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EVALUATION OF COHERENT TERAHERTZ RADIATION GENERATED FROM TILTED ELECTRON BEAMS AIMING FOR HIGHER LIGHT INTENSITY

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Abstract

When a target medium is irradiated by electron beams travelling at relativistic speed, terahertz(THz) radiation is produced by Cherenkov radiation. THz radiation is released at an angle to the direction of travel of the electron beams, and the coherence of the radiation can be improved by tilting the electron beams to match this angle, resulting in higher light intensity. The Cherenkov angle differs according to the refraction index of the target medium. At Waseda University, the generation of high-quality electron beams by a Cs-Te Photocathode RF-gun and its applications are being researched. By utilizing the RF-Deflector, the tilt angle of the electron beam can be controlled to achieve coherent THz radiation. To gain higher light intensity, the use of Silicon and Aerogel as a target medium was challenged and compared to the conventional medium TOPAS. The THz radiation produced from the three target mediums were analysed by use of the power meter and time domain spectroscopy(TDS). At the conference, the generation of THz Cherenkov radiation from different target mediums and the measurement results will be reported along with future perspectives.

INTRODUCTION

In recent years, research on THz radiation has been brought to attention. THz radiation is electromagnetic waves that have a frequency range between 0.1THz ~ 10THz. This range lies between infrared radiation and microwave radiation that it shares some properties such as penetration of materials and line-of-sight propagation. Due to the development of THz generation and observation techniques, research about applications have also proceeded. In comparison to X-rays, THz radiation has extremely low energy and has less biological damage to organisms. Also, it is transmitted through plastic and paper, reflected by metals, absorbed by water, and some materials have specific absorption spectrums within the THz range. By using these characteristics, THz application technology is being researched in a variety of fields including industry, medicine, bio-security and telecommunication [1, 2].

At Waseda University, we have succeeded in the generation of high-intensity coherent THz radiation using electron beams generated from a Photocathode RF-gun. As an application, we have also succeeded in THz imaging of several objects including pre-paid money cards and coins [3].

In order to improve the imaging quality and challenge new applications, further research on the properties of generated THz waves and increasing the light-intensity is needed. As a method to increase the light intensity, we introduced silicon as new target medium to replace the former target medium TOPAS [4]. However, due to the high density and short maximum range of silicon, only low intensity THz could be observed. For this research, we have investigated the possibility of using Aerogel as a target medium and compared the properties of generated THz radiation to those from TOPAS by conducting three experiments.

GENERATION OF THZ RADIATION

Cherenkov Radiation

When the velocity of electrons exceeds the speed of light, electromagnetic waves are produced due to Cherenkov radiation. When charged particles travel through dielectric medium, polarization occurs and when it returns to its former state, electromagnetic waves are released. The Schematic of Cherenkov Radiation is shown in Fig.1.

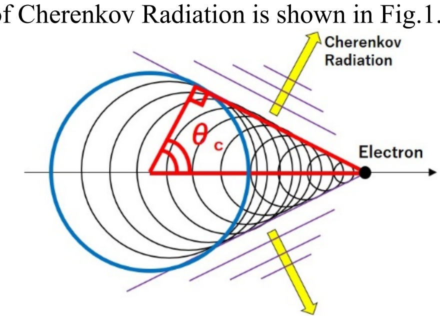

Figure 1: Schematic of Cherenkov radiation.

When the velocity of electrons is v and the refractive index of the medium is n, the condition for Cherenkov radiation can be expressed as the following:

$$v > \frac{c}{n} \tag{1}$$

By using the Lorentz factor $\beta = v/c$, the condition for Cherenkov Radiation can also be expressed as:

$$n\beta > 1 \tag{2}$$

The Cherenkov angle, which is the angle at which the radiation if released relative to the direction the electron travels, is determined by the following:

$$\cos\theta_C = \frac{1}{n\beta} \tag{3}$$

From these equations, it is apparent that the refractive index of the medium is a highly important factor.

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Coherence

In order to increase THz intensity, it is critical to take in account the coherence state. Coherent radiation is produced when the electron bunch length is sufficiently shorter than the radiation wavelength, and light intensity is increased due to phase-matching. Incoherent radiation is produced when the electron bunch length is sufficiently longer than the radiation wavelength, and low light intensity is observed. The overall THz intensity is referred to as the sum of coherent and incoherent radiation produced and is defined as:

$$P_{all} = \begin{cases} NP_R \text{ (incoherent)} \\ N^2 P_R \text{ (coherent)} \end{cases} \quad (4)$$

where P_{all} is the total THz intensity, P_R is the THz intensity per electron, and N is the number of electrons within the electron bunch. [3]

EXPERIMENTAL SETUP

Beamline Layout

THz radiation is generated by Cherenkov radiation when the target medium is irradiated by electron beams. Figure 2 represents the beamline, which is quite compact with a length of about 3 metres. UV laser pulses are aimed at the Cs-Te Photocathode, releasing electrons by the photoelectric effect, which is accelerated by the electric fields within the RF-gun. The solenoid coil modifies the electron beam emittance and beam size. The Q-magnet pair further adjusts the beam size and the steering magnet controls the direction the electron beam travels. The RF-deflector is used to tilt the electron beam, allowing the electron beam to travel at an angle, which is an important factor for producing high intensity coherent THz radiation. Target mediums including TOPAS and Aerogel are placed within the final chamber. Produced THz radiation is observed from the THz window that matches the Cherenkov angle at which the radiation is released. To measure the intensity, a broadband Quasi-Optical Schottky Diode Detector (QOD) is used.

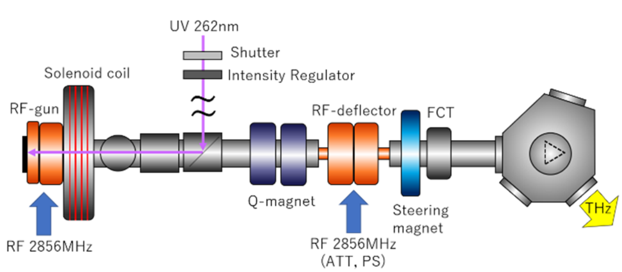

Figure 2: Layout of electron beam line when TOPAS is placed as a target medium.

Target Mediums

TOPAS is a transparent polymer dielectric material and the refractive index is constant within the THz range. It can produce THz radiation over a broad frequency range and is used in previous research. [4]

Aerogel is a solid composed by SiO_2 and contains many cavities. It is also known as "solid gas" for its lightness and has been used as a new target medium.

Table 1 shows the characteristics of the target mediums. TOPAS and Aerogel have been shaped as in Fig. 3 according to the Cherenkov Angle to maximise the light intensity. As in Fig. 4, when the electron beam enters the target medium with no tilt, the length of the electron beam observed from the radiation direction is long thus the light intensity is small due to the incoherence. On the other hand, when the electron beam is tilted to the Cherenkov angle, the length becomes short and maximum light intensity from the coherent radiation can be observed. When the electron is tilted to the inverse angle, the length is the longest thus it is most incoherent and has low intensity.

Table 1: Characteristics of Target Mediums

	TOPAS	Aerogel
Refractive Index	1.52	1.05
Density (g/cm^3)	1.02	0.10
Cherenkov Angle θ_C (deg)	48.9	17.4
Maximum Range (cm)	0.5	5.4
Photon Number / Unit Length (Ratio)	1.0	6.1

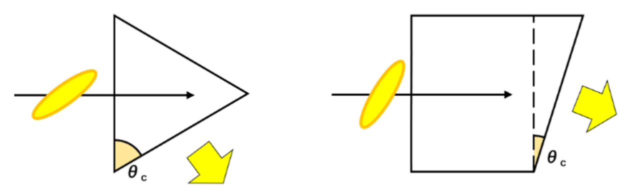

Figure 3: Shape of TOPAS(left) and Aerogel(right).

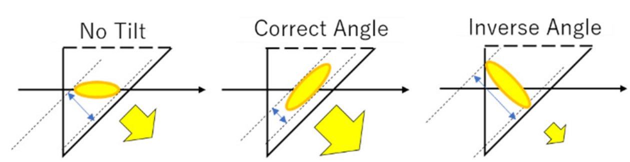

Figure 4: Electron beam tilting relative to medium shape.

RESULTS AND DISCUSSIONS

THz Intensity and Beam Angle Relationship

By controlling the RF intensity and phase of the RF-deflector, the angle of the electron beam can be controlled. By adjusting the voltage of the Attenuator(ATT) and the Phase Shifter(PS), we conducted an ATT vs PS scan. From the results, the relationship between the electron beam angle and the THz radiation intensity can be identified.

Figure 5 represents the results for TOPAS. For this experiment the electron beam charge was 138pC and a 0.3THz BPF was placed in front of the QOD. Maximum THz radiation intensity of 114mV was observed, and this matches to the ATT being around 7.5V. At this voltage, the electron beam is tilted at an angle of approximately 49.5◦, which corresponds to the Cherenkov angle of TOPAS.

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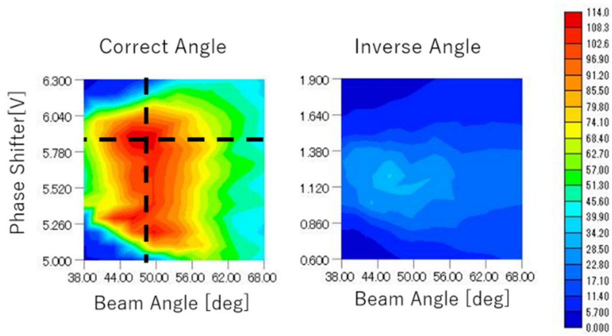

Figure 5: ATT vs PS scan results for TOPAS.

Figure 6 represents the results for Aerogel. The electron beam charge is 138pC and a 0.3THz BPF is used. The maximum THz radiation intensity was 76.5mV, which is lower than TOPAS. When the ATT is around 4.5V, the beam angle is approximately 17.5◦, which corresponds to the Cherenkov angle of Aerogel.

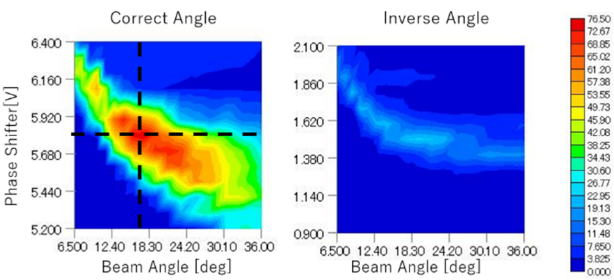

Figure 6: ATT vs PS scan results for Aerogel.

From these results, the match between the beam angle and Cherenkov angle at maximum light intensity was observed, showing that tilting electron beams can increase the intensity.

Coherence Measurements

Electron beams were tilted in the correct angle, inverse angle, and not tilted when hitting the target medium. Fig. 7 shows the change of THz intensity when the electron beam charge is increased. For both TOPAS and Aerogel, a 0.2THz BPF was used and the beams were tilted to match the Cherenkov angle. For both mediums, the relationship between coherence and THz intensity can be observed, where the light intensity increases in proportion to the square of N. However, when the intensity is compared at the same charge, TOPAS has a higher intensity.

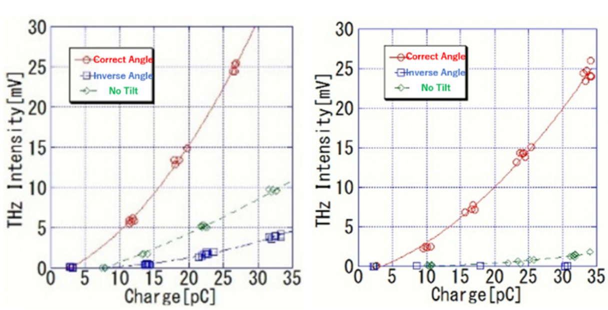

Figure 7: Charge vs THz intensity results for TOPAS (left) and Aerogel (right).

THz Power Measurements

By opening and shutting the UV laser shutter periodically, the power of the THz radiation was measured. Table 2 shows the results for the power measured when using TOPAS. The power was larger when the electron beam was tilted to match the Cherenkov angle. Also when tilted, the power was measurable even when THz BPF were used. The same methods were applied to investigate the THz power when Aerogel is used, however the power was not large enough to reach the measurement limits.

Table2: Power Measured Using TOPAS (Charge 422pC)

THz frequency	Correct Angle[nJ]	No Tilt [nJ]
Total	33.2	4.49
0.3THz	10.6	-
0.6THz	3.98	-

CONCLUSIONS

Two types of target mediums, TOPAS and Aerogel were used and compared to produce THz radiation by Cherenkov radiation. The relationship between THz intensity and the electron beam angle, the intensity depending on coherence state, and the THz power were measured for both mediums. In conclusion, although we also successfully produced THz radiation using Aerogel, higher intensity THz radiation can be obtained by using TOPAS as a target medium. Thus, TOPAS is a more suitable target medium when producing THz radiation using electron beams accelerated by the RF-gun. By utilising these results, we plan on proceeding with the research to obtain even higher THz light intensity, as well as working on methods to analyse the THz radiation produced.

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