CHARACTERISTICS OF TRANSPORTED TERAHERTZ-WAVE COHERENT SYNCHROTRON RADIATION AT LEBRA

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Abstract

Nihon University and National Institute of Advanced Industrial Science and Technology have jointly developed terahertz-wave coherent synchrotron radiation (CSR) at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University since 2011. We have already observed intense terahertz-wave radiation from a bending magnet located above an undulator dedicated for an infrared free-electron laser (FEL), and confirmed it to be CSR. We have transported the CSR to an experimental room, which is next to the accelerator room across a shield wall, using an infrared FEL beamline. The power of the transported CSR was 50 nJ per macropulse, and it was available at frequencies of 0.1–0.3 THz. The transported CSR beam can be applied to two-dimensional imaging and spectroscopy experiments. From two-dimensional imaging performed with the THz-wave CSR, metallic structures concealed by plastic in a smart card were nondestructively detected at a spatial resolution of 1.4 mm.

INTRODUCTION

In order to obtain an FEL with high gain, the electron beam in FEL facilities has a short bunch length and a high charge. The electron beam in the FEL facilities can also generate intense terahertz waves by coherent radiation. Since 2011, then, Nihon University and National Institute of Advanced Industrial Science and Technology have jointly developed intense THz-wave CSR at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University. We have already observed intense coherent synchrotron radiation (CSR) in the THz-wave region using an S-band linac at LEBRA [1]. Because the CSR does not influence a process of infrared FEL oscillations, it is possible to use the THz-wave CSR and infrared FELs simultaneously. If a complex light source composed from the CSR and FEL are developed, we can conduct highly reliable material identifications.

Then, we transported the CSR to the experimental room, which was next to the accelerator room across a shield wall, using an infrared FEL beamline. We could obtain a CSR beam whose intensity was approximately 50 nJ per macropulse. The CSR beam could be used for spectroscopy experiments at frequencies of 0.1-0.3 THz [2]. In this article, characteristics of the CSR transported to the experimental room are reported in detail.

THZ WAVE SOURCE BY CSR

The S-band linac at LEBRA consists of a 100 keV DC electron gun, prebuncher, buncher, and three 4 m long traveling wave accelerator tubes [3]. The electron beam accelerated by the linac is guided to an FEL undulator line by two 45° bending magnets. The electron-beam energy can be adjusted from 30 to 125 MeV, and the charge in a micropulse is up to 30 pC in full-bunch mode, where the electron beam is bunched in 350-ps intervals. The electron-beam energy was set to 100 MeV in the CSR observations. The macropulse duration determined by the flat-top pulse width of the 20 MW klystron output power is approximately 20 μs. The bunch length is compressed from 3 to less than 1 ps by a magnetic compressor using two 45° bending magnets that guide the electron beam to an FEL undulator line [4]. However, there is no optical beam window to extract the CSR in the FEL undulator line. Thus, we developed the CSR emitted at the entrance of the second 45° bending magnet, where the calculated bunch length was approximately 2 ps in full-bunch mode. Although the CSR is emitted along the electron-beam orbit in a bending magnet chamber (internal height, 24 mm), its solid angle which was incident on an entrance of a transfer pipe (diameter, 20 mm; length, 265 mm) was 0.065 radians.

We observed intense sub-THz-wave radiation emitted from the second 45° bending magnet by using a Schottky D-band diode detector (Millitech Inc., DXP-06) [1]. The measured power of the intense sub-THz-wave radiation was proportional to the second power of the electron-bunch charge in full-bunch mode. The vertically polarized component of the intense sub-THz-wave radiation had roughly the same vertical distribution as the synchrotron radiation. Thus, the radiation was identified as CSR. The measured CSR power per macropulse was approximately 0.4 μJ in the D-band region.

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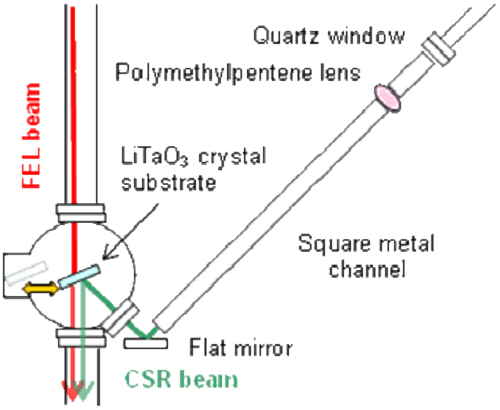

Figure 1: Relationship between the THz-wave source and the infrared FEL beamline.

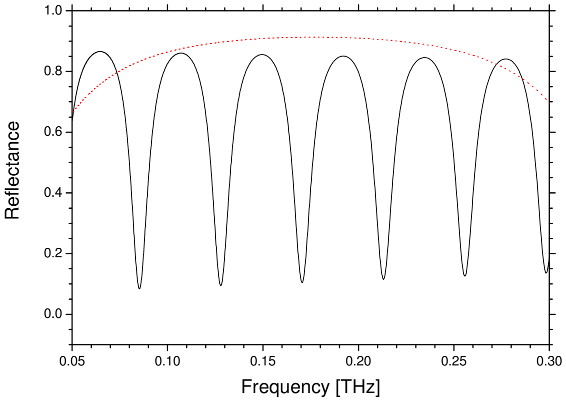

Figure 2: Calculated reflectance spectra of the $LiTaO_3$ substrate with thicknesses of 0.5 (solid line) and 0.06 (dotted line) mm.

TRANSPORTATION OF THE CSR

If the intense THz-wave CSR is transported to the same space as the infrared FEL, we can conduct complex imaging in the two wavelength regions and expect to realize highly reliable material identifications. Then, we planed to transport the CSR beam to an experimental room using the infrared FEL beamline. Outline of the THz-wave source of the CSR and the infrared FEL beamline is shown in Fig. 1. Because the infrared FEL beam is a plane wave in the beamline, the CSR beam should be converted to a plane wave to be transported to the experimental room. A Tsurupica lens (Pax Co., Ltd), which had a focal length of 800 mm and an effective diameter of 36 mm, was installed at a position 800 mm from the upper end of the second 45° bending magnet, where the THz-wave CSR is generated. The CSR beam was converted to a plane wave by the Tsurupica lens, then it deflected 90° by a flat mirror and injected into the infrared FEL beamline through a quartz window. A square metal channel whose inner sides were 36 mm was set between the Tsurupica lens and the flat mirror.

To match the profile of the THz-wave CSR to the profile of the infrared FEL, we needed an optical device that would transmit the infrared FEL and reflect the THz-wave CSR by an angle of 22.5°. Because the optical device needed to maintain the wave front of the infrared FEL, a mesh mirror could not be used. Based on the difference in refractive indices in the THz-wave region

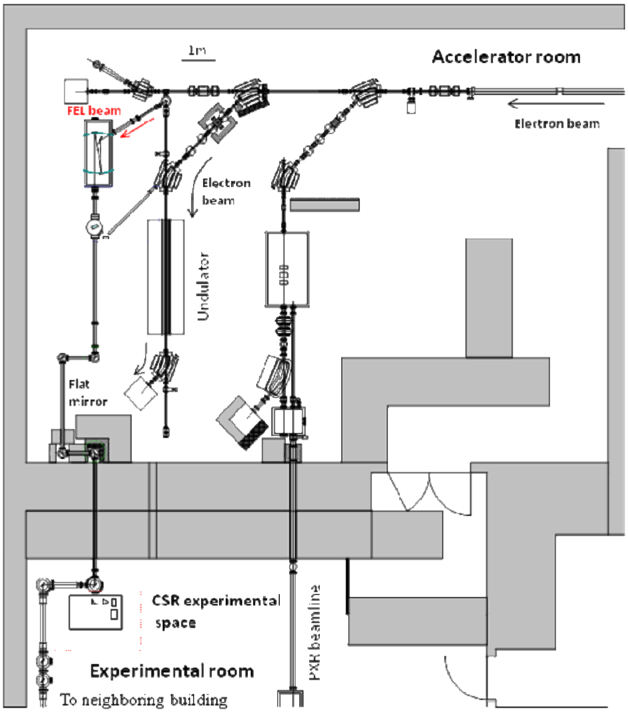

Figure 3: Schematic layout of the transportation of the CSR beam.

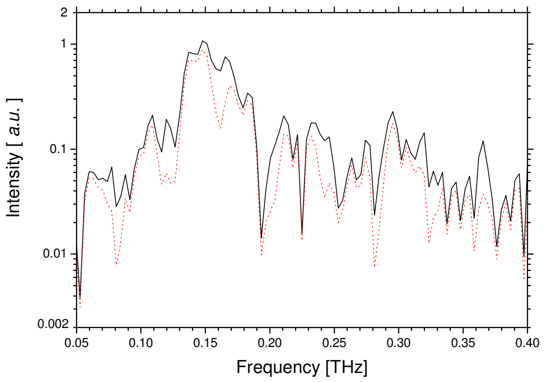

Figure 4: Calculated spectrum of the transported CSR (dotted line) and spectrum after removing the influence of the interference of the $LiTaO_3$ substrate (solid line).

and the infrared region, we used a flat substrate of $LiTaO_3$ crystal with a diameter of 76 mm and a thickness of 0.5 mm. The refractive index of the $LiTaO_3$ crystal is approximately 2.1 in the near-infrared region [5], and it has a transmittance of 75% in the wavelength region of 0.5–5 µm. On the other hand, the refractive index of $LiTaO_3$ crystal is approximately 6.5 around a frequency of 0.2 THz [6]. Figure 2 shows a calculated reflectance spectrum of the $LiTaO_3$ crystal substrate with a thickness of 0.5 mm. There are frequency regions of low reflectance every 42.8 GHz due to interference caused by the substrate. Based on this interference, the optimum thickness of the $LiTaO_3$ crystal substrate was estimated to be less than 70 µm for the reflectance spectrum; however, a thin film of $LiTaO_3$ crystal was not available. We expected this substrate to have an average reflectance of 67% in the frequency region of 0.1–0.3 THz.

Figure 3 shows the outline of the infrared FEL beamline. The CSR beam was transported by four flat mirrors installed in the infrared FEL beamline to the experimental room. The CSR beam was extracted from the infrared FEL beamline through a sapphire window that is attached to the first mirror chamber in the experimental room. The maximum CSR power per macropulse was estimated to be approximately 50 nJ in the D-band region in full-bunch mode. So, transportation efficiency for the CSR beam was 13%.

SPECTRUM OF THE THZ-CSR

In order to investigate the spectral characteristics of the transported CSR, we used a homemade Martin-Puplett type interferometer [7], which was used in step-scan mode with a maximum optical path difference of 50 mm. Metal wire grid mirrors, which had wire diameters of 15 µm and wire spacings of 60 µm, were used as a polarizer and a beam splitter in the interferometer. The CSR beam reflected by the polarizer was concentrated by a parabolic mirror that was then injected into a pyroelectric detector (Gentec Electro-Optics Inc., THZ-I-BNC) that was sensitive at frequencies above 0.1 THz. Figure 4 shows a typical spectrum of the transported CSR beam from calculating with interfrograms measured by the interferometer. Note that a frequency region with low intensity appeared every 41 GHz in the CSR spectrum. The interference from the $LiTaO_3$ crystal substrate caused these periodic dips in the CSR spectrum. Based on the interval of the dips, the refractive index of the $LiTaO_3$ crystal was evaluated to be 6.9, which is almost the value of 6.5. As shown in Fig. 4, although some deep dips of unknown provenance remained in the spectrum after removing the influence of the interference, the transported CSR could be used at frequencies of 0.1–0.3 THz in full-bunch mode.

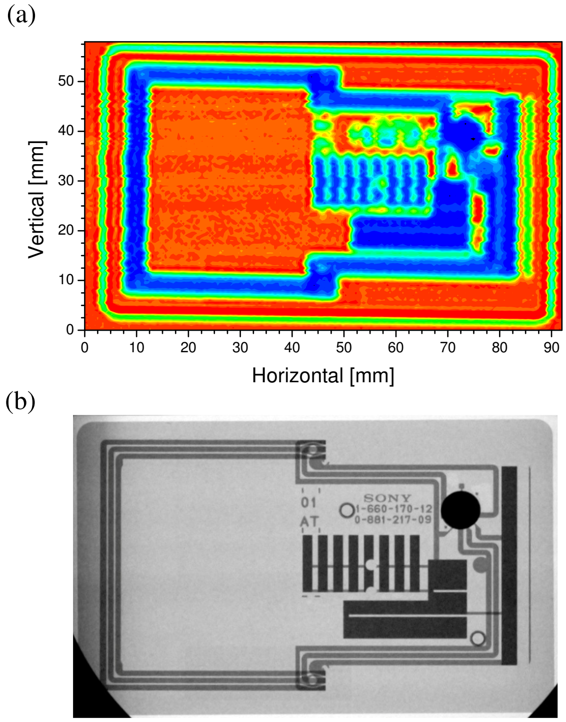

Figure 5: Transmission image of a smart card measured by the CSR beam with a D-band diode detector (a) and by the parametric x ray with an imaging plate (b).

TWO-DIMENSIONAL IMAGING

We have developed a two-dimension imaging experiment by using the transported CSR beam. The CSR beam was extracted through the sapphire window and then concentrated by the parabolic mirror. We used a smart card as a sample. The dimensions of the smart card were 51 mm in height, 85.5 mm in width, and 0.8 mm in thickness. It was set on an acrylic board with a thickness of 2 mm, and the board was located at the focal point of the CSR beam. To limit the irradiated area of the CSR beam, a conical horn, which had a circular output with a diameter of 2 mm, was set at a position 2 mm above the

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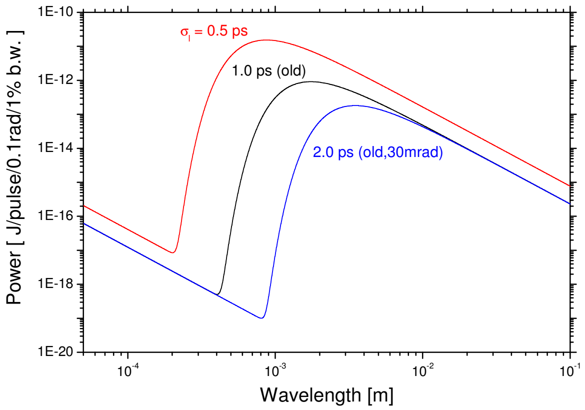

Figure 6: Calculated spectra of the CSR beam for the present light source (black and blue lines) and planning light source (red line).

smart card. To measure transmittance of the smart card, the D-band diode detector was set at a position 2 mm away from the acrylic board. The two-dimensional distribution of transmittance was measured by a raster scan at an interval of 0.5 mm. Figure 5 shows the imaging data for the smart card from the sub-THz-wave CSR and from a parametric X-ray, which was supplied by another beamline in LEBRA [8]. Comparing the CSR and X-ray imagings shows that the CSR beam could sense metals in the plastic body of the smart card. This CSR imaging system distinguished 1.5 mm wide metal plates and 1.0 mm wide gaps between metal plates at the center of the card. It could not distinguish 0.5 mm wide gaps of wires around the edge of the card. When a spatial resolution of the CSR imaging system was defined as a width where the transmittance is from 0.2 to 0.8 at an edge, it was evaluated to be 1.4 mm. However, a narrow wire with a width of 0.5 mm was detected at the right edge; therefore, we could sense a smaller metal piece in the plastic body when another metal structure did not exist around the wire.

FUTURE PLAN OF THz SOURCE

As mentioned above, the bunch length can be compressed to be less than 1 ps in the FEL straight section. Then, we plan to develop a new CSR source, which can supply more intense and shorter-wave THz beam, at the downstream bending magnet in the FEL straight section. A solid angle of the new CSR source will be 0.1 radians. Figure 6 shows a spectrum of the expected CSR beam at the exit of the bending magnet when the bunch length is 0.5 ps. The intensity of the new CSR beam will be approximately 100 times than that of present CSR beam. We will remake the vacuum chamber of the bending magnet to extract the intense CSR and transport it to the experimental room with using the infrared FEL beamline.

CONCULSIONS

We have successfully transported THz-wave CSR from an accelerator room to an experimental room by using an existing infrared FEL beamline at LEBRA. The intensity of the CSR in the experimental room was approximately one eighth of that near the second 45° bending magnet in the accelerator room. The CSR spectrum was measured by a Martin-Puplett type interferometer and a pyroelectric detector, and it was found that the CSR was available in the frequency region of 0.1–0.3 THz. In a two-dimensional imaging experiment on a smart card, the spatial resolution of the imaging system was 1.4 mm. We will investigate characteristics of the CSR at the downstream bending magnet in the FEL straight section and develop a new THz-wave CSR source.

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REFERENCES

[1] N. Sei et al., J. Phys. D: Appl. Phys. **46** (2013) 045104.

[2] N. Sei et al., “Complex light source composed from sub-terahertz-wave coherent synchrotron radiation and an infrared free-electron laser at LEBRA”, J. Opt. Soc. Am. B (in press).

[3] Y. Hayakawa et al., Nucl. Instrum. Methods Phys. Res., Sect. A, **483** (2002) 29.

[4] K. Hayakawa et al., “Operation of near-infrared FEL at Nihon university” Proc. 29th Int. Free Electron Laser Conf., (Novosibirsk, Russia, 2007) p 114 (2007).

[5] J. L. Casson et al., J. Opt. Soc. Am. B, **21** (2004) 1948.

[6] M. Schall et al., Int. J. Infrared Millimet. Waves. **20** (1999) 595.

[7] D. H. Martin and E. Puplett, Infrared Phys. **10** (1970) 105.

[8] Y. Hayakawa et al., J. Inst., **8** (2013) C08001.