MEASUREMENT OF COHERENT TRANSITION RADIATION USING INTERFEROMETER AND PHOTOCONDUCTIVE ANTENNA

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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 presentation, measurement of femtosecond electron beam with 35 MeV energy and < 1 nC from a photocathode based linac will be reported. Frequency- and time- domain analysis of THz pulse of CTR by combining the interferometer and PCA will be carried out.

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 for electron bunch length measurement, 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 [14-16]. 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 [17-20]. 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 [20]. 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]. Generation of high-power THz pulses from a PCA using a high-voltage source has been studied for acceleration of electron beam [23]. Polarization components of radially polarized THz pulses from a PCA with interdigitated electrodes were also investigated using a wire grid polarizer [24]. Time-domain measurement of CTR using the PCA as a detector has been also conducted. The scheme is based on measurement of radially polarized THz pulses of CTR with a large-aperture PCA [24], which has radial polarization components. The combination of an interferometer and PCA will enable frequency and time-domain analysis of THz pulse of CTR.

In this paper, measurement of CTR from a femtosecond electron beam was conducted based on frequency and time-domain schemes. The energy and charge of the electron beam were 35 MeV and <1 nC at a repetition rate of 10 Hz, respectively. Frequency spectra of CTR were measured by a Michelson interferometer. On the other hand, time profiles of CTR were measured by a PCA driven by a femtosecond laser.

EXPERIMENTAL ARRANGEMENT

Femtosecond electron bunches were generated by a photocathode-based linac, 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. The photocathode of RF gun was excited by UV pulses (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 generated in the gun were accelerated in the linac using a 35-MW klystron at a repetition rate of 10 Hz. In the linac, the electron bunches were accelerated to 35 MeV at a linac phase of 100° which is suitable for the bunch compression [16]. The accelerated electron bunches were compressed to femtosecond by the magnetic bunch compressor, which was composed of bending magnets, quadrupole magnets, and sextupole magnets. THz pulses of CTR were generated by the compressed electron bunches and measured.

Schematic diagram and picture of measurement system for CTR using the interferometer and PCA [24] were shown in Fig. 1. CTR was generated on the interface of a mirror (M1) as shown in Fig. 1 (a). The beam energy and bunch charge were 35 MeV and 740 pC/pulse, respectively. Collimated THz pulses of CTR were separated by a beam splitter (BS1). One THz pulse was introduced to the interferometer. In the interferometer, the THz pulse was separated by a beam splitter (BS2) again. Superposed

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THz pulses were detected by a liquid-helium-cooled silicon bolometer. Interferogram, which was the bolometer output as a function of a moving mirror (Delay1), was obtained for the frequency-domain measurement. The other THz pulse was introduced to the PCA. The PCA made from semi-insulating GaAs was irradiated by femtosecond laser pulses from electrode/photomask side. The energy of laser pulses was set to 300 μJ/pulse (800 nm, <130 fs FWHM, Tsunami with Spitfire, Spectra-Physics). The time delay of the laser pulses was adjusted by a delay line (Delay2). Output of electric-field-induced current due to CTR was changed by photo-induced charge carriers on the PCA only when the laser pulse was irradiated on the PCA. Therefore, electric field profile of CTR was obtained as a dependence of the current from the PCA on the time delay for the time-domain measurement. A current transformer (CT) was set in the upstream for the both measurement systems to evaluate bunch charge. The signal from the PCA through pads on the GaAs was measured by an oscilloscope through a 50 Ω terminator and an amplifier (5307, NF, gain 100). In the bolometer, a filter of crystal quartz with garnet powder was used for the detection of THz pulse with frequencies of <3 THz. The signal from the bolometer was measured by another oscilloscope. The two signals were obtained with the both schemes at the same time although the sweeping ranges were different. The both beam splitters were made of high-resistivity silicon with a thickness of 0.38 mm. Some components were set in a vacuum chamber as shown in Fig. 1 (b).

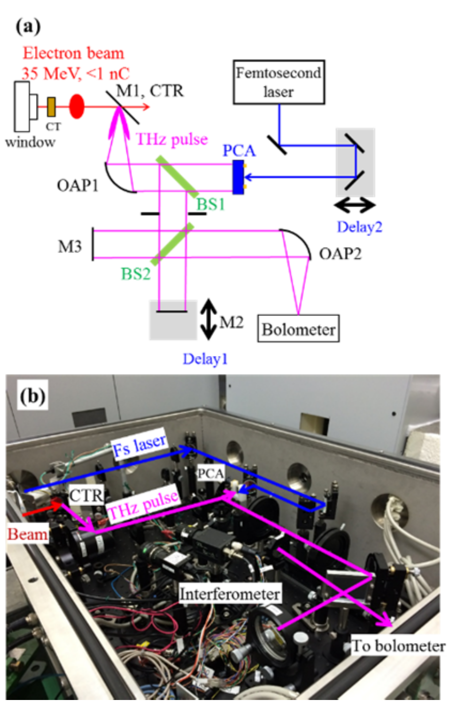

Figure 1: (a) Schematic diagram of measurement system for CTR. CT: a current transformer; M: a plane mirror; OAP: an off-axis parabolic mirror; BS: a beam splitter; I: an iris with an aperture of 9 mm in diameter. (b) Picture of the optical system set in a vacuum chamber.

RESULTS AND DISCUSSIONS

The results of frequency and time-domain measurement of CTR are shown in Fig. 2. Time-domain data from the interferometer and PCA were shown in Fig. 2 (a). The time delays of the interferometer and PCA corresponded to the position of Delay 1 and Delay 2, respectively, in Fig. 1 (a). Each data was calculated by the average of 10 sweeps. Fitting lines of filtered model [15,16] and Gaussian distribution were shown for the data of interferometer and PCA, respectively, based on an assumption of Gaussian electron bunch distribution. Calculated bunch lengths were obtained as 94 and 430 fs in rms for the cases of interferometer and PCA, respectively. The discrepancy of the bunch lengths would be due to the difference of detectable bunch length of each method, which corresponds to each bandwidth. Detectable fast signal in the PCA would depend on laser pulse width of the femtosecond laser, response time of PCA, timing jitter between the laser and electron bunch, and spectral absorption of semi-insulating GaAs although the qualitative analysis is difficult at this point. Figure 2 (b) shows frequency spectra calculated by the Fourier transform using the data in Fig. 2 (a). The detectable ranges of the interferometer and PCA in this study would be estimated as <2 and <1 THz roughly, respectively, according to the decrease in the spectral components. Previously, a similar PCA [24] was used for the generation of THz pulses at frequencies of <1 THz. The detectable range of the PCA would be reasonable with compared the experimental results in the generation of THz pulses from a PCA. There seemed to be some instabilities in the case of the PCA, however the frequency and time-domain measurements were conducted by the interferometer and the PCA. The optimization of the termination resister for the PCA would be required for the stabilization of data because of a current measurement. In the future, driving the PCA with a shorter laser pulse [19] would be also carried out for improving the PCA detector system based on broadband detection.

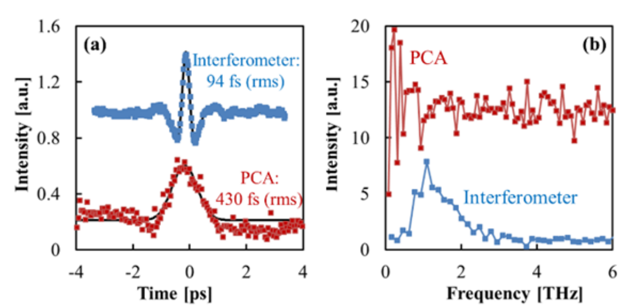

Figure 2: Results of (a) time and (b) frequency-domain measurement of CTR obtained by the interferometer and PCA. (a) Fitting lines of filtered model and Gaussian distribution were shown for the data of interferometer and PCA, respectively. Factors and offset were adjusted for comparison. (b) Only factors were adjusted for comparison.

THZ ELECTRIC FIELD DIRECTION

The PCA was also studied for an application for measurement of THz electric field direction. Schematic diagram and results of the measurement were shown in Fig. 3. The beam trajectory of CTR was changed by a bending magnet in the upstream of the CTR generation as shown in Fig. 3 (a). In the preceding section, beam alignment of the middle beam trajectory (red dashed arrow) was used. However, in this section, beam trajectories for the CTR generation were changed to the top and bottom trajectories (blue and green arrows), which were far a few mms from the case in the preceding section. As a result, detected polarity of THz waveform changed according to the beam trajectories as shown in Fig. 3 (b). A negative shoot was observed in the early time using the top beam trajectory (green). On the contrary, a positive shoot was observed in the early time using the bottom beam trajectory (blue). Previously some researchers reported measurement of radially polarized THz waves from a PCA and dependence of THz waveform (electric field direction) on detecting positions [25]. In this study, the detected electric field is from CTR, but the polarity change would be caused from radial polarization characteristics and the geometry of CTR and the PCA. In the future, detailed analysis will be conducted.

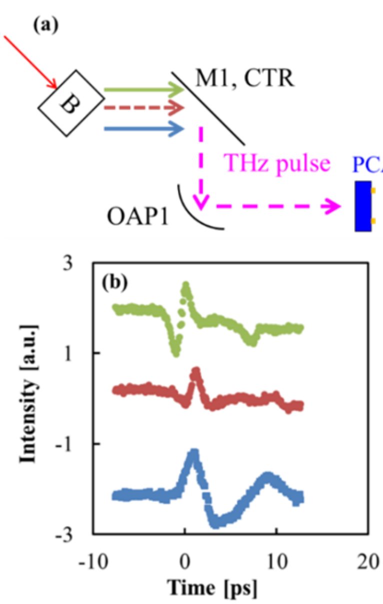

Figure 3: (a) Schematic diagram of the measurement of THz electric field direction. In the preceding section, the middle beam trajectory (red dashed line) was used. (b) Detected THz electric field from PCA in the cases of the top (green) and bottom (blue) beam trajectory. The trajectory and electric field with the same colour correspond to the trajectory condition and result, respectively.

CONCLUSION

Measurement of CTR from a femtosecond electron beam was conducted based on frequency and time-domain schemes. The system was composed of a Michelson interferometer and PCA. Calculated bunch lengths were obtained as 94 and 430 fs in rms for the cases of interferometer and PCA, respectively. The detectable ranges of the interferometer and PCA were estimated as <2 and <1 THz, respectively. Instabilities in the case of the PCA were observed, however the frequency and time -domain measurements were conducted by the interferometer and PCA. And the scheme using the PCA would indicate a possibility of detecting electric field detection of CTR.

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