Application of a Compact Terahertz Free-Electron Laser on T-ray Imaging

Young Uk Jeong, Hyuk Jin Cha, Seong Hee Park, Byung Cheol Lee
Laboratory for Quantum Optics, Korea Atomic Energy Research Institute (KAERI), P.O. Box 105, Yusong, Daejon, 305-600, Korea
yujung@kaeri.re.kr

1. Introduction

T-ray which means THz radiation imaging technology was selected as one of '10 emerging technologies that will change your world' by a magazine named MIT's Technology Review of January 31, 2004. If we see the other selected technologies, e.g. universal translation, synthetic biology, and so on, the potentiality of the THz radiation technology might go beyond the usual understanding of us. THz radiation has several remarkable advantages for imaging compared with other conventional sources, such as safe energy range without ionization to the materials, foot-print spectral region o f most chemicals and bio-materials, and relatively high spatial resolution for bio-medical imaging.

There are several kinds of THz radiation sources [1–5]. Table-top THz sources generated by conventional lasers have been developed and used for various applications in the THz range [6–8]. Inexpensive and compact THz FEL [5,9] can play the important role of encouraging the advanced THz applications due to its higher power and spectral brightness compared to the table-top sources.

We have developed a THz users facility based on a compact FEL [9]. The wavelength range of the FEL is 100-1200 μm and we could construct a users experimental stage for the wavelength of 100–300 μm. The THz FEL beam shows good performance in pulse-energy stability, polarization, spectrum and spatial distribution. The peak power of the FEL micropulse having pulse duration of 30 ps is approximately 100 W at the experimental stage. We could get the 2-D imaging of various materials with the THz FEL beam.

2. Characteristics of the THz FEL beam for imaging

The fluctuation of the pulse energy of the THz FEL beam is less than 10% in r.m.s value. If we monitor and normalize the pulse energy fluctuation of the FEL beam, the measuring error is decreased to be less than 1%. With the stable THz pulses, we could measure 2-D scanned imaging, interference patterns, or spectroscopic information of species with high resolution.

The polarization of the THz FEL beam has been measured by using a metal-wire polarizer having 20 μm spacing. The FEL beam is highly polarized with a linear component of more than 98% due to wiggling motion of the electron beam inside a planar undulator. We could understand that the polarization of the FEL beam is not disturbed by the long distance (~10 m) propagation with more than 10 pieces of mirrors, windows and lens.

Spectra of the FEL beam have been measured by a high resolution spectrometer having resolution of 10^{-4}. And the results were compared by the measured value of the coherence length of the FEL micropulses. Coherent length of the FEL micropulse could be measured by the Michelson configuration of the interferometer. The FWHM of the FEL line width is between 0.7 μm to 2 μm, which corresponds to 0.4-1.2% of the wavelength. The measured coherence length from the interferogram is between 10 mm to 16 mm in FWHM, which corresponds to the FEL bunch length of 25-40 ps (8-12 mm, FWHM) in the case of the Gaussian-shaped pulse. The bunch length from the coherence length measurement agrees well with the estimation of the FEL bunch length from the calculated value of the electron beam.

The spatial distribution of the FEL beam was measured on the experimental stage as shown in Ref. [10]. The results show the distribution of the THz FEL beam is near Gaussian shape. We have focused the beam having spot size of 7 mm and wavelength of 110 mm with a parabola mirror (F/2). The focal length of the mirror is 50 mm. The measured beam waist at the focal point is 0.3 mm, which is close to value of the diffraction limitation from the 7-mm-diameter THz FEL beam.

We could understand that our THz FEL beam has excellent performance in power stability, polarization, spectral width, spatial distribution and wavefront. We hope that the THz radiation could be used for the advanced application of THz imaging for 3-D coherence tomography.

3. 2-D THz imaging

Figure 1 shows schematics of the experimental setup for THz transmitted imaging with 2-D scanning of the samples. The 2-D scanning and data acquisition are automatically performed by a personal computer with a controller. For the first experiment on the THz imaging, we did not perform spectral study on the sample. Therefore the used wavelength for the THz imaging experiment was not optimised.

Figure 2 shows a transmitted THz imaging through an invisible paper box containing metal and silicon rings. We could see the shape of the rings clearly. Additionally the density information inside the silicon ring could be measured by the THz radiation, which means that the big dynamic range is very useful to recognize the nature of sample with THz spectral information. Without any additional processing of the imaging data, we could get the dynamic range of 10^5 for the measurements.

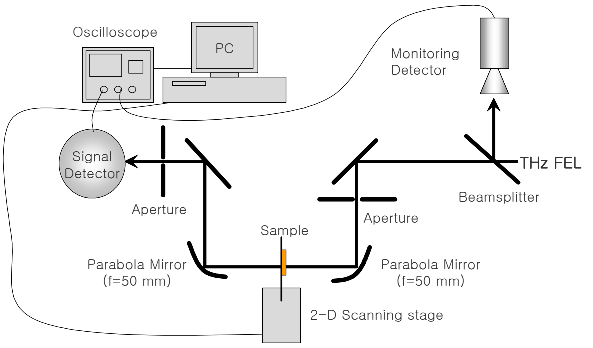

Figure 1. Schematics of the experimental setup for THz transmitted imaging with 2-D scanning of the samples.

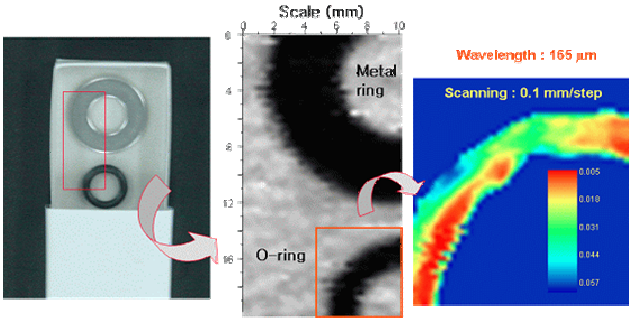

Figure 2. Transmitted THz imaging through an invisible paper box containing metal and silicon rings. We could see the shape of the rings clearly. Additionally the density information inside the silicon ring could be measured by the THz radiation.

Figure 3 shows a THz imaging of a head part of a mantis. We could see its structure information near mouse and neck part with the T-ray image. If we use several wavelengths of THz range for the same imaging, we could recognize more information inside the bug. These simple examples are demonstration for T-ray imaging with the monochromatic FEL beams. We will extend the imaging technology to spectroscopic imaging and coherent 3-D holography.

We are constructing a fast imaging system with a single micropulse of the THz beam by using the electro-optic (EO) detection and switching method. The linearly polarized visible or IR laser beam is collinearly incident to the EO crystal with the THz beam. The image of the THz beam is transferred to the visible or IR laser beam and the transferred image can be captured by an intensified CCD camera.

4. Conclusion

We have developed a compact THz FEL and the main activity of its application for THz imaging is introduced in this paper. The FEL beam showed good performance in pulse-energy stability, polarization, spectrum and spatial distribution. We could get the 2-D imaging of various materials with the THz FEL beam. To perform spectroscopic imaging, we will develop a Fourier transform spectrometer for THz range.

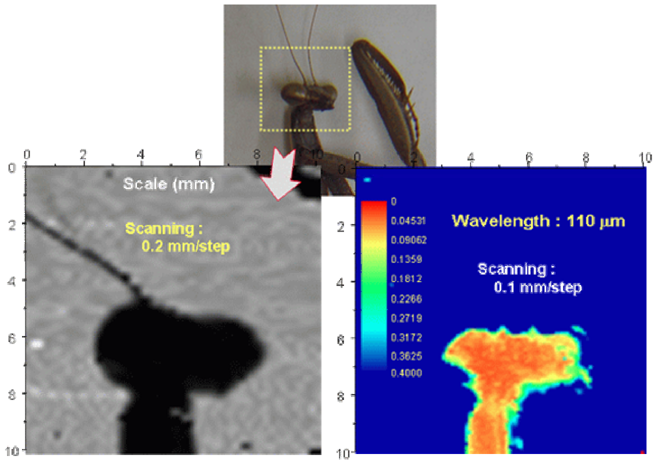

Figure 3. Transmitted THz imaging through a head part of a bug (mantis). We could see its structure information near mouse and neck part with the T-ray image.

REFERENCES

[1] Rudeger Kohler, et al., "Terahertz semiconductor-heterostructure laser," Nature, 417 (2002) 156.

[2] Kodo Kawase, et al., "A Transform-limited, Narrow-Linewidth, THz-wave Parametric Generator," Appl. Phys. Lett. 78 (2001) 2819.

[3] Q. Wu and X.-C. Zhang, "Free-space electro-optic sampling of terahertz beams," Appl. Phys. Lett. 67, (1995) 3523.

[4] M. Abo-Bakr, et al., "Steady-state far-infrared coherent synchrotron radiation detected at BESSY II," Phys. Rev. Lett. 88 (2003) 254801.

[5] Y.U. Jeong, et al., "First lasing of the KAERI compact far-infrared free-electron laser driven by a magnetron-based microtron," Nucl. Instr. and Meth. A 475 (2001) 47.

[6] D.M. Mittleman, et al., "Recent advances in terahertz imaging," Appl. Phys. B 68 (1999) 1085.

[7] K. Kawase, et al., "Non-destructive terahertz imaging of illicit drugs using spectral fingerprints," Opt. Express 11 (2003) 2549.

[8] T. Loffler, et al., "Terahertz dark-field imaging of biomedical tissue," Opt. Express 9 (2001) 616.

[9] Y.U. Jeong, et al., "Laboratory-scale wide-band FIR users facility based on a compact FIR FEL," Nucl. Instr. and Meth. A 528 (2004) 88.