# 1 kHz Terahertz Imaging

R. Rungsawang, A. Mochiduki, S. Okuma, and T. Hattori

Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki, 305-8573 Japan
e-mail: nok@laserlab.bk.tsukuba.ac.jp

## Abstract

We have succeeded in acquiring terahertz (THz) images at a frame rate of 1 kHz. We used intense THz pulses emitted at a repetition rate of 1 kHz from a large-aperture photoconductive antenna, and THz images were obtained at the same rate using a high-speed CCD camera. THz field images were obtained by adopting a phase-sensitive detection method. The delay time of the probe pulse of the electro-optic (EO) detection was fixed at the time when the temporal change in the THz field was steepest.

## Introduction

THz imaging, one of recent entrants to the arena of noninvasive monitoring, has great potential in real-time detection although significant advances are still needed for the applications such as real-time product monitoring and security check. By using a biased large-aperture photoconductive antenna, one can obtain intense THz pulses having a large beam area, and simultaneous detection of two-dimensional distribution of the THz field can be obtained using an EO sampling method and a CCD camera [1]. In order to achieve real-time, high-repetition rate imaging, however, several difficulties are still to be solved. THz pulses emitted from a photoconductive antenna have a broad spectrum and the spatial distribution of the THz field depends on the frequency, or in the time domain, it depends on the time delay [1,2]. Difficulty in lock-in detection causes a poor signal-to-noise ratio (SNR). Ordinary CCD cameras allow limited imaging rates.

Real-time THz imaging system using electro-optic (EO) detection technique and a CCD camera was first demonstrated by Wu *et al.* [3], in which two-dimensional intensity distribution of a focused THz beam was obtained using a thermoelectrically cooled CCD camera at a rate of 7.5 frames/s. Jiang and Zhang performed using spatio-temporal detection of few-cycle THz pulses at a capture rate up to 69 frames/s with an improved SNR using a dynamic subtraction technique [2]. Recently, THz images of moving objects were obtained by Usami *et al*. [4]. They showed clear snapshots of a moving biological sample that were taken at a frame rate of 10 frames/s. In these studies, each THz image was obtained using a number of femtosecond laser pulses to achieve good image quality. In order to attain real-time high-speed monitoring, however, single-shot THz imaging is required. Single-shot THz imaging, which means that one image is obtained using a single THz pulse, can also be applied to the observation of single-time ultrafast events, such as explosion and laser ablation, which occur in the picosecond and femtosecond time regime.

In this paper, we report the success in obtaining real-time high-speed movies in the THz frequency region at a rate of 1000 frames/s based on single-shot field imaging. The image quality was improved using a Gaussian filtering method. A movie of a moving object was obtained.

### Imaging System

The schematic of the experimental setup is displayed in Fig.1. In experiments, a large-aperture photoconductive antenna was used as the THz source, which enabled a large beam size and a high electric field when biased with a high DC voltage. The source gives almost half-cycle electric pulses. The spatial resolution obtained was limited by the central wavelength of the emitted THz waves, which was around 1 mm. The sample object was placed in front of the antenna. A single TPX lens was used to image the spatial distribution of the THz waves onto an EO crystal (ZnTe). The THz field distribution on the EO crystal was recorded by a high-speed CCD camera (Photron, FASTCAM-PCI 2K) using the optically heterodyne detected (OHD) EO sampling method [5-7]. The setup is similar to that described in a previous paper [7] except that the pump laser, the bias voltage generator, and the CCD camera were synchronized to a 1-kHz external clock.

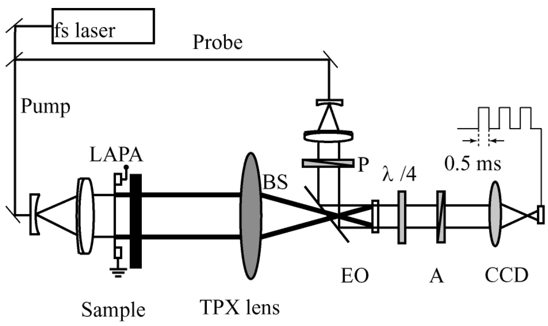


**Fig. 1**: Imaging system – LAPA: a large-aperture photoconductive antenna, BS: a pellicle beam splitter, EO: an electro-optic crystal (ZnTe), λ/4: a quarter-wave plate, P: a polarizer, A: a polarization analyzer. The exposure time of the CCD camera was 0.5 ms.

The emitter was made of a 350-μm-thick semi-insulating GaAs wafer and the gap length between electrodes was 30 mm. It was pumped by regeneratively amplified femtosecond Ti:sapphire laser pulses, whose pulse width, center wavelength, and repetition rate were 150 fs, 800 nm, and 1 kHz, respectively. Generated THz radiation was collimated using a TPX lens having a focal length $f$ = 98.3 mm onto a 1-mm thick ZnTe crystal placed at the distance of 3$f$/2 from the lens. The probe pulse of the EO sampling measurement covered almost the whole area, 18 x 20 mm$^2$, of the crystal. The ZnTe crystal was placed between crossed polarizers, and a quarter-wave plate was placed between the crystal and the analyzer for electric field detection using the OHD method.

The procedures of the THz field detection using the OHD EO sampling method are as follows. The axis of the quarter-wave plate was adjusted to be parallel to the axis of the polarizer. The analyzer was then rotated by a small angle, $\delta$, from the perpendicular orientation in order to induce a local oscillator field. The phase retardation angle of the probe light due to the EO effect, $\theta$, which is proportional to the THz electric field, can be expressed as [7]

$$\theta = -\delta + \sqrt{\delta^2 + \frac{I - I_b}{I_0}} \qquad (1)$$

when $|\delta|, |\theta| \ll 1$. Here, $I_0$ is the incident probe light intensity, $I_b$ is the background intensity of the probe light transmitted through the $\delta$-rotated analyzer, and $I$ is the intensity of the transmitted probe light in the presence of the THz field. In our experiment, the orientation angle of the analyzer was set at

$\delta$=0.02 radian, where probe intensity modulation due to the EO effect was almost optimized [7]. Using this method, we could achieve sensitivity of the measurement so high that imaging by a single THz pulse became possible.

The modulated probe pulse, after passing through a quarter wave plate and an analyzer was captured by the monochrome high-speed video camera. The image size at the position of the CCD chip was reduced to 1/5 time of that at the ZnTe crystal. The CCD camera can capture images of 256 x 120 pixels with 8 bit gray scale at a rate of 1000 frames/s, which is more than 30 times of the standard video rate. The image size corresponds to a dimension of 8.8 x 7.4 $mm^2$ on the object plane. The captured image data were stored in the on-board memory, and then transferred to a PC for display and storage.

## Results and Discussion

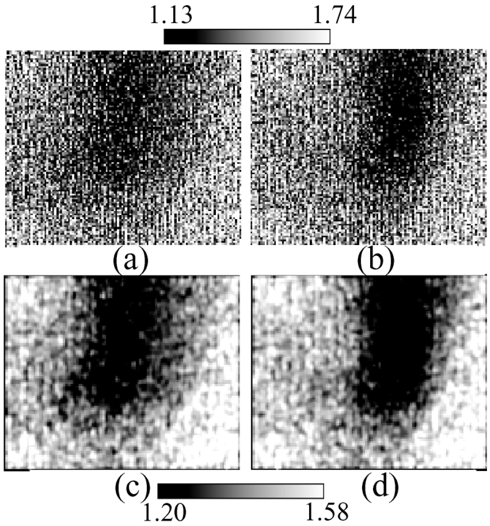


**Fig. 2**: Snap shots of a moving metal rod. Image (a) was obtained 20 ms before image (b). They were divided by the reference (*i.e.*, the THz image without the object). Image (c) and (d) were obtained by applying a Gaussian filter to images (a) and (b), respectively. The upper and lower color bars indicate the gray scale for two upper and two lower images, in which the extreme values were mapped to the percentile range of 10%-90%.

We captured images of a moving object at a frame rate of 1000 frames/s using the setup. First, the reference image, *I*, which is the THz beam image without the object, was pre-scanned over the time delay. Then the delay time was fixed at the falling edge of the temporal THz profile at the beam center, where the clearest images are obtained [8]. The sample object was a metal rod of 2.6 mm in diameter. The rod was hung by string and, when at rest, placed vertically at the center of THz beam at a distance of 3*f* from the lens. Real-time images of the rod, while swinging, were obtained. The CCD camera captured an image for each probe pulse that mapped THz field on the EO crystal. Some field images of the rod selected from the series are illustrated in Fig. 2. Image (b) was obtained 20 ms after image (a). They were divided by the reference that captured in absence of the sample in order to get rid of the focusing effect of half-cycle THz pulses. We can ascertain the rod in the figures although they are not so clear. The images shown here are contaminated by a variety of noise sources, especially significant among them is those from the CCD camera itself. In this experiment, photon noises and thermal noises dominated because the probe pulse was weak and the images were taken at a high frame rate. The photon noises occur from incorrect counting of the same number of photons for consecutive frames. In addition, thermal noises are from stochastic source of electrons in a CCD well. Another noise can come from instability of the laser. We applied a Gaussian filter to reduce these noises. The Gaussian filter has been applied for many purposes such as edge finding and scale space analysis. Since commercially available image processing software typically affects only one image at a time, we implemented a computer code that can manipulate the whole set of the images at a time. This provides an efficient framework for image processing tasks. Zeros were padded to the data images to make the data size of 256 pixels in each dimension, and they were two-dimensionally Fourier transformed. The variance of Gaussian shape was set to be 1 in the calculation. In the calculation, the Fourier transformed image data were multiplied by the Fourier transform of the filter function, and inversely transformed to spatial domain data. The results of applying the Gaussian filter operator are shown in Fig. 2 (c) and (d). The calculation process took 0.5 s per each frame on a PC. A larger value of variance in filtering makes the image smoother. The result of Gaussian filtering provides clearer images. We could obtain 3000 images consecutively, which corresponds to duration of 3 s. High-speed movies could be constructed using these images, which clearly showed the swinging motion of the metal rod.

In conclusion, real-time high-speed imaging in THz region was demonstrated at a rate of 1000 frames/s. Each image was obtained by single-shot detection of the THz field distribution, division by the reference image, and Gaussian filter image processing. Since each THz pulse is only about 1 ps in duration, this technique allows to measure phenomena which occur on a very short time scale. The frequency-resolved images can also be constructed in real time if the delay time of probe pulses is scanned.

## References


[1] R. Rungsawang et al., “Ring formation of focused half-cycle terahertz pulse”, J. Phys. D: Appl. Phys., **36**, (2003) 229-235.

[2] Z. Jiang et al., “2D measurement and spatio-temporal coupling of few-cycle THz pulse”, Opt. Express, **5**, (1999) 243-248.

[3] Q. Wu et al., “Two-dimensional electro-optic imaging of THz beams”, Appl. Phys. Lett, **69**, (1996) 1026-1028.

[4] M. Usami et al., “Development of a THz spectroscopic imaging system”, Phys. Med. Biol., **47**, (2002) 3749-3753.

[5] G. L. Eesley et al., “Optically heterodyned coherent Raman spectroscopy”, IEEE J. Quantum Electron., **14**, (1978) 45-49.

[6] Z. Jiang et al., “Electro-optic sampling near zero optical transmission point”, Appl. Phys. Lett., **74**, (1999) 1191-1193.

[7] T. Hattori et al., “Phase-sensitive high-speed THz imaging”, J. Phys. D: Appl. Phys, **37**, (2004) 770-773.

[8] R. Rungsawang, K. Tukamoto, and T. Hattori, in preparation.