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DEVELOPMENT OF AN EO SAMPLING SYSTEM FOR THE ANALYSIS OF THz WAVES GENERATED BY COHERENT CHERENKOV RADIATION

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Abstract

THz wave, which is located between microwaves and light waves, have permeability, rectilinearly, and fingerprint spectrum of specific materials. Therefore, they are expected to be useful for various applications. We have been studying THz waves generation via Cherenkov radiation with electron beams from a photocathode rf-gun. In our early studies, we have succeeded in the generation of coherent Cherenkov radiation by tilted electron beams using an rf-deflector. Furthermore, we have generated quasi-monochromatic THz waves by spatially modulated electron beams and have succeeded in its measurement by bandpass filters. This study aims to obtain the THz wave form in time domain by electro-optic (EO) sampling, which is an useful detection system for obtaining the information of the electric field and the phase simultaneously with high S/N. In this conference, we report about our probe laser system, results of the time-domain spectroscopy measurement of THz waves by EO sampling, and future prospects.

INTRODUCTION

Terahertz (THz) wave, which is located between microwaves and light waves, have permeability, rectilinearity and excitation energy of intermolecular vibration such as a polymer chain. Therefore, they are expected to be used in applied researches, including transmission imaging technology [1] and property modification of polymers [2]. Intense monochromatic THz light sources are required to realize these applied studies. Those that satisfy these requirements are currently achieved only at large facilities.

Considering the current situation, we have been aiming to develop a compact monochromatic THz light source with high intensity. To achieve this goal, we are conducting experiments to generate the quasi-monochromatic THz pulse by spatial modulation of the tilted electron beam using a slit. The tendency of quasi-monochromatic THz pulse was confirmed by bandpass filters. For more rigorous evaluation of the quasi-monochromatic THz pulse, we are trying to obtain its waveform in time domain and its spectrum by electro-optic (EO) sampling measurement. In this study, we constructed a probe laser system for EO sampling, and conducted experiments to obtain the waveform of the quasi-monochromatic THz pulse in time domain.

THz PULSE GENERATION

Cherenkov Radiation

Cherenkov radiation occurs when an electron travels faster than the phase velocity of light in a medium. The principle diagram of Cherenkov radiation is shown in Fig. 1. The requirements for the generation of Cherenkov radiation is expressed as follows:

$$\beta > \frac{1}{n}, \tag{1}$$

where $\beta (= v/c)$ is the relative velocity of an electron to the phase velocity of light and n is the refractive index of a medium. The direction of Cherenkov radiation depends on the velocity of the electron and the refractive index of the medium. This direction is expressed as follows and is called the Cherenkov angle [3],

$$\theta_c = \cos^{-1}\left(\frac{1}{n\beta}\right). \tag{2}$$

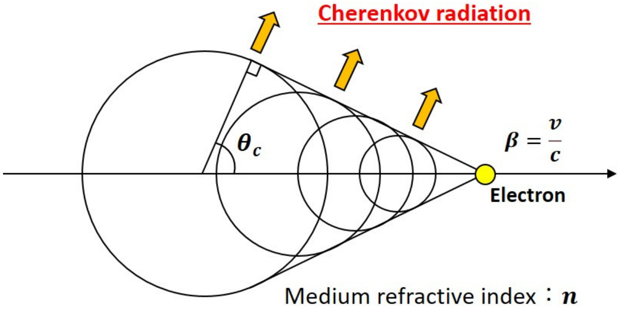

Figure 1: The principle diagram of Cherenkov radiation.

Coherent Radiation

As shown in Fig. 2, coherent radiation is obtained when the phase of each radiation match. On the other hand, incoherent radiation is when they do not overlap. The radiation intensity $P(\lambda)$ of an electron bunch is given by the following equation:

$$P(\lambda) = P_0(\lambda)N\{1 + (N-1)f(\lambda)\}, \tag{3}$$

where $P_0(\lambda)$ is the radiation intensity from an electron, N is the number of electrons in an electron bunch, and $f(\lambda)$ is form factor ($0 \le f(\lambda) \le 1$) [4]. For fully coherent $f(\lambda) = 1$ and fully incoherent $f(\lambda) = 0$, Eq. (3) can be rewritten as:

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$$P(\lambda) = \begin{array}{l} NP_0(\lambda)\ (incoherent\ limit), \\ N^2P_0(\lambda)\ (coherent\ limit). \end{array} \qquad (4)$$

The radiation intensity can be greatly increased by coherent radiation because N is approximately 10^{10} in our experiment.

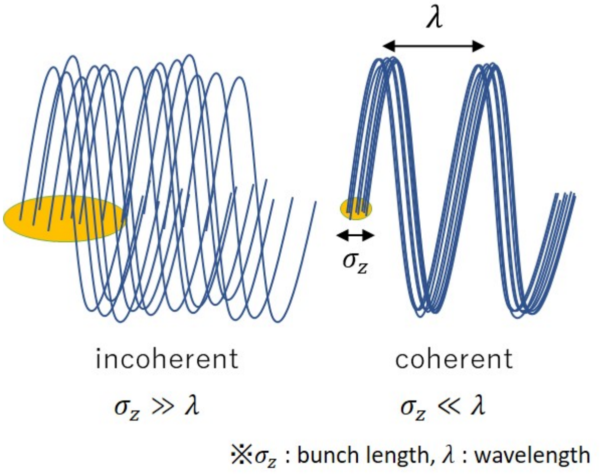

Figure 2: The schematic diagram of coherent radiation and incoherent radiation.

THz PULSE GENERATION BY COHERENT CHERENKOV RADIATION

We have generated the THz pulse by coherent Cherenkov radiation. The schematic diagram of our THz pulse generation method is shown as Fig. 3. When the electron beam is tilted at the Cherenkov angle and injected into the medium, the radiation from the first electron and that from the following electron overlap, so that coherent Cherenkov radiation can be generated. The spectrum of the electromagnetic waves generated in this method depends on the beam size in the cross-sectional direction. Since our beam size is approximately 1 mm, broadband THz pulse across 0.1 to 0.3 THz can be generated by coherent Cherenkov radiation.

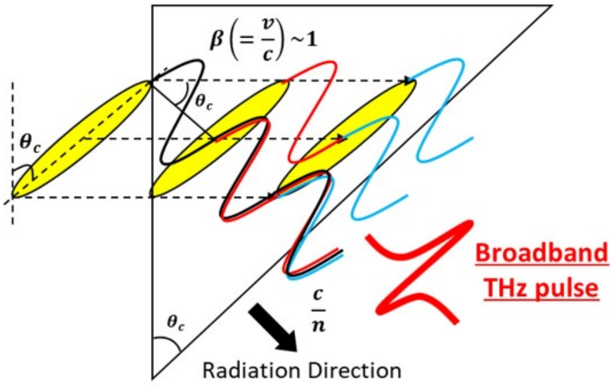

Figure 3: The principle of THz pulse generation by coherent Cherenkov radiation.

QUASI-MONOCHROMATIC THz PULSE

As shown in Fig. 4, the spatial structure of the electron beam in the x direction can be controlled using a slit before tilting the electron beam. Because this technique can convert the spatial structure of the electron beam into the time structure of the THz pulse, quasi-monochromatic THz pulse is generated with the specific frequency corresponding to the slit period.

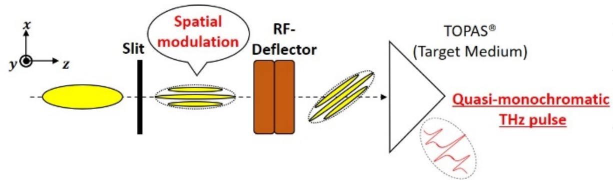

Figure 4: Quasi-monochromatic THz pulse.

EO SAMPLING

EO sampling is an effective detection method which can obtain simultaneously the electric field and the phase of a THz pulse with high S/N [5]. The principle diagram of EO sampling is shown as Fig. 5. The THz pulse induces birefringence that depends on its electric field strength in the EO crystal. At the same time, by irradiating the probe laser, THz electric field information can be induced in its polarization change. The waveform of the THz pulse in time domain can be reproduced by scanning the timing of the probe laser.

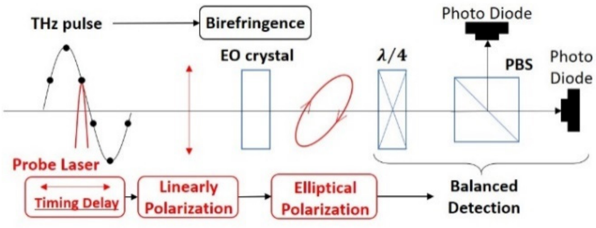

Figure 5: The principle diagram of EO sampling.

EXPERIMENTAL SETUP

Beamline Layout

The beamline is shown in Fig. 6. Electron bunches are generated by irradiating the 262 nm pulse laser to the Cs-Te photocathode. The 1.6 cell rf-gun excited at a resonance frequency of 2856 MHz accelerates the electron beam to 4.8 MeV. The electron beam is spatially modulated using the slit and tilted to the Cherenkov angle using an rf-deflector. The tilted and spatially modulated electron beam is injected into the target medium, and quasi-monochromatic THz pulse is generated. The target medium is TOPAS, which has low absorption and a constant refractive index across the THz band [6].

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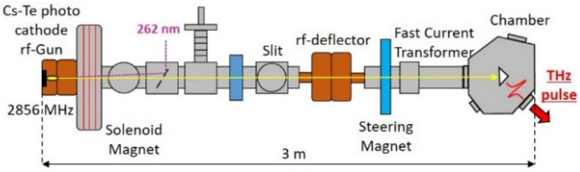

Figure 6: The beamline layout of this experiment.

EO Sampling Measurement

The experimental setup for EO sampling is shown in Fig. 7. The timing of the probe laser is scanned at a step of 100 fs using the delay stage. The pellicle beam splitter can realize the collinear incidence with the quasi-monochromatic THz pulse and the probe laser against the EO crystal. The EO crystal is <110> oriented Zinc telluride. The probe laser is split by polarization beam splitter into s- and p-polarization, and each component is detected by two photo diodes.

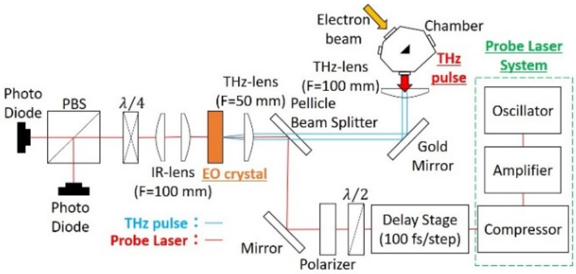

Figure 7: The EO sampling setup of this experiment.

RESULTS AND DISCUSSIONS

Probe Laser System

The probe laser system consists of three parts: the oscillator, the amplifier, and the compressor. The parameters are shown in Table 1. The oscillator is a mode-locked Yb-doped fiber laser with nonlinear polarization rotation, the pulse energy is amplified about 3 times by the amplifier. Furthermore, we compressed the pulse duration of the probe laser by the compressor using a transmission grating pair to compensate its dispersion. The time resolution of EO sampling measurement depends on the pulse duration of the probe laser. Considering the wavelength of the expected THz pulse is to be a few mm, the required pulse duration is sub-ps. The repetition frequency was adjusted to the 18 th harmonic of the resonance frequency of 2856 MHz.

Table 1: The Parameters of the Probe Laser System

Center Wavelength	1030.4 nm
Repetition frequency	39.66 MHz
Pulse energy	3.73 nJ
Pulse duration (FWHM)	180 fs

EO Sampling Measurement

The waveform of quasi-monochromatic THz pulse in time domain could not be obtained by this experiment. Two causes can be considered. The first is the intensity of the quasi-monochromatic THz pulse. It might be too weak. We are planning to amplify the intensity of the pulse by developing an optical enhancement cavity. The second is the timing synchronization between the quasi-monochromatic THz pulse and the probe laser. Since the pulse duration of the probe laser is 180 fs, the required accuracy of the timing synchronization is sub-ps, but it was 1 ps in this measurement.

CONCLUSIONS

We have constructed the probe laser system for EO sampling and tried to obtain the waveform of the quasi-monochromatic THz pulse in time domain. The probe laser consists of the oscillator, the amplifier, and the compressor. We have succeeded in the pulse duration of 180 fs. We could not obtain the waveform of the quasi-monochromatic THz pulse by EO sampling. The causes may its intensity and the accuracy of the timing synchronization.

In near future, we are going to amplify the THz pulse intensity using an optical enhancement cavity and optimize the timing synchronization system. After that, we are planning to try again to obtain the waveform.

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