TERAHERTZ-WAVE SPECTROPHOTOMETRY
– EXPERIMENTS OF COMPTON BACKSCATTERING OF CONTINUOUS-SPECTRUM COHERENT TRANSITION RADIATION –

N Sei[#] and T. Takahashi

[#]Research Institute of Instrumentation Frontier, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Research Reactor Institute, Kyoto University, 2 Asashiro-nishi, Kumatori, Osaka 590-0494, Japan

Abstract

We have studied a terahertz (THz) wave spectrophotometry by using Compton backscattering of coherent radiations at the Kyoto University Research Reactor Institute. In the THz-wave spectrophotometry, the characteristics of the continuous-spectrum THz-waves are converted into those of the other wavelengths which are easily measured by colliding the THz-waves with a relativistic electron beam. We achieved to observe a continuous-spectrum visible beam resulting from Compton backscattering using coherent transition radiations from an L-band electron linear accelerator. The measured spectrum of the Compton backscattered photons was similar to that calculated from the spectrum of the coherent transition radiation.

INTRODUCTION

Because there are unique absorptive and dispersive properties of the useful organic compounds in the terahertz (THz) wave region, the THz-wave spectroscopy is effective as material identification and imaging tools. Although powerful THz-wave source based on electron accelerators have been developed before 1990, recently, THz-wave source sources based on short-pulse lasers and parametric oscillators have been developed. These THz-wave sources based on the short-pulse laser and parametric oscillator enabled the THz-wave spectroscopy to be compact, and the THz-wave spectroscopy was drastically applied in many fields. Then, to exploit the feature that a THz-wave source based on the electron accelerator was high power, the THz-wave spectroscopy by Compton backscattering (THz-SCB) was proposed [1]. In THz-SCB, the spectra of the continuous THz-waves are converted to those of electromagnetic waves of other wavelengths; these can be easily generated and measured by colliding the THz-waves with a relativistic electron beam. Although such a continuous-spectrum light beam resulting from the Compton backscattering has been observed in outer space [2], it has not yet been achieved in a laboratory. So, one may say that the THz-SCB artificially reproduce the high-energy radiations observed in outer space. If one can obtain the continuous-spectrum light beam resulting from Compton backscattering that is from the near-infrared to the vacuum ultraviolet region, then one can perform simultaneous spectrophotometry using a photo-counting technique with a polychromator and a multichannel analyzer. Then, we conducted experiments of THz-SCB using an L-band electron linear accelerator at the Kyoto University Research Reactor Institute (KURRI-LINAC). We observe for the first time to our knowledge a continuous-spectrum light beam resulting from Compton backscattering. Moreover, a transmission measurement of an organic film was achieved by THz-SCB [3]. Experimental results of THz-SCB at the KURRI-LINAC are shown below.

THEORY

Here, an intense light beam generated from an electron accelerator, such as coherent synchrotron radiation (CSR) or coherent transition radiation (CTR), is regarded to be a THz-wave source. When the THz-wave beam is monochromatic, the wavelength of the Compton backscattered photon λ_{CB} is given by the wavelength of the THz-wave beam λ as

$$\lambda_{CB} = \frac{\left[1+(\phi\gamma)^2\right]\lambda}{4\gamma^2}, \tag{1}$$

where ϕ is the angle between the electron orbit and the direction of emission of the Compton backscattered photon [4]. When an aperture with a small angle of $\phi << 1/\gamma$ is used to make the energy of the Compton backscattered photons uniform, a relationship $\lambda \approx 4\lambda_{CB}\gamma^2$ holds. Therefore, the visible Compton backscattered photons are obtained with the electron-beam energy of around 20 MeV in the case of $\lambda = 1$ mm.

The number of the Compton backscattered photons $N_{CB}(\lambda)$ is given with the photon number of the THz-wave beam $N_p(\lambda)$ as

$$N_{CB}(\lambda) = \frac{\sigma_c N_e N_p(\lambda)}{A_{eff}(\lambda)}, \tag{2}$$

where N_e is the number of electrons in the beam and σ_c is the total Compton cross section. The parameter $A_{eff}(\lambda)$

ISBN 978-3-95450-117-5

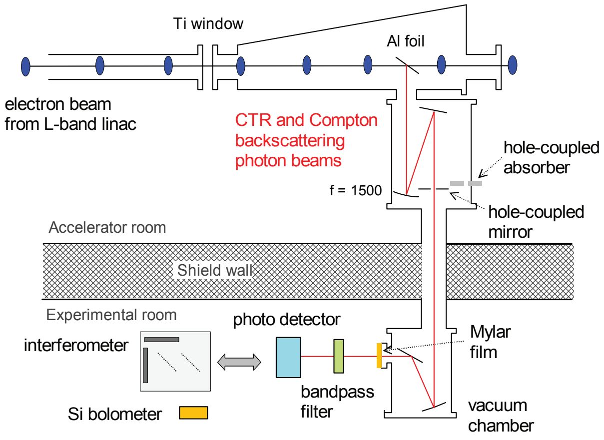

Figure 1: Schematic layout of the experimental setup at the KURRI-LINAC.

gives the effective area for the overlap between the electron beam and the THz-wave beam, and is given by

$$A_{eff}(\lambda) = 2\pi\left[\sigma_e^2 + \sigma_p^2(\lambda)\right], \qquad (3)$$

where σ_e and σ_p are the standard deviations in the size of the electron beam and the THz-wave beam, respectively. Extracting the Compton backscattered photons around the axis of the electron orbit with using an small aperture, the number of the extracted photons, $N_m(\lambda_{CB})$, is approximately given by

$$N_m(\lambda_{CB}) \approx 1.5\Delta E \int_{\lambda(1-\Delta\lambda/2\lambda)}^{\lambda(1+\Delta\lambda/2\lambda)} N_{CB}(\xi)d\xi\,, \qquad (4)$$

where $\Delta\lambda/\lambda$ is the divergence of the THz-wave and ΔE is divergence of the Compton backscattered photons passing over the aperture [3,5]. The factor 1.5 is derived from the energy distribution of the Compton backscattering in the case of $\Delta E << 1$. Although $N_m(\lambda_{CB})$ is generally small, an intense coherent radiation in the THz-wave region can realize to observe the continuous-spectrum light beam resulting from the Compton backscattering.

COHERENT TRANSION RADIATION IN THE KURRI-LINAC

To demonstrate the THz-SCB, we made use of the KURRI-LINAC. The KURRI-LINAC uses coherent transition radiation as the light source to produce the beamline for millimetre-wave and THz-wave spectroscopy [6]. As shown in Fig. 1, CTR is generated at a titanium window and an aluminium foil, and it is transported in vacuum to the experimental room as a parallel beam of 150 mm diameter. CTR is penetrated through a Mylar window of the 100 μm thickness, which is at a distance of approximately 9 m from the aluminium foil, and then it is injected into a Martin-Puplett-type interferometer [7]. Deep ultraviolet rays cannot penetrate the Mylar window, so that the measurable wavelengths were from the near ultraviolet to the visible region for a conventional photon-counting detector. The macropulse time of the electron beam can be discretely adjusted from 2 to 100 ns in the short-pulse mode. The KURRI-LINAC can generate 10^{12}~10^{14} photons/s/μA for a bandwidth of 1% in the millimetre-wave region [8]. Because the accelerating frequency is 1.3 GHz, the interval between the micropulses of electron beam is 770 ps.

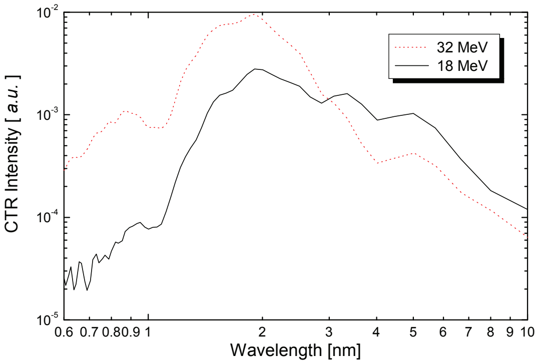

Figure 2: Spectra of the CTRs measured using the interferometer at the electron-beam energy of 18 (solid line) and 32 (dotted line) MeV.

Although the KURRI-LINAC can accelerate an electron beam up to approximately 40 MeV, the electron beam energy is determined for the Compton backscattered photons that are in the near ultraviolet or visible region where a detector for photon counting is available. The CTR spectra were measured using the interferometer with a silicon bolometer. As shown in Fig. 2, the CTR spectra have their maxima at a wavelength of around 2 mm regardless of the electron-beam energy. Because the charge of the electron beam decreased with the decrease of the energy, the CTR intensity was considerably low at the energy of 18 MeV. However, the spectrum of the Compton backscattered photons had a maximum in the visible region. Then, the operation at 18 MeV was most suitable for the electron beam energy. The charge of the electron beam was 0.35nC for one micropulse. The energy spread of the electron beam was measured by using a bending magnet and a beam current monitor, and it was evaluated to be 10%. The number of CTR photons at the exit of the interferometer in a micropulse is expected to be approximately 10^{12} for a bandwidth of 1% at a wavelength of 2 mm [8].

EXPERIMENTS OF THZ-SCB

Generating Compton backscattered photons, it is necessary to return the CTR beam to the electron beam. We inserted a hole-coupled flat mirror in a parallel CTR beam to separate the light beam caused by Compton backscattering from the CTR beam. The diameter of the hole-coupled flat mirror was 130 mm, and the diameter of the hole was 30 mm. Ignoring the electron-beam size, the radiation angle of the Compton backscattered photons is less than 10 mrad. Because the electron-beam size is smaller than the diameter of the hole, this assumption holds approximately. The distance between the hole-

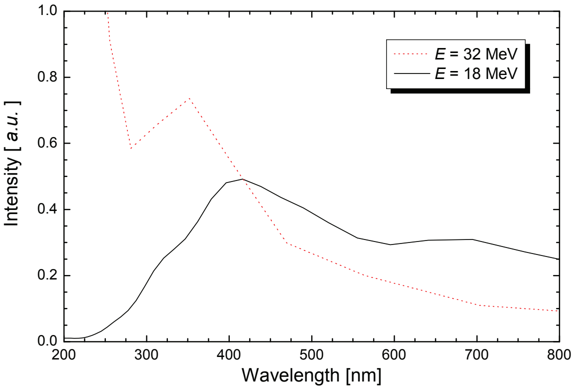

Figure 3: Spectra of the Compton backscattered photons calculated using the CTR spectra.

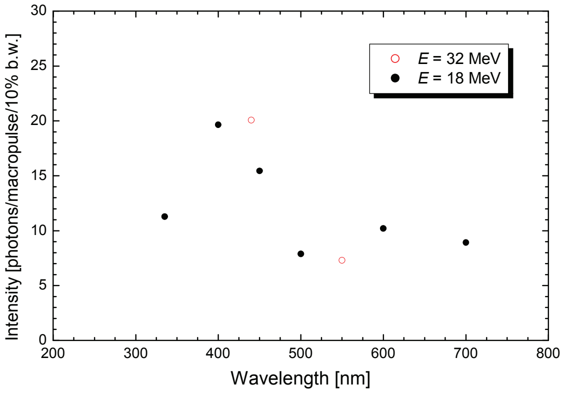

Figure 4: Spectra of the Compton backscattered photons measured using the light sensor module with the bandpass filters.

coupled flat mirror and the aluminium foil was 2.2 m. The round-trip time, which is the time taken by the CTR pulse to return back to the electron beam, was 15 ns. Then, we set the macropulse time to be 100 ns. The CTR pulses collided with the seven electron bunches between the aluminium foil and the titanium window [3].

The spectrum of the Compton backscattered photons can be estimated by using the measured CTR spectrum. For electron beam energy of 18 MeV, the Compton backscattered photons that had energy spread of 11% from the Compton edge penetrated the hole-coupled flat mirror due to the 30 mm aperture. Figure 3 shows the spectra of the Compton backscattered photons calculated using the CTR spectra at the beam energy of 18 and 32 MeV. Effects of the polarization of the CTR on the Compton backscattering and the beam sizes are ignored in these estimations. It is noted that the spectrum of the Compton backscattered photons at the beam energy of 18 MeV has a maximum at a wavelength of approximately 400 nm. In the case of the beam energy of 32 MeV, a maximum of the spectrum of the Compton backscattered photons is in the ultraviolet region, and it is difficult to observe a dependence of the spectrum of the Compton backscattered photons on the wavelength in the visible region.

Intense optical transition radiation (OTR) generated by the aluminium foil also penetrated the Mylar window with the same transportation system. The intensity of the OTR was much stronger than that of the Compton backscattered photons. To isolate the effect of the Compton backscattered photons, a millimetre-wave absorber with the same cross section as the hole-coupled flat mirror was inserted in front of the hole-coupled flat mirror. The intensity of the Compton backscattered photons could be calculated as the difference with and without the millimetre-wave absorber. A light sensor module built in a photomultiplier tube (Hamamatsu H8249) was used for the measurements of the Compton backscattered photons. This detector has sensitivity in a wavelength region from 180 to 900 nm. To obtain the spectrum of the Compton backscattered photons, several bandpass filters with the band-widths of 50-80 nm in a wavelength region from 330 to 700 nm were placed in front of the detector. Figure 4 shows the spectra of the Compton backscattered photons at the electron-beam energy of 18 and 32 MeV. The sensitivity of the photomultiplier tube and transmissions of the Mylar film and bandpass filters were considered in the evaluation of the measured spectra of the Compton backscattered photons. It was difficult to observe the Compton backscattered photons at the electron-beam energy of 32 MeV in a wavelength region more than 600 nm. However, we could observe the Compton backscattered photons at the electron-beam energy of 18 MeV because of the lower OTR. This was initial observation of the significant spectrum of the Compton backscattered photons. The measured spectrum at the electron-beam energy of 18 MeV had a maximum at a wavelength of 400 nm, and it was similar to the calculated spectrum shown in Fig. 3 [3]. Moreover, we could observe the Compton backscattered photons at wavelengths of 440 and 550 nm in the case of the electron-beam energy of 32 MeV, which were valid for the calculated spectrum.

Because the spectrum of the Compton backscattered

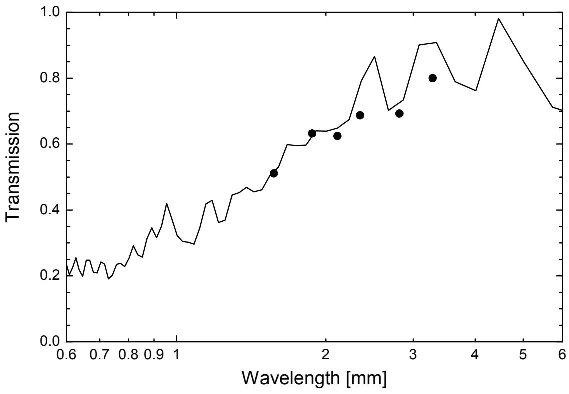

Figure 5: Transmissions of the Mylar film with the thickness of 0.6 mm measured using the THz-SCB (solid circle) and the interferometer (solid line).

ISBN 978-3-95450-117-5

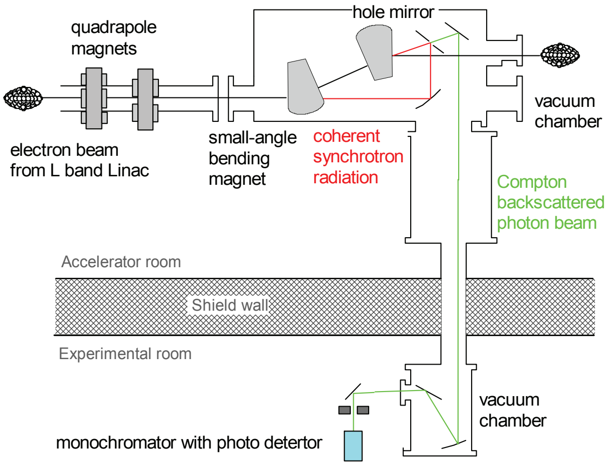

Figure 6: Schematic layout of the experimental setup with the CSRs.

photons was obtained at the electron-beam energy of 18 MeV, it was able to conduct THz-SCB experiments using the KURRI-LINAC. We inserted a hole-coupled Mylar film with a thickness of 0.3 mm instead of the millimetre-wave absorber. The effective thickness of the Mylar film was 0.6 mm because the CTR pulse passed through the Mylar film twice. Figure 5 shows the transmissions of the Mylar film measured using THz-SCB and the Martin-Puplett-type interferometer with the silicon bolometer. It is noted that the transmissions measured using the two methods were in good agreement. This experimental result validates the practical applicability and effectiveness of THz-SCB in the THz-wave and millimetre-wave regions.

GENERATION OF COHERENT SYHNCROTRON RADIATION

Although the optical system of the THz-SCB is simple by using CTR as a THz-wave source, intense OTR which could not be separated to Compton backscattered photons decreases accuracy of THz-SCB experiments. Then, we plan to develop a new measurement system which makes use of CSR as a THz-wave source for THz-SCB as shown in Fig. 6. The CSR will be generated by a bending magnet composed a pair of permanent magnet. A gap of the bending magnet is 40±5 mm, and the magnetic field on the centre axis is 0.155 T at the gap of 40 mm. Because the critical wavelength of this bending magnet is estimated to be 37 μm at the electron-beam energy of 18 MeV [1], synchrotron radiations are not generated from the bending magnet in the visible and ultraviolet regions. We will insert the bending magnets in the vacuum chamber and measure the CSR spectrum from the bending magnet by the Martin-Puplett-type interferometer next year.

CONCLUSIONS

In conclusions, we measured the spectra of the Compton backscattered photons using the KURRI-LINAC. The measured spectrum at the electron-beam energy of 18 MeV was similar to that calculated using the CTR spectrum. A transmission spectrum of the Mylar film was measured by THz-SCB, and it was in good agreement with that measured by the Martin-Puplett-type interferometer. This experimental result validates the practical applicability and effectiveness of THz-SCB. To improve the accuracy of THz-SCB experiments, we plan to change the THz-wave source from a CTR to a CSR.

ACKNOWLEDGEMENT

This work was supported by Grant-in-Aid for challenging Exploratory Research of Japan Society for the Promotion of Science.

REFERENCES

[1] N. Sei *et al.*: Appl. Phys. Express. **1** (2008) 087003.
[2] K. Koyama *et al.*: Nature. **378** (1995) 255.
[3] N. Sei *et al.*: Appl. Phys. Express. **3** (2010) 052401.
[4] N. Sei *et al.*: Nucl. Inst. and Meth. **A483** (2002) 429.
[5] T. Yanagida *et al.*: Jpn. J. Appl. Phys. **46** (2007) 400.
[6] T. Takahashi *et al.*: Rev. Sci. Instrum. **69** (1998) 3770.
[7] T. Takahashi *et al.*: Infrared Phys. Technol. **51** (2008) 363.
[8] Y. Shibata *et al.*: Phys. Rev. A **45** (1992) R8340.