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DESIGN OF AN OPTICAL CAVITY FOR GENERATING INTENSE THz PULSES BASED ON COHERENT CHERENKOV RADIATION

P. Wang†, Y. Tadenuma, T. Murakami, K. Murakoshi, Y. Koshiba, M. Washio
Waseda University Research Institute for Science and Engineering, Tokyo, Japan
K. Sakaue, Photon Science Center, The University of Tokyo, Tokyo, Japan
R. Kuroda, National Institute of Advanced Industrial Science and Technology, Chiba, Japan

Abstract

We have been studying terahertz (THz) generation via Cherenkov radiation with high quality electron beams from a photocathode rf (radio frequency) gun. In our early studies, we have succeeded in the generation of coherent Cherenkov radiation by controlling the tilt of the electron beam using an rf-deflector. For further enhancement, we are planning to stack the THz pulses in an optical cavity. Multi-bunch operation of the rf-gun will generate electron beams with a repetition rate of 119 MHz, and THz pulses as well. These pulses will be accumulated in the cavity up to 150 pulses. In this conference, we report the design study of the enhancement cavity and discuss the performance of the THz source.

INTRODUCTION

Terahertz wave is an electromagnetic wave with a frequency range from 0.1 to 10 THz [1]. It has both the penetration property like radio waves and the rectilinear propagation property like light waves. With the lower energy than X-rays, it is generally considered biologically harmless. Since it can penetrate opaque materials, it is used in various fields, including medicine, security inspection, and short-range communication [2]. However, THz sources are not yet matured since the terahertz spectrum is at the gap of conventional technologies. Aiming for a high-power source, accelerator-based THz sources have been developing [3]. Optical resonant cavities have been developed and used in a wide area of optical science applications. One attractive use of a resonant cavity is its ability to achieve high power by coherently stacking laser pulses in the cavity [4].

Our previous study demonstrated the generation of THz pulses by a coherent Cherenkov radiation with a tilted electron beam utilizing an rf-gun and an rf-deflector [5].

In this study, we have designed an optical cavity for further enhancement of the coherent Cherenkov radiation, including the optimum design of the chamber, mirrors, and the target medium. We are also conducting research on the development of an EO sampling system for the analysis of THz waves generated by coherent Cherenkov radiation [6].

PRINCIPLE

Cherenkov radiation is the electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. The ratio of the electron velocity to the light velocity in vacuum is defined as the Lorentz factor β. Using the refractive index n of the medium and the Lorentz factor β of the electron, the Cherenkov radiation angle can be expressed by the following equation:

$$\cos\theta_{ch} = 1/n\beta. \tag{1}$$

Coherence is very important for the enhancement of the Cherenkov radiation intensity. An electron bunch contains a large number of electrons. When the bunch length is smaller than the wavelength of the radiation, radiations emitted from each electron overlap and interfere with each other. The radiation intensity satisfies the following equation:

$$P_{all}(\lambda) = N_e P(\lambda) + N_e(N_e - 1)\mathcal{F}(\lambda)P(\lambda), \tag{2}$$

where N_e is the number of electrons, $P(\lambda)$ is the intensity from an electron, and the form factor $\mathcal{F}(\lambda)$ shows the electron distribution with a consideration of the radiation wavelength. When the form factor is equal to 1, the radiation is coherent, and the intensity is proportional to the square of the number of electrons.

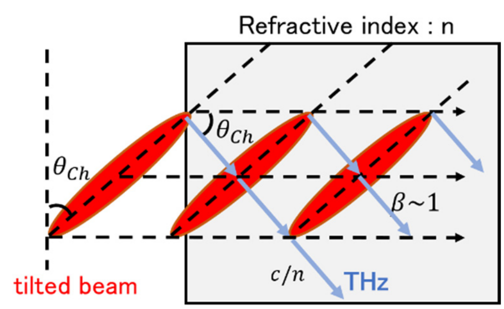

Figure 1: Phase matching coherent Cherenkov radiation.

As shown in Fig. 1, since the phase velocity of Cherenkov radiation in medium, which depends on the refractive index, is slower than the velocity of electron beam, radiation from each electron overlaps as the electron bunch traverse inside the medium by controlling the tilt of electron beam to match the Cherenkov radiation angle. This scheme is named as the phase matching coherent Cherenkov radiation. In addition, the bunch length of tilted electron beam in radiation direction is shorter than the electron beam without tilt.

We chose TOPAS as the target medium for its low absorption and constant refractive index at the THz range, shown in Table 1. In this study even if the energy of the electron beam drops from 5 MeV to 3 MeV, the Cherenkov radiation angle of TOPAS is almost constant to 48.9 degrees.

† chjilm@fuji.waseda.jp

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In our previous studies, the radiation intensity from the tilted electron beam was proportional to the square of the number of electrons, shown in Fig. 2. The maximum is obtained when the tilt angle is controlled to match to 48.9 degrees, the same as the Cherenkov radiation angle, shown in Fig. 3. Broadband radiation in the THz band has been emitted using the TOPAS.

Table 1: Parameters of the Experiment

TOPAS Parameter	
Refractive index	1.53
Density	1.02 g/cm^3
Reflectivity	4.39%
ChR angle	48.9 deg
Critical angle	40.8 deg
Brewster angle	56.8 deg
Beam Parameter	
Beam size (RMS)	1.0 mm
Bunch length (RMS)	3.0 ps
Repetition rate	119 MHz
Beam energy	5.0 MeV
Cavity Parameter	
Cavity length	126 mm
Radius of curvature of mirror	126 mm
Diameter of mirror	50 mm
Material of mirror	Au-coated mirror

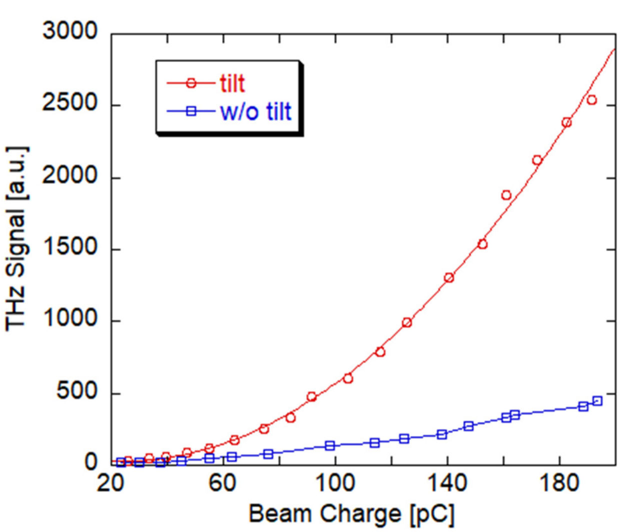

Figure 2: THz signal. The red line is the THz intensity of electron beam with tilt. The blue line is the THz signal of electron beam without tilt. THz signal of titled electron beam is proportional to the square of the number of electrons obviously.

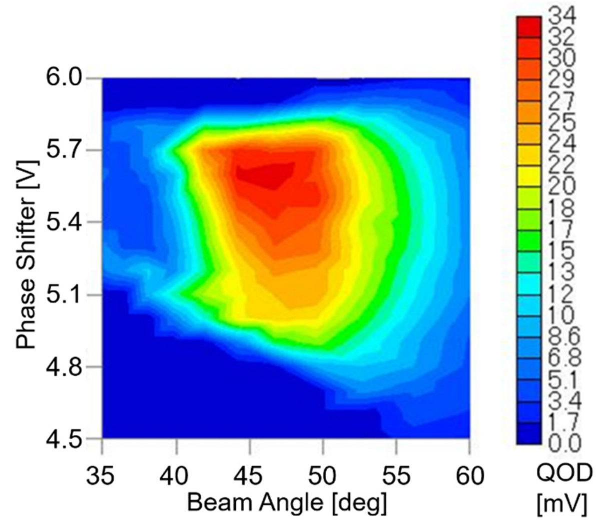

Figure 3: Radiation intensity measured by QOD with 0.5 THz band pass filter.

EXPERIMENTAL SETUP

The experiment setup is shown in Fig. 4. The IR laser generated by the Yb fiber laser system, is converted into UV by BBO crystals. Electron beam is generated by irradiating UV laser onto a Cs-Te (cesium telluride) photocathode, which can be accelerated up to 5 MeV with a 1.6-cell rf-gun. The electron beam is then optimized to best focus on the target by solenoid magnet and quadrupole magnets. The tilt of the electron beam is controlled by an rf-deflector to match the Cherenkov radiation angle at TOPAS, and then coherent Cherenkov radiation can be obtained.

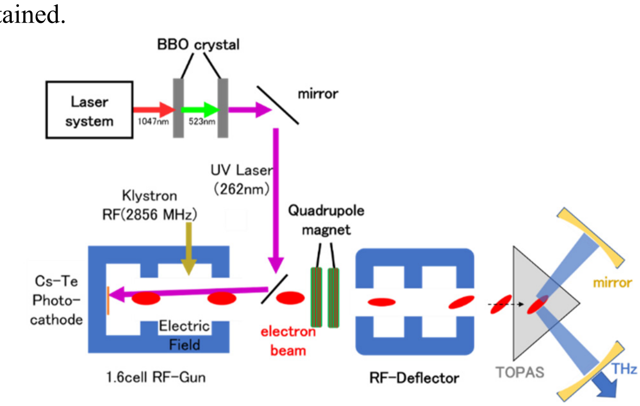

Figure 4: Experimental setup.

In order to amplify the intensity of the THz pulse, we are planning to stack in an optical cavity. In the optical cavity, the coherent Cherenkov radiations emitted from TOPAS using the multi-bunch electron beam are reflected by two mirrors and accumulated.

RESULT

The amplified electric field E_n in cavity in this study can be calculated by the following equation [7]:

$$E_n = E_0 + E_0\sqrt{1-L} + E_0\left(\sqrt{1-L}\right)^2 + \cdots \quad (3)$$

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$$= \sum_{k=0}^{n} E_0 \left(\sqrt{1-L}\right)^k , \quad (4)$$

where E_0 is the electric field of incident radiation, and L is the total loss of the cavity within one loop. The extracted power I_n can be calculated by the following equation:

$$I_n = T|E_n|^2 , \quad (5)$$

where the T is the transmittance of the output coupler.

In the cavity, losses are assumed as follows; the reflectance of the mirrors is 99%, the absorption coefficient of TOPAS is 0.0019 /cm [8], and the Fresnel reflection on the plane of TOPAS is 4 %. The total loss in cavity is about 17%, including two reflections by mirrors, absorption about 1 mm in TOPAS, and four times Fresnel reflections. The total loss of one loop is 31% when the transmittance of the output coupler is 17%. With 150 electron bunches, the intensity is expected to be amplified by 5.86 times as shown in Fig. 5.

To reduce the total loss especially on the plane of TOPAS, we have considered the incidence at Brewster's angle. Phase-matched THz pulse is almost perfectly linearly polarized, so at Brewster's angle of incidence, the Fresnel reflection is expected to be zero. With the incidence at Brewster's angle, the total loss is reduced to 4.7% when the optimized transmittance of the mirror is 2.4%. With 150 electron bunches, the intensity is expected to be amplified by 40 times as shown in Fig. 5.

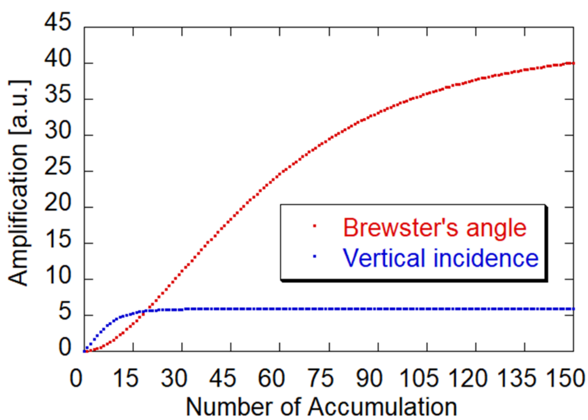

Figure 5: Calculation result of amplification. The red line is the incidence with Brewster's angle and the blue line is the vertical incidence.

The design of chamber and mirrors are shown in Fig. 6. The chamber to set TOPAS is designed to accept both the vertical incidence and the incidence of Brewster's angle. Windows are designed to be at the opposite of chamber for the alignment of each mirror. Since the Cherenkov radiation angle is larger than the critical angle, the THz pulse is totally reflected at the incident plane of the beam on TOPAS. Cavity length is designed to be 126 mm considering the electron bunch repetition interval of 8.4 ns. The radius of curvature of the mirrors is designed to 126 mm for a confocal cavity. The diameter of mirrors is designed to 50 mm for the beam spot size. Au-coated mirror will be used. These design values are shown in Table 1.

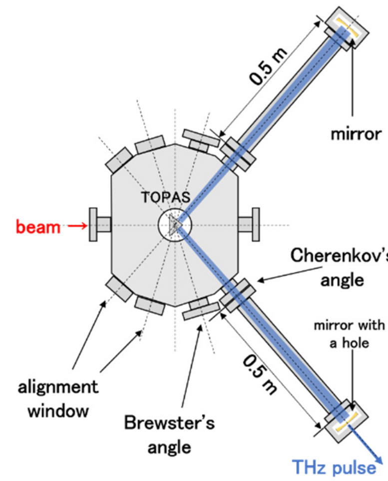

Figure 6: The design of optical cavity.

CONCLUSION

With an rf-gun and an rf-deflector, we have succeeded in the generation of THz pulse by Coherent Cherenkov Radiation [6]. In this study, we have designed an optical cavity for further enhancement of the coherent Cherenkov THz radiation. The enhancement factor is expected to be 5.9 with simple configuration of vertical incidence and can be enlarged to 40 by utilizing Brewster's angle.

We are planning to conduct the experiment within this year after the chamber and mirrors are prepared.

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