ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE007

MEASUREMENT OF TEMPORAL ELECTRIC FIELD OF ELECTRON BUNCH USING PHOTOCONDUCTIVE ANTENNA

K. Kan[#1], J. Yang, A. Ogata, T. Kondoh, M. Gohdo, I. Nozawa, T. Toigawa, Y. Yoshida[#2]
ISIR, Osaka University, Osaka 567-0047, Japan

Abstract

A temporal electric field profile, which is a radially polarized terahertz (THz) pulse from an electron bunch, was measured by a large-aperture photoconductive antenna (PCA) with micro-structured concentric electrodes for the detection of THz pulses. Photo-induced charge carriers were generated by irradiation of femtosecond laser pulses on semiconductor plane of the electrodes on the PCA. Time-domain measurement of coherent transition radiation (CTR) was conducted by the measurement of electric-field-induced current output from the PCA with sweeping the timing of the laser irradiation. The measurements on femtosecond electron bunches of 32 MeV and >80 pC will be reported.

INTRODUCTION

Short electron bunches with durations of picoseconds to femtoseconds are useful for generation of light in terahertz (THz) range [1] and time-resolved studies of ultrafast phenomena and reactions, including ultrafast electron diffraction (UED) [2] and pulse radiolysis [3,4,5]. 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]. 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 [12,13]. Photoconductive antennas (PCAs), which are composed of semi-insulating (SI) semiconductor with electrodes, are widely used for both generation and detection of THz pulses in THz time-domain spectroscopy [14,15,16,17,18]. 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 [17]. Fabrication of a large-aperture PCA is expected to enhance both generation efficiency and detection sensitivity of THz pulses with designed polarization character. Enlarged aperture of PCA and concentric electrode configuration scheme in the present study utilizes the application of PCAs with enhanced sensitivity and radial polarization feature. The application of those PCAs on the detection of THz pulses from electron bunches will be a new methodology for beam diagnostics.

In this paper, analysis of the temporal electric field profile of CTR using a large-aperture PCA with micro-structured concentric electrodes is demonstrated. CTR was emitted by femtosecond electron bunches from a photocathode-based linac. The PCA enabled the detection of radially polarized THz pulses with adequate sensitivity according to the geometry of electrodes. Photo-induced charge carriers were generated by irradiation of a femtosecond laser on the PCA. Electric-field-induced current was obtained as THz electric field strength of CTR at the duration of the laser irradiation.

EXPERIMENTAL SETUP

Generation of Femtosecond Electron Beam

Femtosecond electron bunches were generated by the photocathode-based linac [13,19,20], which consists of a 1.6-cell S-band radio frequency (RF) gun with a copper cathode, a 2-m-long traveling-wave linac, and an arc-type magnetic bunch compressor as shown in Fig. 1. The photocathode of RF gun was excited by 4th harmonic (262 nm) of a picosecond laser with an energy of <180 μJ/pulse and a pulse width of 5 ps FWHM at 10 Hz. The electron bunches were accelerated in the gun and the linac using a 35-MW klystron. In the linac, the electron bunches were accelerated to 32 MeV at a linac phase of 100° for an optimal energy modulation of electron bunches [13]. The accelerated electron bunches were compressed to femtosecond by the magnetic bunch compressor, which was composed of bending magnets (B), quadrupole magnets (Q), and sextupole magnets (S). CTR was generated by the compressed femtosecond electron bunch.

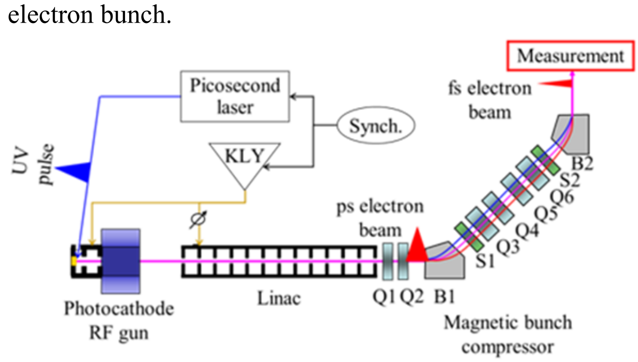

Figure 1: Diagram of photocathode-based linac.

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

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE007

Measurement of CTR

THz pulses of CTR are radially polarized [21] due to the diverging electric fields from the beam center. Radially polarized THz pulses from electron bunches were also measured experimentally using a Shchottky diode detector and a THz camera [22]. Therefore, a PCA with radial polarization character 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 [23]. Polarization components of radially polarized THz pulses from a similar PCA were also investigated using a wire grid polarizer [24]. The PCA in the present study was fabricated on SI-GaAs substrate with dimension of 8.8 mm diameter and 0.6 mm thickness with 220 concentric gaps of 10-μm-width electrodes, which was the same design of the previous report [24].

Diagram of simplified azimuthal cross section of the large-aperture PCA and picture were depicted in Fig. 2. Concentric micro-structured electrodes and photomasks were fabricated on semiconductor as shown in Fig. 2(a). A radially polarized THz pulse, i.e., THz electric field in the direction of *r* in Fig. 2(b), will be introduced to the electrodes of the PCA from the direction of plane SI-GaAs side (*z*>0). Output of electric-field-induced current due to CTR will be obtained by photo-induced charge carriers from the electrodes only when the laser pulse irradiate on the PCA from the electrode/photomask side (*z*<0) within the duration of CTR irradiation on PCA. Photomasks shield every other gap between electrodes from laser irradiation and enable effective detection of THz pulses. If there were no photomasks, inflow and outflow of the electric-field-induced current would be cancelled out at each electrode resulting in the decrease of the current output. The effects of the photomasks on the PCA were discussed as destroyed "interference" "in the far field" [25]. A picture of a PCA is shown in Fig. 2 (b). The electrode/photomask patterns were fabricated on ~25 mm square semiconductor of SI-GaAs.

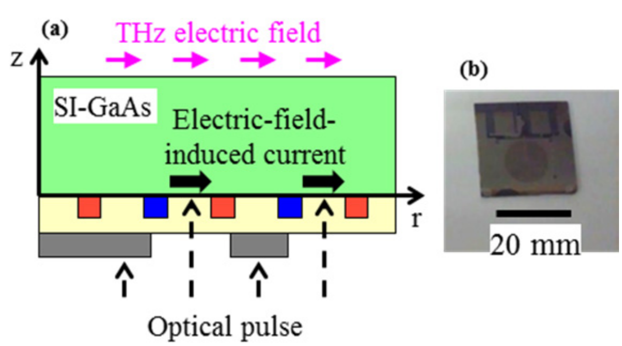

Figure 2: (a) Diagram of simplified azimuthal cross section of the large-aperture PCA (red and blue: conducting electrodes, yellow: insulating layer, gray: photomask). (b) Picture of a PCA.

Figure 3 shows the schematic diagram of time-domain measurement of CTR using the PCA. Compressed electron bunches generated by the linac passed through a titanium foil with 20 μm thickness set by a metal O-ring to the measurement system in the air. The distance between the foil and a plane aluminum mirror (M1) was 200 mm. CTR was generated on the surface of M1 with beam energy dependent opening angle. The CTR is considered to have radial electric field components with respect to the axis of the CTR. The radially polarized THz pulses of CTR were collimated by an off-axis parabolic mirror (OAP1) with a focal length of 191 mm. The collimated THz pulses were directly introduced to the PCA from the plane SI-GaAs side. Spot size of THz pulses on the PCA was estimated to be 6.0 mm in diameter from calculation of the opening angle and collimation. The PCA was irradiated by femtosecond laser pulses from the electrode/photomask side. The light source for the photo-excitation of SI-GaAs was Ti-sapphire fs laser (800 nm, <130 fs FWHM, a repetition rate of 1 kHz, <800 μJ/pulse, Tsunami with Spitfire, Spectra-Physics). The laser spot size on the PCA was estimated to be 4.6 mm FWHM using Gaussian fitting from beam profile measurement using a CCD camera. The time delay of the laser pulses was adjusted by a delay line (M2 and M3 on the delay line). Photo-induced charge carriers were generated by the laser irradiation. Electric field strength of THz pulses can be converted to the electric-field-induced current when laser pulses are irradiated on the PCA. Therefore, temporal electric field profile of CTR will be obtained as a dependence of the current on the time delay. The output of the electric-field-induced current was fed to a preamplifier (model 5307, NF) with gain of 500. The amplified current was acquired on an oscilloscope (WaveRunner 6100A, LeCroy) with bandwidth limiting of 20 MHz. Peak-to-peak voltage of the current in a time window of 30 ns was used as THz electric field strength. This peak-to-peak voltage of each shot was recorded as a function of the time delay of the laser pulses.

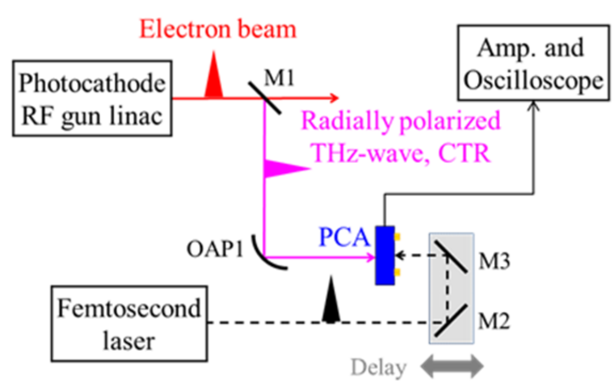

Figure 3: Schematic diagram of time-domain measurement of CTR using the PCA.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE007

RESULTS AND DISCUSSIONS

Electric field profiles of CTR measured by the PCA were shown in Fig. 4. THz electric field of CTR gave an increase in electric-field-induced current only when the laser pulse was irradiated on the electrodes. Three single sequence scans were shown in Fig. 4(a). The bunch charge and energy of laser pulses were 170 pC and 21 μJ/pulse, respectively. Instabilities can be observed near the peak of electric-field-induced current due to single-shot measurement for each point. However, averaged electric-field-induced current indicated electric field profile with a Gaussian pulse shape as shown in Fig. 4(b) The averaged profile was calculated using twelve sweeps. Under the assumption of electron bunch with a Gaussian distribution, the electric-field-induced current *I*, will be given as follows: $I(t) \cong a \exp[-(t-b)^2/(2\sigma^2)]$, where *t*, *a*, *b*, and σ denotes time delay, signal intensity corresponding to peak electric field strength of THz pulse, the timing which give the maximum signal intensity, and the bunch length in rms, respectively. According to the fitting result, the bunch length (σ) of the averaged profile was 0.55 ps in rms. It is better to analyze the time profile with a calibration of the frequency dependence of the sensitivity of PCA, but at present moment, all analyses were made without correction of sensitivities. Current output from PCA is considered to be proportional to the detected electric field [17]. On the other hand, electric field strength of coherent radiation is supposed to be proportional to electron bunch charge according to an analytical calculation [26]. Thus, the PCA could detect THz electric field of CTR from electron bunches. In the future, precise synchronization between stabilized electron beams and optical pulses would realize broadband detection using ultrashort optical pulses of the order on 10 fs [16]. Irradiation system of THz pulse and laser on the electrodes of PCA should be also designed from a viewpoint of THz absorption in semiconductor [16].

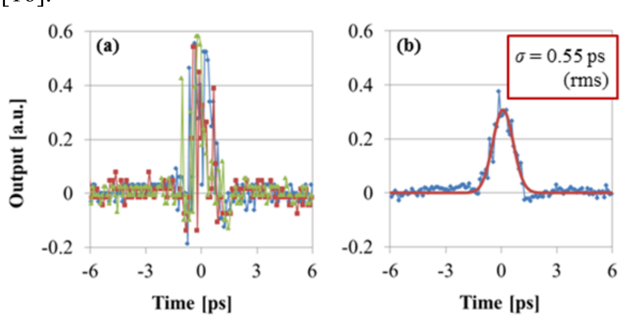

Figure 4: Temporal electric field profiles of (a) three sequential sweeps and (b) averaged data using twelve sweeps.

CONCLUSIONS

In conclusion, the time-domain measurement of CTR using the large-aperture PCA with concentric micro-structured electrodes was demonstrated. The longitudinal electric field profiles of CTR generated by an electron bunch of 0.55 ps in rms were successfully measured as the electric-field-induced current of the PCA with an irradiation of the femtosecond laser pulses.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI (25870404, 26249146, and15H05565) and a fund of support for international technological interaction (TEPCO Memorial Foundation).

REFERENCES

[1] A. F. G. van der Meer, Nucl. Instrum. Meth. A 528, 8 (2004).
[2] P. Musumeci et al., Ultramicroscopy 108, 1450 (2008).
[3] T. Kondoh et al., Radiat. Phys. Chem. 84, 30 (2013).
[4] J. Yang et al., Nucl. Instrum. Meth. A 629, 6 (2011).
[5] K. Kan et al., Rev. Sci. Instrum. 83, 073302 (2012).
[6] M. Nagai et al., Opt. Express 20, 6509 (2012).
[7] I. Wilke et al., Phys. Rev. Lett. 88, 124801 (2002).
[8] G. Berden et al., Phys. Rev. Lett. 99, 164801 (2007).
[9] B. I. Greene et al., Appl. Phys. Lett. 59, 893 (1991).
[10] A. M. Cook et al., Phys. Rev. Lett. 103, 095003 (2009).
[11] K. Kan et al., Appl. Phys. Lett. 99, 231503 (2011).
[12] T. Takahashi et al., Phys. Rev. E 50, 4041 (1994).
[13] I. Nozawa et al., Phys. Rev. ST Accel. Beams 17, 072803 (2014)..
[14] D. H. Auston, Appl. Phys. Lett. 26, 101 (1975).
[15] M. Tani et al., Jpn. J. Appl. Phys. 36, L1175 (1997).
[16] S. Kono et al., Appl. Phys. Lett. 79, 898 (2001).
[17] M. Tani et al., Semicond. Sci. Technol. 20, S151 (2005).
[18] K. Takano et al., Appl. Phys. Lett. 99, 161114 (2011).
[19] J. Yang et al., Nucl. Instrum. Methods A 556, 52 (2006).
[20] K. Kan et al., Nucl. Instrum. Methods A 597, 126 (2008).
[21] D. Daranciang et al., Appl. Phys. Lett. 99, 141117 (2011).
[22] Y. Taira et al., Vib. Spectrosc. 75, 162 (2014).
[23] S. Winnerl et al., Opt. Express 17, 1571 (2009).
[24] K. Kan et al., Appl. Phys. Lett. 102, 221118 (2013).
[25] A. Dreyhaupt et al., Appl. Phys. Lett. 86, 121114 (2005).
[26] M. Schwarz et al., Phys. Rev. ST Accel. Beams 17, 050701 (2014).