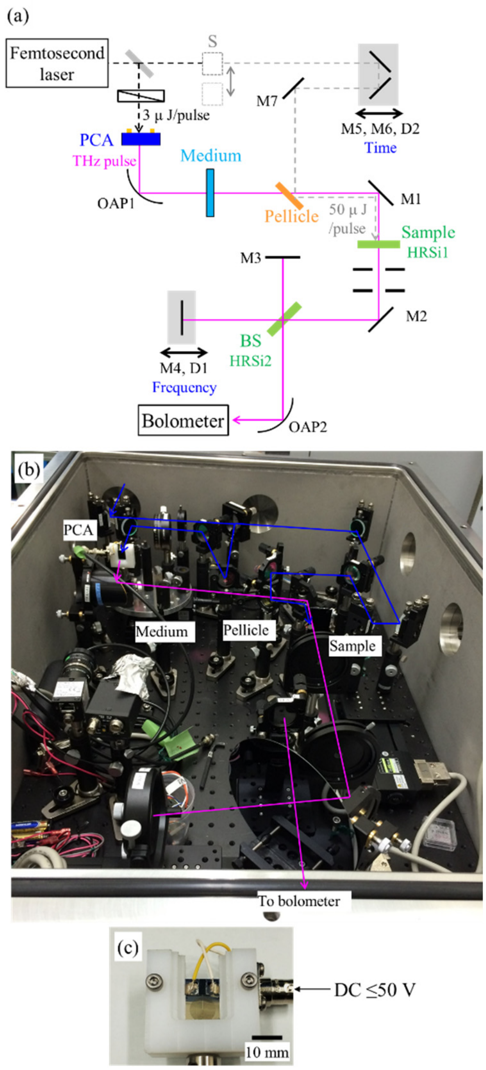

Figure 1: (a) Diagram and (b) picture of the frequency and time-domain measurement of THz pulses from the PCA. (c) Picture of the PCA mounted to a holder.

RESULTS AND DISCUSSIONS

Frequency-domain Measurement

The emitted THz pulses from the PCA was measured by a Michelson interferometer [11,15,23]. The THz pulses were collimated by an off-axis parabolic mirror (OAP1). The THz pulse was transported through a medium, pellicle, and a sample (0.38 mm-thick high-resistivity silicon, HRSi1). In the measurement, media of vacuum or fused silica were used. The sample was not photoexcited by shielding (S) the separated laser. In the interferometer, THz pulse was separated to two pulses by a beam splitter (0.38 mm-thick high resistivity silicon, BS, HRSi2). One THz pulse was reflected by a fixed mirror (M3). The other pulse was reflected by a mirror mounted on delay line (M4 and D1). Finally, the separated THz pulses were superposed on a liquid-helium-cooled silicon bolometer (general-purpose 4.2-K system, Infrared Laboratories). An interferogram, which was the bolometer output as a function of the mirror (M4) position, was measured. And, a frequency spectrum was obtained using the Fourier transform of the interferogram. Far-infrared filter in the bolometer of crystal quartz with garnet powder (100 cm^{-1} cut-on) was used and the gain of an equipped preamplifier was 1000. The bolometer output was measured by a lock-in amplifier (LI5640, NF Corporation) using a 1 kHz trigger from the regenerative amplifier. In the measurement using delay lines, analogue output of the lock-in amplifier (bolometer output) and trigger signal from a delay controller (Shot-202, OptoSigma) for moving distance of the delay line were acquired by a data acquisition system (NI USB 6353, National Instruments). The trigger signal from the delay controller was used for both voltage measurements of the bolometer output and pulse count of the moving distance.

Figure 2 shows interferograms and frequency spectra of the THz pulses from the PCA. The data was acquired in vacuum condition of <80 Pa. The sample was not photoexcited by shielding the separated laser for photoexcitation. The medium in the THz path was changed. The interferograms using media of vacuum (no medium) and 2 mm-thick fused silica are shown in Fig. 2 (a). In the measurement, time constant of lock-in amplifier and delay speed were 300 ms and 30 μm/s, respectively. The both parameters were optimized for the measurement of the oscillating interferogram and S/N ratio. If THz pulses pass through dispersive media, frequency components changes. As the result, offset of interferogram of THz pulse through the fused-silica was reduced as compared with the case of vacuum (no medium). Difference of the oscillation components of the both interferograms does not seem to be obvious. However, the frequency spectra, which were obtained by the Fourier transform of the interferograms, differed at high frequencies. According to a previous report of THz time-domain spectroscopy of glasses, fused silica has high absorption coefficients in high THz frequency [25]. In this study, the decrease of the transmitted frequency components was also observed at frequency of >0.7 THz.

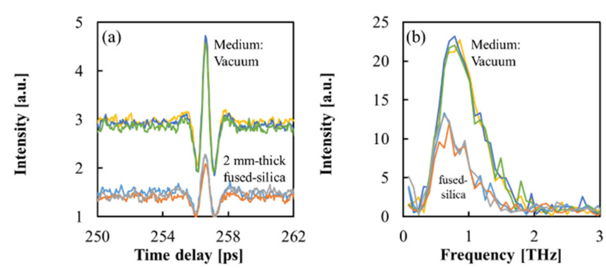

Figure 2. Effects of the media to (a) interferograms and (b) frequency spectra. The data was obtained at vacuum condition (< 80 Pa) and three sweeps for each medium are shown.

Time-domain Measurement

To investigate the THz pulse with changed frequency components, a time-domein measurement was introduced by using photoexcited semiconductor. Separated laser pulse with energy of 50 uJ/pulse was used for the photoexcitation of the silicon (HRSi1). The shield (S) of the separated laser was removed. When the silicon is photoexcited, photoinduced carriers are generated and plasma frequency of the silicon is changed. Thus, transient THz transmittance decreases due to the laser irradiation. When photoexcitation is occurred before the THz transmission, transient transmitted THz intensity decreases. However, when photoexcitation is occurred after the THz transmission, transmitted THz intensity is not changed. Figure 3 shows transient transmittance of THz pulse measured by the time-domain measurement. The timing of the photoexcitation was adjusted by the delay line (D2). For THz intensity measurement, the position of the moving mirror in the interferometer (D1) was set to 6 ps far from the centerburst position. The bolometer output as a function of delay line (D2) was measured as shown in Fig. 3. As expected, low THz intensity was observed in the case of small optical delay, which corresponds to photoexcitation of sample before THz transmission. Transient transmittance profiles for the media of vacuum and 2 mm-thick fused silica are shown. The rise time of the transient response would depend on laser pulse width, THz pulse width, and response time of the silicon. It would be difficult to specify each contribution to the rise time at this point. The effect of the media was evaluated using a simplified model of convolution. The time profiles, $f(t)$, were fitted by the following equation,

$$f(t)=\int aU(t-b)\exp\left(-\frac{(t-\tau)^2}{2\sigma^2}\right)d\tau+c, \qquad (1)$$

where U denotes the step function; σ, a fitting parameter of the rise time; a, b, and c, fitting parameters of factor, time, and offset. According to the fitting of the time profile, σ of 0.37 and 0.43 ps were obtained for the media of vacuum and 2 mm-thick fused silica, respectively, using averages of five sweeps. According to the fitting parameter of σ, slight difference of the fitting parameter due to the media was observed by using photoexcited silicon. However, usage of photoconductive antenna for the detection of THz pulses of CTR will enable more detailed analysis of electric field profile of THz pulse than previous methods. And, this PCA is valid for the measurement of THz pulse in the range of ~1 THz, according to the THz frequency spectrum in Fig. 2 (b) although the spectra were observed in the THz generation condition.

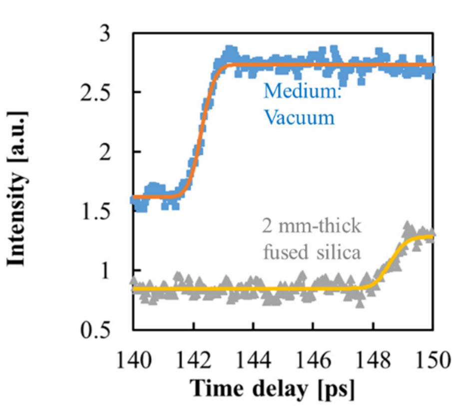

Figure 3. Examples of transient transmittance of THz pulses. Single sweeps for the cases of the media are shown. Curves denote fitting functions using Eq. (1).

CONCLUSION

Frequency and time-domain information of THz pulses from the PCA was investigated. The PCA in this paper is valid for the measurement of THz pulses at a frequency of ~1 THz according to the frequency-domain measurement. Transient response times in the photoexcitation were obtained to be 0.37 and 0.42 ps as fitting parameters in the cases of transmission of vacuum and 2 mm-thick fused silica, respectively. In the future, frequency and time-domain measurement of CTR will be conducted.

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