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DESIGN AND CONSTRUCTION OF AN INTENSE TERAHERTZ-WAVE SOURCE BASED ON COHERENT CHERENKOV RADIATION MATCHED TO CIRCLE PLANE WAVE*

N. Sei†, H. Ogawa, Research Institute for Measurement and Analytical Instrumentation, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan
Y. Hayakawa, T. Sakai, Y. Sumitomo, T. Tanaka, K. Hayakawa, K. Nogami, Y. Takahashi
Laboratory for Electron Beam Research and Application, Nihon University, Funabashi, Chiba, Japan
T. Takahashi, Institute for Integrated Radiation and Nuclear Science, Kyoto University, Kumatori, Osaka, Japan

Abstract

In order to obtain a terahertz (THz) wave source with higher intensity, we have undertaken a development of a new THz-wave source based on coherent Cherenkov radiation (CCR) matched to circle plane wave. By passing an electron beam through a hollow conical dielectric having an apex angle equal to the Cherenkov angle, the wave front of the CCR generated on the inner surface of the hollow conical dielectric matches on the basal plane. Therefore, it is possible to obtain a high-power beam which is easy to transport. We have already produced a hollow conical dielectric made of high-resistivity silicon and a position controller for the hollow conical dielectric. It is expected that the hollow conical dielectric generates intense THz pulses with the energy of 1 μJ and the peak power of 1 MW or more. We will demonstrate generation of the CCR matched to circle plane wave at Laboratory for Electron Beam Research and Application at Nihon University this summer.

INTRODUCTION

National Institute of Advanced Industrial Science and Technology has been studied THz coherent radiation in collaboration with Nihon University and Kyoto University [1]. We have been developed a coherent transition radiation (CTR) source with macropulse power of 1 mJ using a screen monitor in the parametric X-ray (PXR) section at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University. However, the energy of the CTR was 80 nJ per micropulse, and the peak power was approximately 0.1 MW. The peak power did not reach 1 MW where nonlinear optical effect in the THz region became noticeable. Therefore, to develop an intense THz-wave source that was more powerful than the CTR, we focused on CCR. Because the CCR spread on a conical surface, it was difficult to converge the CCR generated along the electron orbit, and CCR was not widely used in spite of its high power. However, we have proposed that the CCR beam can be extracted as a circular plane wave by using a hollow conical dielectric [2]. In demonstration experiments at Kyoto University, it was confirmed that the CCR beam had the properties predicted by a theory [2], and the power of the CCR beam was higher than that of the CTR [3]. Therefore, we planned that the THz light source based on coherent Cherenkov radiation matched to circle plane wave (CCR-MCP) would be developed at a PXR section at LEBRA. In this article, the current state of the THz-wave source is reported.

COHERENT THz LIGHT SOURCES AT LEBRA

LEBRA is a unique electron accelerator facility which has monochromatic light sources, an infrared free-electron (FEL) and a PXR [4]. It has a S-band linac which can accelerate an electron beam up to the energy of 100 MeV. The macropulse duration of the electron beam is as long as 20 μs in order to oscillate FELs. In full bunch mode, where the electron bunches are accelerated with repetition of 2856 MHz in a macropulse, and the maximum charge in a micropulse is approximately 30 pC. In burst mode, where the electron bunches are accelerated with intervals of 22.4 or 44.8 ns by adjusting grid bias of the electron gun, micropulses with charge of several hundred pC are formed.

Because the electron beam is transported from the linear accelerator to each straight section that generates a monochromatic light source using a 90-degree arc, the electron bunch length can be compressed to 0.5 ps or less. Therefore, intense coherent radiation in the THz region can be developed in the straight sections. As shown in Fig. 1, we have already developed a coherent synchrotron radiation source and a coherent edge radiation (CER) source in the FEL section and a CTR source and a CER source in the PXR section. Because the CER beam generated at the downstream bending magnet in the FEL section can be measured without damaging FEL oscillations, we can observe the electron bunch just after interacting with the FEL. Recently, we have reported that FEL oscillations increase the CER power and shorten the electron bunch length [5]. The CTR in the PXR section has an energy of 1 mJ per macrpulse with a duration of 4–5 μs [1]. Because the CTR beam is measurable with pyrodetectors which operate at room temperature, it is transported to the experimental room and used for two-

† sei.n@aist.go.jp

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dimensional imaging and spectroscopic experiments in the THz region under dry air. The peak power of the CTR was approximately 0.1 MW, which was insufficient to study nonlinear optical phenomena in the THz region. A development of more intense THz-wave source has been desired.

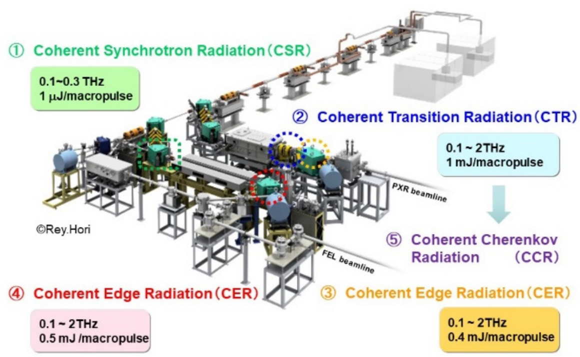

Figure 1: Schematic view of coherent radiation sources at LEBRA.

PRINCIPLE OF COHERENT CHERENKOV RADIATION MATCHED TO CIRCLE PLANE WAVE

Cherenkov radiation is attractive for its high energy, and many novel studies have been reported on it recently [6-8]. Even a dielectric distant from the electron beam generates Cherenkov radiation in a low frequency region, so that the Cherenkov radiation has the advantage that it can be used without damaging the electron beam. We proposed the CCR-MCP which can generate plane wave [2].

When an electron beam passes through the hollow part of the conical dielectric, Cherenkov radiation generates on the inner surface of the hollow conical dielectric. The components radiated with the Cherenkov angular become high power because they are in phase. As shown in Fig. 2, when an apex angle of the hollow conical dielectric is equal to the Cherenkov angle, the components radiated with the Cherenkov angle are totally reflected by the conical surface and reach the bottom surface of the conical dielectric. Because all Cherenkov radiation generated inside the hollow conical dielectric has the same optical distance from the inner surface to the bottom surface, all Cherenkov radiation emitted from the bottom surface parallel to the electron beam orbit become in phase. Therefore, the Cherenkov radiation generated in the hollow conical dielectric can be extracted from the bottom surface as a circle plane wave. This is the principle of the coherent Cherenkov radiation matched to circle plane wave. By using a material having ignorable absorption coefficient in the THz region for the hollow conical dielectric, the radiation power can increase as the length of the conical dielectric increases. Although the power of the Cherenkov radiation increases as refractive index of the dielectric is higher, transmittance at the bottom surface of the hollow conical dielectric is lower. The optimum refractive index, at which power of the CCR-MCP extracted from the hollow conical dielectric is maximized, has been derived to be 2.7 without anti reflection coating on the bottom surface. It is possible to focus the CCR beam by processing the bottom surface into a spherical surface [8]. In demonstration experiments performed at Kyoto University, the power of the CCR-MCP was more than twice that of CTR [3].

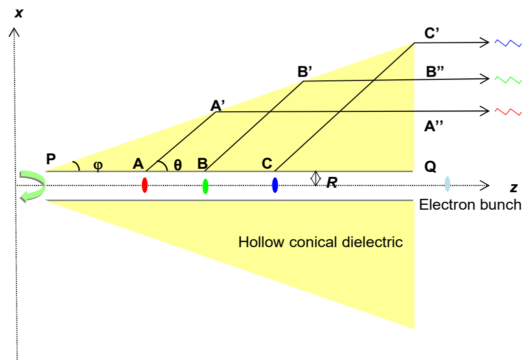

Figure 2: Configuration of CCR-MCP.

CCR-MCP SOURCE AT LEBRA

Because there is no space to install a hollow conical dielectric in the FEL section, we are developing a THz-wave source based on CCR-MCP in the PXR section. By improving a beam position monitor used as the CTR source in the PXR section, the hollow conical dielectric is inserted in the electron beam orbit. The schematic diagram of the PXR section is shown in Fig. 3.

A device that controls position of the hollow conical dielectric can not only insert the aluminum-deposited thin silicon substrate on the electron-beam orbit to generate the CTR beam but also pull out the dielectric and the substrate to pass through the electron beam. The hollow conical dielectric is fixed to a biaxial piezo stage, and the polar angle and the azimuth angle of the dielectric are remotely controlled with an accuracy of 0.1 mrad. High-resistance (HR) silicon with a resistivity of 20 kΩ·cm or more, which is easily available, is adopted as the material for the hollow conical dielctric. This material is transparent in the THz region and has an absorption coefficient of 0.05 cm^{-1} or less in a frequency region below 2 THz. The refractive index of the HR silicon in the THz region is 3.42, which is slightly larger than the optimum value, and then the Cherenkov angle is 73.0 degrees. Although the root-mean-square (RMS) electron-beam size can be reduced to 0.2 mm or less, the inner diameter of the hollow part is set to be 10 mm, which is larger than the previous report [9]. Because the inner height of the vacuum chamber of the bending magnet located downstream of the CTR target is 40 mm, the diameter of the bottom surface is set to be 42 mm. Therefore, the height of the hollow conical dielectric is approximately 20 mm. Figure 4 shows a photograph of the produced hollow conical dielectric. The bottom of the hollow conical dielectric is a spherical surface with a radius of curvature of 1.579 m, and the CCR-MCP beam emitted from the bottom is designed to not collide with the inner

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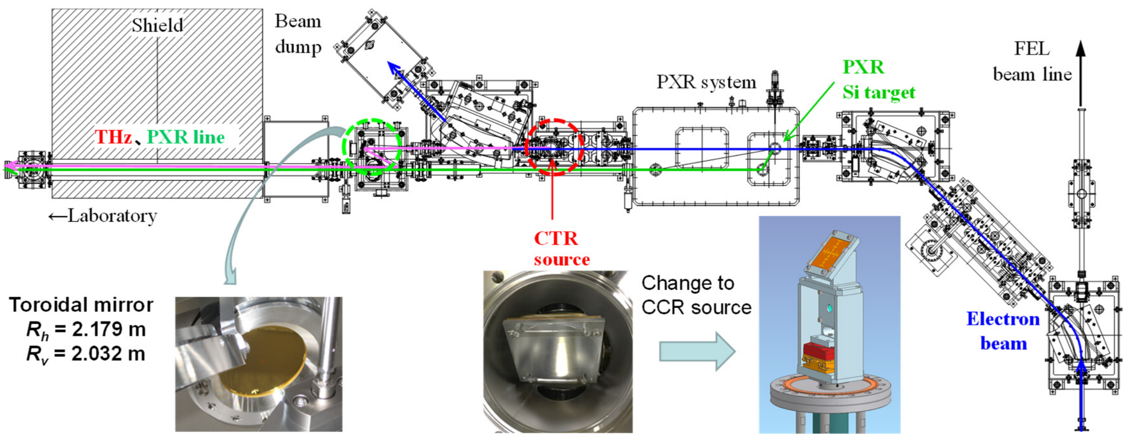

Figure 3: Schematic layout of CCR-MCP in the PXR section at LEBRA.

vacuum chamber of the downstream bending magnet. The CCR-MCP beam is formed into parallel light by a toroidal mirror with a focal length of 1.05 m placed at a position 1.7 m from the hollow conical dielectric and transported to the experimental room by using the PXR beamline. The RMS length of the electron bunch in the PXR section is estimated to be 0.2 ps from the measured CER spectrum. The energy of the CCR-MCP beam emitted from the hollow conical dielectric is estimated to be 1 μJ per micropulse. Assuming that the pulse width of the CCR-MCP is equal to the electron bunch length, the peak power of the CCR-MCP would be approximately 2 MW, exceeding the target of 1 MW. The device for controlling the position of the hollow conical dielectric has already been completed, and demonstration experiments will be performed this summer.


Figure 4: Photograph of the hollow conical made of HR silicon.

CONCLUSION

We are developing an intense THz-wave source based on the CCR-MCP in the PXR section of LEBRA at Nihon University. Considering the electron-beam characteristics, we produced a hollow conical HR silicon with the height of 20 mm and the inner diameter of the hollow part of 10 mm. The diameter of the bottom of the hollow conical made of HR silicon is 42 mm, and the bottom has a spherical surface with a radius of curvature of 1.579 m so that the CCR beam emitted from the bottom does not collide with the vacuum chamber of the transport beamline. The energy of the CCR-MCP beam is estimated to be 1 μJ per micropulse, and then the peak power exceeds 1 MW. We schedule to perform demonstration experiments this summer. The CCR-MCP beam has radial polarization. By focusing the CCR-MCP beam, high-intensity longitudinally polarized THz wave can be obtained at around the focal point [8]. The CCR-MCP, which is a unique high-power THz wave, will contribute to pioneer cutting-edge applications.

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