STUDY OF CHERENKOV DIFFRACTION RADIATION FROM RADIATOR WITH PERIODIC STRUCTURE IN THz-REGION*

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Abstract

We have been conducting studies on non-invasive bunch length measurement using Smith–Purcell radiation (SPR) and on the application of Cherenkov diffraction radiation (ChDR) when relativistic electrons pass in the vicinity of the dielectric medium at the test accelerator as a coherent terahertz source (t-ACTS) of the Research Center for Accelerator and Radioisotope Science (RARiS), Tohoku University. Although the ChDR spectrum is generally broadband, using a radiator with a periodic structure likely induces monochromatization via interference effects, similar to SPR. We report the results of a proof-of-principle experiment at the t-ACTS that successfully narrowed the bandwidth of ChDR in the terahertz region.

INTRODUCTION

Cherenkov radiation (ChR) is emitted when an electron beam passes through a dielectric medium, while Cherenkov diffraction radiation (ChDR) is generated when the beam passes in the vicinity of a dielectric medium. Typically, the ChDR spectrum is broad such as ChR [1]. We have been developing a non-invasive bunch length monitor using Smith–Purcell radiation (SPR) [2]. Drawing inspiration from the SPR, we considered that a dielectric with a periodic structure could monochromatize ChDR via interference effects. A schematic of narrow-band Cherenkov diffraction radiation (NBChDR) is shown in Fig. 1. NBChDR is expected to have applications as a monochromatic light source and a beam diagnostic tool. NBChDR in the GHz region has been achieved using a radiator with a periodic structure [3]. Accordingly, we aim for the first observations of NBChDR in the THz region.

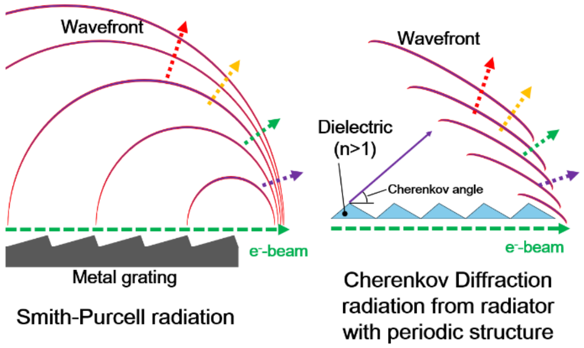

Figure 1: Schematic view of SPR (left) and NBChDR (right) both representing radiation from periodic structures.

THEORETICAL BACKGROUND

Resonant wavelength

Consider a triangle of the same shape and compare the light emitted by $P1_s$ and $P2_s$ at the same position within one cycle as the beam passes from A to B (Fig. 2). t_1 is the time taken for the light emitted at $P1_s$ to reach $P1_e$, and t_2 is the combined time for the light emitted at $P2_s$ to reach $P2_e$ and an electron to travel from A to B. In this case, the transit times, t_d, of light propagating from $P1_s$ and $P2_s$ within the medium to the observer were equivalent. The time difference, $\Delta t=t_2-t_1$, can be calculated using Eq. 1.

$$\Delta t = \frac{d}{\beta c} - \frac{d\cos\theta}{c}, \tag{1}$$

where d, β, c, and θ are the period length at the radiator, relative velocity of the electron, speed of light, and observation angle, respectively. Based on Huygens' principle, the resonance condition is expressed as $\Delta\varphi = \omega\Delta t = 2\pi m\ (m = 0, 1, 2, \ldots)$, where $\Delta\varphi$ is the phase difference. The resonant wavelength satisfying the resonance condition is given by Eq. 2.

$$\lambda = \frac{d}{m}\left(\frac{1}{\beta} - \cos\theta\right), \tag{2}$$

This equation for the resonant wavelength is the same as that for SPR [4].

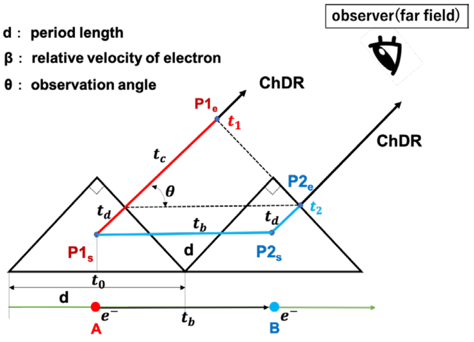

Figure 2: Schematic of ChDR from periodic structures.

NBChDR Spectrum

The frequency spectrum of NBChDR at the Cherenkov angle was calculated using the Liénard-Wiechert potential. Notably, the velocity of the electric field is c/n within the dielectric, in contrast to the propagation speed c in vacuum. Since we assumed a triangular-shaped radiator, the phase difference varies depending on the position at which the electric field is incident on the radiator, thus making it difficult to solve analytically; thus, the frequency spectrum was obtained by numerical calculations.

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* Work supported by JSPS KAKENHI grant number 22K12660 and 18K11915
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Numerical calculations were performed assuming a dielectric radiator refractive index of 1.536, period length of 1.6 mm, 20 periods, an impact parameter of 1 mm (distance between an electron and dielectric radiator), and the electron Lorentz factor of 43. Figure 3 shows the NBChDR (1st to 7th order) and ChDR spectra. These estimated spectra indicate that a radiator with a periodic structure can produce narrow-band Cherenkov light.

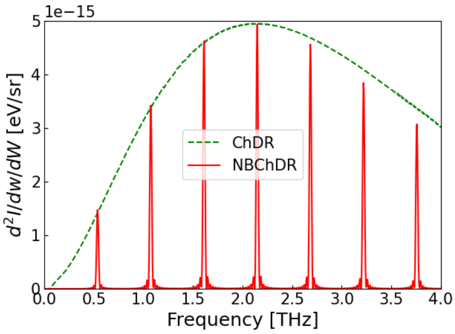

Figure 3: ChDR and NBChDR spectra.

EXPERIMENTAL

t-ACTS

A test facility, the test accelerator as a coherent THz source (t-ACTS), was developed at Tohoku University to produce ultrashort electron bunches. The beam parameters of the t-ACTS are presented in Table 1. The bunch length was deduced from an analysis of the coherent transition radiation interferogram, as measured in the beam diagnostics section of the t-ACTS.

Table 1: t-ACTS Beam Parameters

Parameter	Value
Beam energy	22 MeV
Macropulse duration	~ 2 µs
Normalized horizontal emittance	~ 3 mm.mrad
Normalized vertical emittance	~ 30 mm.mrad
Micro-bunch charge	7 pC
Bunch length	~ 80 fs
Beam size	σ_x, σ_y: ≈ 100 µm

Radiator for NBChDR

The radiator with a periodic structure for NBChDR was made of high-density polyethylene (HDPE). Period lengths of 0.8 mm and 1.6 mm were selected to achieve fundamental frequencies of approximately 0.5 THz and 1 THz at the Cherenkov angle. The number of periods was set to 40 and 20, considering the limitations of the vacuum chamber. Furthermore, we developed a 32 mm long single-period radiator to compare NBChDR and ChDR. The refractive index of the radiator was measured to be 1.536 ± 0.003 using a THz-TDS system (Advantest TAS7500TS-000); this value was almost constant below 4 THz. To eliminate the refraction effect on the radiator surface, the angle (θr) between the radiator and the beam axis was designed to be equal to the Cherenkov angle of 49.7°. To verify the external dimensions of the fabricated NBChDR radiators, the period length (d) and angle (θ_r) were obtained by image analysis using an optical microscope. Table 2 presents the results of the measurement. The radiator was fabricated with almost the desired value.

Table 2: Measured Values of Radiators

Designed Period Length [mm]	Measured Period length (d) [mm]	Angle (θr) [°]
0.8	0.817 (0.021)	48.02 (0.54)
1.6	1.601 (0.047)	51.53 (0.96)

Experimental Setup

The measurement setup is illustrated in Fig. 4. A pyroelectric detector (Sensor and Lasertechnik GmbH, THz10 [5]) was used to measure NBChDR after passing it through a Z-cut quartz window. To minimize absorption by water vapor, the detector is operated in a dry-air atmosphere with a dew point maintained below -20 °C. The distance from the center of radiation to the detector is 190.6 mm, and the acceptance angle of the detector is ±1.5°; the detector position can be adjusted to measure the angular distributions of NBChDR intensity. Before each measurement, an aluminum plate was placed over the vacuum window to measure the background signal; it was subsequently subtracted from the angular distribution of the NBChDR intensity measurement. Angular distribution measurements of the NBChDR intensity were performed along the beam's longitudinal axis; therefore, the azimuthal angle was 0°. Spectroscopic measurements were performed using a Michelson interferometer.

To verify the impact parameters, the beam profile and position were observed by placing an aluminum mirror at the entrance of the radiator to generate optical transition radiation. The impact parameters and beam size can be easily controlled. Beam current transformers were installed upstream and downstream of the beam diagnostics section to monitor the transmission rate of the beam current during measurement. We observed a very small beam loss effect, such as a slight change in the vacuum level inside the chamber, despite no change in the transmission rate, when the impact parameter was set to less than 0.5 mm. Therefore, the impact parameters were set to 1.0, 1.5, and 2.0 mm in the experiment.

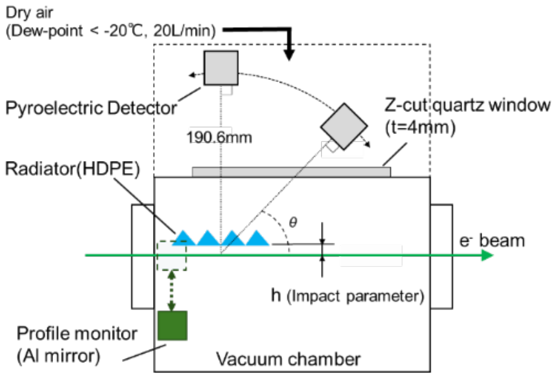

Figure 4: Schematic of detection apparatus for NBChDR.

RESULTS OF TEST EXPERIMENT

Angular Distribution

Figure 5 shows the measured angular distribution of the NBChDR intensity. Angular distribution measurements of the NBChDR intensity were performed for three radiators in 5° increments, ranging from 30° to 90°. To reduce the effect of electrical noise owing to the klystron system of the t-ACTS, the output signal of the detector was measured 30 times at each position, with the intensity evaluated based on the average value and its error. A radiation peak was detected near the Cherenkov angle using a radiator with a periodic structure. However, considerable radiation was also observed at angles outside this peak, in contrast to the ChDR.

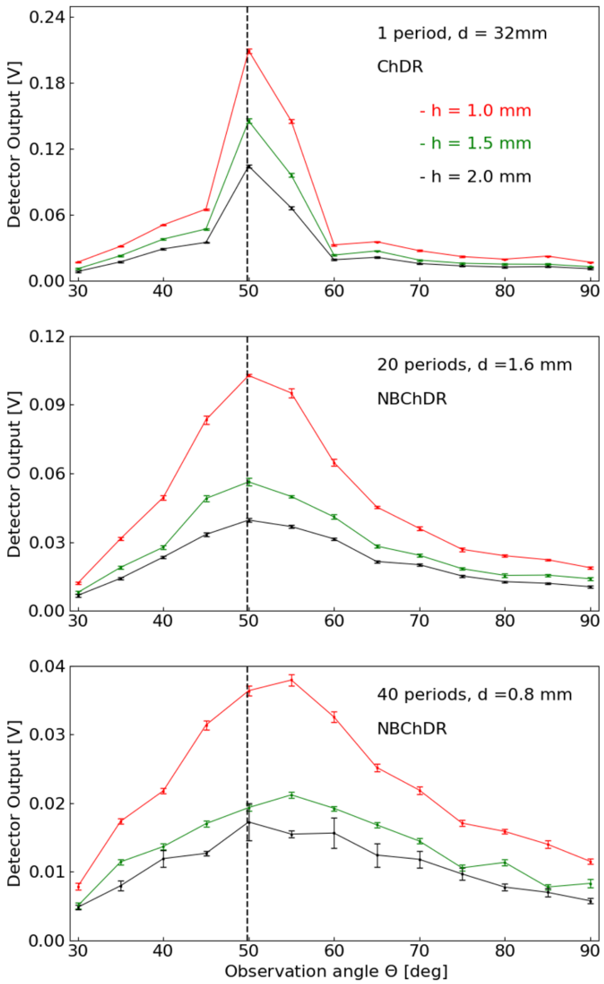

Figure 5: Measured angular distributions of ChDR and NBChDR. Dashed black vertical lines denote the Cherenkov angle.

Spectroscopy

Spectral measurements were performed using a Michelson interferometer. To convert the light to parallel, an off-axis parabolic mirror with an effective focal length of 190.6 mm was placed at the detector's position during the angular distribution measurements, and the NBChDR light was incident on the Michelson interferometer. The interferograms were recorded at observation angles ranging from 40° to 60° in 5° steps. The frequency spectrum was obtained using the fast Fourier transform of the measured interferogram. Figure 6 shows the 1st resonant frequency vs. the observation angle. The error bars represent the FWHM of its bandwidth. As expected, the resonant frequency changed with variations in the radiator period length and observation angle.

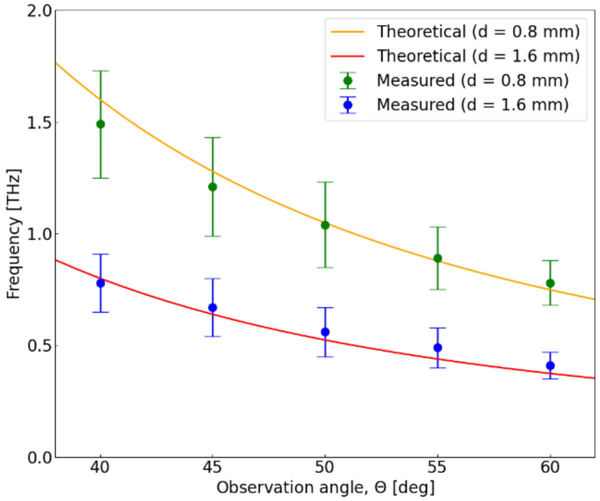

Figure 6: Comparison between estimated and observed 1st order frequency vs. radiation angle.

CONCLUSION

The first observation of NBChDR in the THz region was attempted in t-ACTS using an HDPE radiator with a periodic structure. Angular distribution measurements revealed strong radiation intensity near the Cherenkov angle and significant radiation intensity at other angles. The resonant frequency of the NBChDR varied with the observation angle and closely matched the expected value. However, further studies are required to understand the characteristics of NBChDR and to investigate the possibility of using a beam diagnostic probe. To suppress the refraction effect in the vacuum window when Cherenkov light passes through it, a new vacuum window fabricated from HDPE has been prepared and installed, and an experiment will be performed.

ACKNOWLEDGEMENTS

Part of this work was conducted based on Kumagai's master's thesis [6]. We thank the Beam Physics Group at the Research Center for Accelerator and Radioisotope Science, Tohoku University, for their cooperation in these experiments.

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