Development of a Scanning Near-Field Sub-THz-Wave Microscopy with Coherent Transition Radiation

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Abstract. In order to establish the technique of near-field microscopy using an accelerator-based coherent radiation, some basic properties are experimentally investigated with coherent transition radiation (CTR) from a linac. In the transmission mode, the spatial resolution power in accepting whole wavelengths of CTR was 4.4, which was obtained by scanning the metallic plate edge with a metallic conical cone as an illumination probe. It was found that the probe with a dielectric film effectively scattered the near-field. The dependence of the resolution power with the wavelength was investigated with a conical cone of Teflon coated by silver paste on the tapered surface as an illumination probe. The resolution power became large with increasing the wavelength. In the reflection mode, two types of optical configuration were prepared to detect the reflected light, i.e. the beam-splitter type and the light-guide type. The spatial resolution powers in the two configurations were 4.4 and 4.6, respectively.

1. Introduction
In recent years, various types of coherent radiation, i.e. coherent synchrotron radiation [1], transition radiation [2], Cherenkov radiation [3], diffraction radiation [4] and Smith-Purcell radiation[5], emitted from a relativistic electron beam have been investigated experimentally and attracted a considerable attention as a new and powerful light source in the THz-wave region. The technique of near-field THz-wave microscopy is a characteristic application of such brilliant coherent radiation. This technique provides high spatial resolution below the diffraction limit. In the storage ring BESSY-II (Germany), spatial resolution of $\lambda/40$ was obtained at 2 cm$^{-1}$ using coherent synchrotron radiation [6]. In this paper some basic properties, i.e. spatial resolutions and spectra, have been experimentally investigated using coherent transition radiation (CTR) in order to establish the technique of near-field THz-wave microscopy with an accelerator-based coherent radiation.

2. Experimental Procedures
The experiment was performed at the coherent radiation beamline [7] at the 40-MeV L-band linac of the Research Reactor Institute, Kyoto University. The width of the macro pulse and the repetition rate of the electron beam were 47 ns and 46 Hz, respectively. The charge of a bunch was 1.2 nC. The
schematic layout of this experiment is shown in Fig. 1. The sub-THz-wave source was the superposition of the forward CTR emitted from a titanium window 30 µm thick and the backward CTR from an aluminum-foil 15-µm thick. The CTR was guided to the experimental room as a parallel beam 15 cm in diameter and was detected by a liquid-helium-cooled Si bolometer through a spectrometer. This beamline is equipped with two interferometers and one monochromator. In this experiment the spectrum of CTR was measured by a Martin-Puplett type interferometer in a vacuum chamber as shown at the right-hand side in Fig. 1. The output signal from the detector was amplified by a lock-in amplifier synchronized with the repetition rate of the electron beam.

Aperture probes were used both in the transmission and the reflection mode as illumination and collection probes. In the reflection mode, two types of optical configuration were prepared in order to detect the reflected radiation, namely the beam-splitter type and the light-guide type. Their details are explained in section 3.2.

Figure 1. Schematic layout of the beamline at KURRI-LINAC. Keys are M1, a plane mirror of aluminium foil; M2, M5, plane mirrors; M3, M4, spherical mirrors. The light source was the superposition of CTR from a titanium window and from an aluminium-foil mirror. A Martin-Puplett type interferometer in a vacuum chamber was used with a liquid-helium-cooled Si bolometer.

3. Results and discussion

3.1. Transmission mode
The metallic conical cone with an aperture 260 µm in diameter was used as an illumination probe. The detector was equipped with the collection probe with an aperture 3mm in diameter at the incident window. In order to investigate the spatial resolution, an opening of 1 mm in diameter on a stainless steel (SUS) sheet 50 µm thick was scanned in front of the aperture on the top of the illumination probe. The observed intensity of the transmitted radiation through the opening is plotted in Fig. 2 and its first derivative curve is shown by a dotted curve in Fig. 3. The solid curve of this figure is the Gaussian fitting. The width of the derivative curve is equivalent to the spatial resolution. Then, the spatial resolution was estimated to be 170 µm.

In Figure 4, the solid and dashed curves show the observed CTR spectra through the illumination probe and without it, respectively. The former intensity was multiplied by 1000 in this figure to clarify the difference of the spectral shape from the latter. The shift of the spectral distribution to shorter wavelengths arises from passing through the pinhole. Considering the wavelength of 750 µm at the peak intensity, the spatial resolution power was evaluated to be 4.4.
One of the theoretical models of the near field is the dipole-dipole interaction [8]. Therefore, the probe made of material with large refractive index has high efficiency of scattering the near field. In order to confirm the effect of the dielectric medium on the probe, the dependence of intensity with the distance between the illumination and the collection probe. The openings of the illumination and the collection probes are 2 mm and 200 μm in diameter, respectively. The detector equipped with the collection probe was moved to vary the distance. The solid circles connected by the solid line in Fig. 5 represent the experimental result using a sheet of Kapton film (polyimide film, Du Pont-Toray Co. Ltd) 25 μm thick on the top of the collection probe. The refractive index of Kapton and air are 1.7 and 1.0003 (sodium D line), respectively. The intensity is drastically enhanced within the distance equivalent to the size of aperture 200 μm. One of the possible reason of the dip around the distance of 250 μm is the Fraunhofer diffraction. If so, the dip should be also observed on the experimental result without the Kapton film. The reason of the dip is not clear at present. On the other hand, in the experimental result plotted by the open squares the Kapton film was not used, i.e. the collection probe had an empty opening only. The enhancement of intensity was not observed. The dielectric material with large refractive index on the probe has experimentally proved to scatter and detect the near field effectively.
As the CTR has wideband spectrum, it is important to investigate the dependence of the spatial resolution power with wavelength experimentally. We have observed the dependence in the transmission mode. The conical cone of Teflon coated by silver paste on the tapered surface was used as an illumination probe. The size of the aperture was 450 μm. The collection probe with an opening 3mm in diameter was put on the detector. In order to measure the spatial resolution, the edge of a stainless steel plate 0.3 mm thick was scanned as a sample in front of the aperture on the top of the illumination probe. First, the spectra were measured at each scanning position of the sample. Second, the observed data were reconstructed to the scanning curves at each wavelength. The spatial resolution was estimated by the same way as Fig.3, i.e. the width of the first derivative of the scanning curve. The calculated spatial resolutions and resolution powers were summarized in Table 1. It was made clear that the resolution power became large with increasing the wavelength.

| Wavenumber (cm⁻¹) | Wavelength (μm) | Spatial Resolution (μm) | Spatial resolution power λ/Δx |
|------------------|-----------------|--------------------------|-------------------------------|
| 3.70             | 2700            | 371                      | 7.3                           |
| 4.94             | 2025            | 360                      | 5.6                           |
| 6.17             | 1620            | 341                      | 4.8                           |
| 7.41             | 1350            | 292                      | 4.6                           |
| 8.64             | 1157            | 243                      | 4.8                           |
| 9.88             | 1012            | 226                      | 4.5                           |
| 11.1             | 900.1           | 214                      | 4.2                           |
| 12.4             | 809.7           | 204                      | 4.0                           |
| 13.6             | 736.4           | 195                      | 3.8                           |
| 14.8             | 675.2           | 195                      | 3.5                           |
| 16.1             | 623.1           | 192                      | 3.2                           |
| 17.3             | 578.7           | 183                      | 3.2                           |

3.2. Reflection mode

Reflection measurement is also important for the THz-wave spectroscopy. The metallic conical cone with an aperture of 775 μm in diameter was used as an illumination probe. Two types of optical configuration were prepared to detect the reflected radiation. One was the beam-splitter type as shown in Fig.6 where the reflected radiation was divided by the Mylar beam splitter, focused by a Teflon lens, and guided to the detector. The other was the light-guide type as shown in Fig.7 where the reflected radiation was guided to the detector through the light pipe made of copper with an inside diameter of 10 mm.

In order to investigate the spatial resolution, the edge of a SUS plate 0.3 mm thick was scanned as a sample in front of the aperture on the top of the illumination probe. In the beam-splitter type configuration the observed intensity of the reflected radiation is plotted in Fig. 8 and the spatial resolution of 396 μm was derived from the Gaussian fitting of the first derivative curve. In Figure 9, the observed CTR spectrum with the sample is shown by open circles. The observed intensity remained even without the sample as shown by the dashed curve, which was considered to be the stray light reflected by the inside of the probe. The calculated net spectrum reflected by only the sample is represented by the solid curve. Considering the wavenumber of 5.7 cm⁻¹ at the peak intensity of this spectrum, the spatial resolution power was evaluated to be 4.4.

Similarly, the spatial resolution and the spectra were measured in the light-guide type configuration. The scanning curve of the edge of a SUS plate is represented in Fig. 10. The intensity overshot around the edge. This phenomenon was not observed in the beam-splitter type configuration. The enhancement of intensity around the position of the edge is considered to arise from the stray light reflected at the cross-section face or the corner. In the beam-splitter type configuration the stray light
is expected to stray off the optical path to the detector. On the other hand, it can be guided through the light pipe to the detector without a significant loss. The spatial resolution of 324 µm was obtained by the first derivative curve of Fig. 10. The spectra were shown in Fig. 11. The net spectrum subtracted the stray light without the sample (dashed curve) from the observed spectrum with it (open circles) is shown by the solid curve. Considering the wavenumber of 6.7 cm⁻¹ at the peak intensity of this spectrum, the spatial resolution power was evaluated to be 4.6. This value is equivalent to that of the beam-splitter type.

**Figure 6.** Schematic layout of the optics of the beam-splitter type.

**Figure 7.** Schematic layout of the light-guide type.

**Figure 8.** Scanning curve of the edge of a SUS plate 0.3 mm thick in the beam-splitter type configuration.

**Figure 9.** Observed spectra of CTR with (circles) and without (dashed) a sample. The solid curve shows the difference between the two spectra.

**Figure 10.** Scanning curve of the edge of a SUS plate 0.3 mm thick in the light-guide type configuration.

**Figure 11.** Observed spectra of CTR with (circles) and without (dashed) a sample. The solid curve shows the difference between the two spectra.
4. Summary
Average spatial resolution powers in accepting whole wavelengths of CTR were around 4.5 both in the transmission and reflection mode. The near field was effectively scattered and detected by usage of Kapton film with larger refractive index than air. The resolution power became large with increasing the wavelength. The scanning near-field THz-wave microscopy will be planned to be performed in the new THz-CSR beamline constructing at UVSOR. The average power of detected CTR without the aperture in the KURRI-LINAC was 0.5 μW. The pulse energy in a macro pulse and a micro bunch were 10 nJ and 160 pJ, respectively. The bandwidth of spectrum was wide around the frequency of 0.2 THz. At UVSOR the CSR is planned to be quasi-monochromatic with the pulse energy of 120 nJ at 1THz. Therefore the near-field imaging at the target frequency of absorption will be possible in the THz region.

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