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Quasi-monochromatic THz pulse generation using Cherenkov radiation from a spatially modulated electron beam

Y. Tadenuma,[a,1] T. Murakami,[a] M. Brameld,[a] M. Washio,[a] K. Sakaue,[a,b] R. Kuroda[c] and Y. Taira[c]

[a]*Research Institute for Science and Engineering, Waseda University, 17 Kikuicho, Shinjuku-ku, Tokyo 162-0044, Japan*
[b]*Photon Science Center, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[c]*National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan*

E-mail: yt4869@ruri.waseda.jp

Abstract: Cherenkov radiation forms a wave front in a direction that depends on the density of the medium and the velocity of charged particles; therefore, ordinary electron bunches do not generate coherent radiation unless they are sufficiently compressed. In this work, we present the generation of a quasi-monochromatic THz pulse using an electron bunch with a periodic structure generated from a small rf gun. A coherent THz pulse was generated by matching the tilt angle of the electron bunch and Cherenkov radiation angle with a rf deflector. Furthermore, we attempted to render the THz pulse quasi-monochromatic by adding a periodic structure to the electron bunch using a multi-slit. Finally, using several band-pass filters, we successfully confirmed that the quasi-monochromatic operation was performed at frequencies of 0.2 and 0.3 THz.

Keywords: Accelerator Applications; Beam Optics; Beam dynamics

[1]Corresponding author.

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Contents

1 Introduction

Terahertz (THz) light is located between radio and light waves and comprises electromagnetic waves in the frequency range of 0.1–10 THz. Frequency in the THz band correspond to vibrations of intermolecular, and exhibit characteristic absorption in various substances. An extensive number of applications such as the detection of explosives, medical diagnoses, biology, and semiconductor carrier dynamics are being studied using these characteristics [1–5]. THz light sources are primarily divided into laser- and accelerator-based sources, each of which has advantages and disadvantages. Laser-based THz light sources use nonlinear optical effects in high-intensity femtosecond lasers, which are developed as compact table-top light sources suitable for time-domain spectroscopy because of their wide bandwidth and elevated time resolution [6–8]. THz light sources, using large accelerators, are superior in monochromaticity and peak electric field. Furthermore, they are often used as pump lights for exciting a specific frequency [9–11].

Our pervious study demonstrated the generation of high-intensity THz pulses by a coherent Cherenkov radiation with a tilted electron beam using a small rf electron gun and an rf deflector. Cherenkov radiation forms a conical wave front at an angle that depends on the refractive index of the medium and the velocity of charged particles. For an electron bunch without tilt, the wave front formed by former electrons and the wave front formed by latter electrons of the electron bunch do not overlap. However, as shown in figure 1, by matching the tilt angle of the electron beam with the Cherenkov radiation angle, the radiation from each electron contained in the electron bunch proceeds during overlap such that phase matching is automatically achieved. Using this method, we already succeeded in significantly increasing THz pulse intensity by increasing the number of electrons contributing to coherent radiation [12]. Furthermore, we measured the waveform in the time domain using an electro-optic (EO) sampling method and confirmed broadband radiation of ~0.1–2.0 THz using Fourier transformation.

As an applied research, we succeeded in effecting imaging with both the transmitted and reflected light of a THz pulse. However, using a THz pulse as a pump source requires the pulse to have high monochromaticity. Therefore, we conducted additional experiments to generate a quasi-monochromatic THz pulse by giving a periodic structure to an electron beam using a multi-slit. In this study, we report the results of the quasi-monochromatic THz pulse generation experiment and discuss future prospects of the approach.

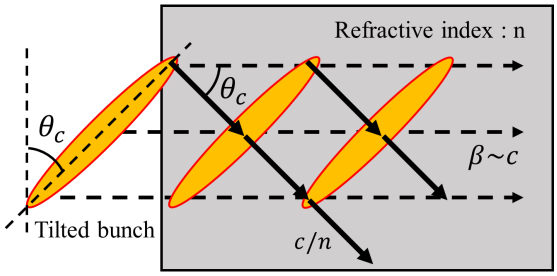

Figure 1. Phase matching by a tilted electron beam.

2 Quasi-monochromatic THz pulse generation by multi-slit

A radiation pulse, generated from a macropulse formed by multiple micropulses, becomes a monochromatic pulse with an enhanced wavelength depending on the interval between micropulses. Such a radiation pulse has already been practically implemented in, for example, free electron lasers [13]. In this study, variable wavelength and quasi-monochromatic THz pulses were generated by adjusting the interval between micropulses. In our previous study, in the spectrum obtained using the EO sampling method, the intensity was highest at 0.1–0.5 THz; therefore, 0.2 and 0.3 THz were selected for proof of the quasi-monochromatization principle, while multi-slits were designed for use with these frequencies. These multi-slits were composed of stainless steel (SUS304) having a thickness of 2 mm, which was able to almost completely shield the 5-MeV electron beam. Furthermore, for the slit portion through which the electron beam passed, the hole section was rendered constant at 0.5 mm, and the interval between them was set to a length corresponding to wavelengths of 0.2 and 0.3 THz. Table 1 shows the multi-slit parameters; moreover, as shown in figure 2, the slits each had a side length of x: 20 mm and y: 15 mm, which was sufficient for the entire electron beam to pass through.

Table 1. Multi-slit parameters.

	Slit A (0.2 THz)	Slit B (0.3 THz)
Thickness (mm)	2.0	2.0
Slit width (mm)	0.5	0.5
Period (mm)	1.3	0.8

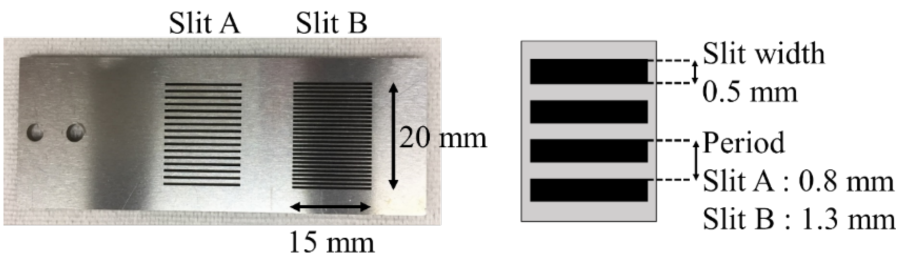

Figure 2. Photograph and schematic design of multi-slit. Slit A corresponds to 0.2 THz and slit B corresponds to 0.3 THz.

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3 Experimental setup

Figure 3 shows the beamline layout and the transport path for THz light used for the experiment. The electron beam used in the experiment was generated by a 1.6 cell Cs-Te photocathode rf gun having a resonant frequency of 2856 MHz. A picosecond pulse laser of 1047 nm, generated by an Yb fiber laser was converted to 262 nm by passing two beta barium borate (BBO) crystals, and irradiated to Cs-Te. Electron bunches generated from Cs-Te by the photoelectric effect were accelerated to ~5 MeV and weakly focused using a solenoid magnet. The periodic structure was shaped by the multi-slit then the electron bunch was tilted by the rf deflector. The tilted angle in the x direction was determined by the magnetic force in the rf deflector such that the tilt angle of the electron bunch was appropriate at the target position. The generated THz pulse was extracted from the z-cut quartz window into the atmosphere, and using two THz lenses, transported to the detector by ~30 cm. We used a quasi-optical detector (QOD) as a THz detector, which is a Schottky diode combined with a Si lens.

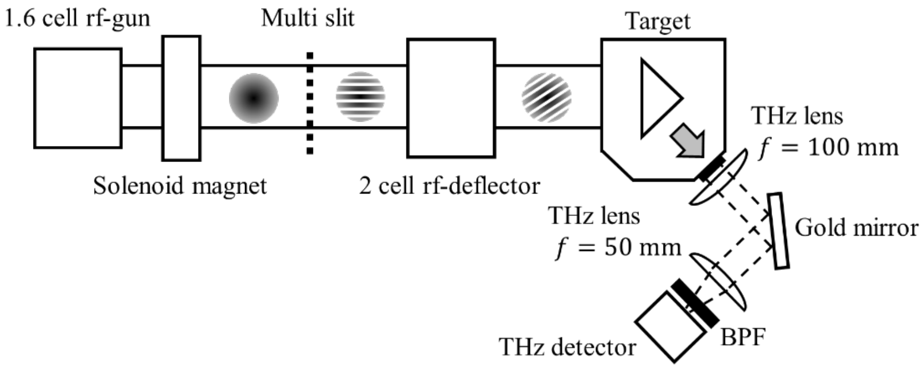

Figure 3. Beamline layout.

The repetition rate of the rf gun was 5 Hz, and the experiment was conducted using a bunch length of 1.5 ps and a charge amount of 100 pC, after passing through the multi-slit. The tilt angle of the electron beam was controlled by adjusting the amplitude and phase of the rf, applied to the rf deflector by an attenuator and phase shifter, respectively. A cyclic olefin copolymer (TOPAS) medium was applied as a target. Because both the refractive index change and absorption were minimal within the THz band, broadband THz radiation was possible [14]. To efficiently extract the generated THz pulse, the target shape was designed such that the angle formed by the electron bunch at the entrance surface of the TOPAS, and the THz pulse radiation surface matched the Cherenkov radiation angle. Moreover, the intensity of each frequency (quasi-monochromaticity of the THz pulse) was measured using three types of band pass filters (BPFs): 0.2, 0.3, and 0.5 THz.

4 Results

First, the generated comb-shaped electron bunch was analyzed using an alumina fluorescent plate and charge-coupled device (CCD) camera. Because the target and the alumina fluorescent plate could be moved up and down at the same position using a linear feedthrough, the irradiated electron bunch shape was observed at the target position. Figure 4(a) shows the beam profile when the current

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of the solenoid electromagnet was 100 A, and figure 4(b) shows the result of multi-Gaussian fitting to the projection. The peak position of each Gaussian fitting was analyzed, and the corresponding frequency was calculated at observed intervals. Moreover, we confirmed that the beam size of the entire electron bunch at the target position decreased as the focusing force of the solenoid magnet increased, and the intervals between the microbunches changed. Figure 5 shows the result of plotting the corresponding frequency, calculated from the intervals of microelectron bunches, for each slit against the change of solenoid magnet current. Both slit A and slit B matched the design frequency in the vicinity of the solenoid current between 100 and 120 A. The beam size of the microbunch at the target position was ~350 μm (rms).

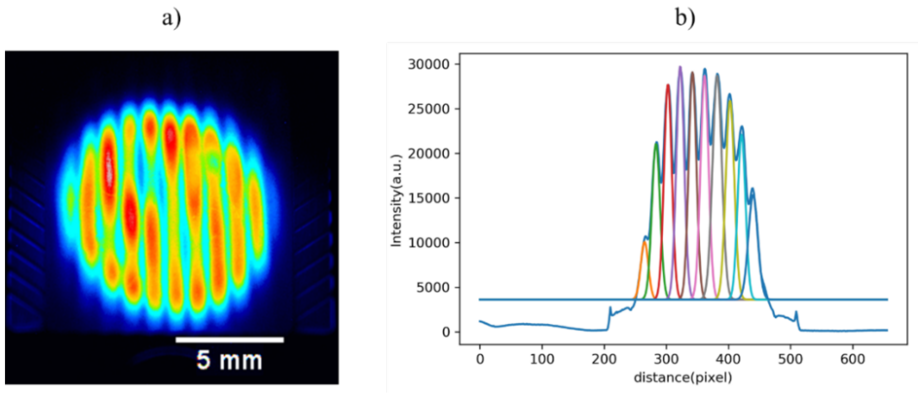

Figure 4. a) The electron beam profile; b) the result of multi-Gaussian fitting when the solenoid magnet current was 100 A.

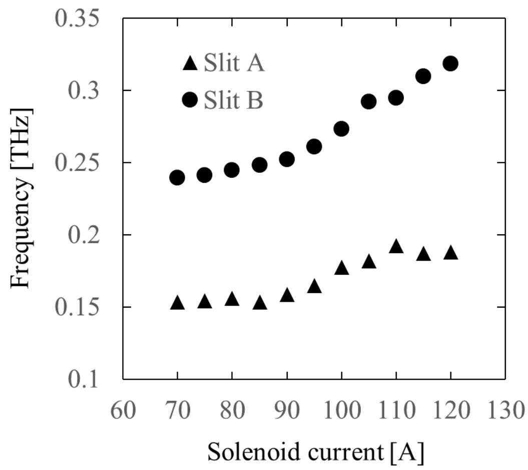

Figure 5. Relation between solenoid current and corresponding frequency. The triangular plot is slit A, and the round plot is slit B.

Next, tilt-angle dependency was measured. Solenoid current was set to 120 A and quasi-monochromaticity measurement was simultaneously performed using three types of BPF. Figure 6 shows the change in THz intensity when the tilt of the electron bunch changed using each slit. In slit A, 0.2 THz was confirmed as the maximum range close to the Cherenkov radiation angle $\theta_c = 48.9°$. In slit B, the designed value of 0.3 THz was similarly maximized near θ_c. For both

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slits, the intensity change with respect to the tilt angle change was minimal at frequencies other than the designed values. As anticipated, quasi-monochromatic THz pulse generation using the multi-slit was successfully measured.

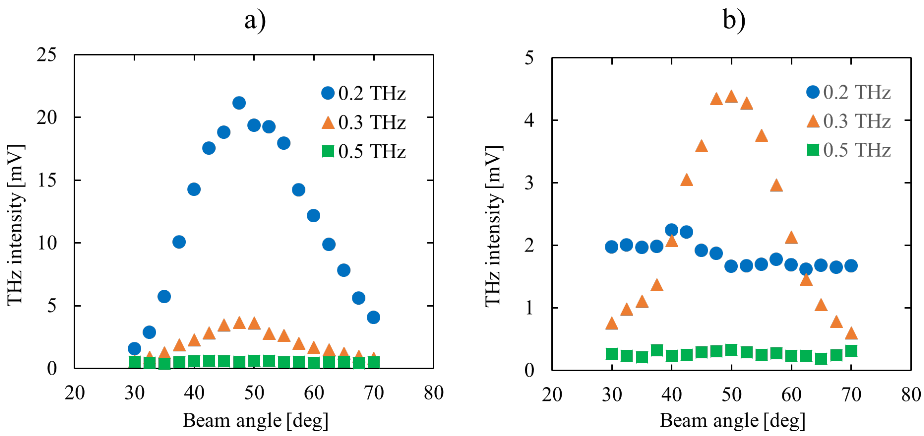

Figure 6. Relationship between beam angle and THz intensity when using BPFs of 0.2, 0.3, and 0.5 THz: a) slit A (0.2 THz); b) slit B (0.3 THz).

Finally, figure 7 shows the result of measuring the THz light intensity when the charge amount of the entire bunch was 40 and 140 pC, after passing through the multi-slit (using each slit). In the measurement, the tilt angle was $\boldsymbol{\theta_c}$, and the solenoid current was 105 A. In slit A, tilt control considerably increased the THz intensity to 0.2 THz. Similarly, in slit B, an increase in THz intensity to 0.3 THz was confirmed. For both slits, the increase in intensity because of tilt was considerable compared with that observed when the charge amount was high; the reason for this was attributed to an increase in the number of electrons contributing to coherent radiation by the periodic structure.

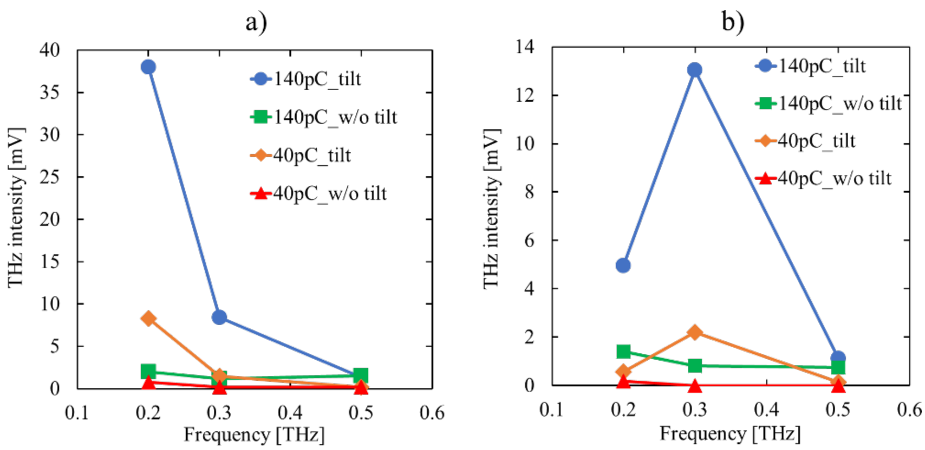

Figure 7. Charge dependence of THz intensity: a) slit A (0.2 THz); b) slit B (0.3 THz).

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5 Conclusion

In this study, further improvements to the THz pulse light source were suggested using coherent Cherenkov radiation. By controlling the tilt of an electron beam, we proposed the quasi-monochromatic method adding a periodic structure to the electron beam. By observing the spatially modulated electron bunches with an alumina fluorescent plate, the anticipated enhanced frequency was analyzed. We confirmed that the electron bunches had been divided at the designed intervals. Moreover, the THz pulse, generated using two types of slits, was measured using quasi-monochromatic transmission via BPFs. Even when a multi-slit was used, radiation intensity was maximized at the tilt angle, which coincided with Cherenkov radiation angle, as in the case of the conventionally focused electron beam without tilt. The resulting quasi-monochromatic THz pulses successfully confirmed center frequencies of 0.2 THz (slit A) and 0.3 THz (slit B). In future, to confirm the spectrum of the generated THz pulse, the time domain waveform will be acquired using the EO sampling method. Furthermore, we aim to apply high-intensity monochromatic THz pulses in applications such as the modification of polymer materials.

Acknowledgments

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