Single-shot terahertz imaging

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Abstract: The appropriate timing for imaging an object was discovered for a half-cycle terahertz (THz) pulse generated from a large-aperture photoconductive antenna. Two-dimensional THz imaging with single-shot detection was conducted. This enables observation of ultrafast phenomena at a frame rate of 1000 frames/s.

OCIS codes: (320.7120) Ultrafast phenomena; (110.2970) Image detection systems

1. Introduction

Imaging with electromagnetic pulses in THz region (10GHz-10THz) is attractive for real-world applications because it can provide a noninvasive monitoring method. Furthermore, it can be applied for time-resolved spectroscopy that has the potential to read out both amplitude and phase information simultaneously. Since the THz pulses have pulse widths of less than 1 ps, they can be used in many types of time-resolved measurements. To achieve these applications, we need real-time imaging that is powerful enough for investigating real-time events in this frequency region. Two-dimensional detection of THz intensity generated from an unbiased photoconductive antenna using electro-optic (EO) detection was first reported by Wu *et al.* [1]. The readout time of the experiment was 0.133 s. Spatio-temporal detection with a higher frame rate was performed by Jiang and Zhang [2]. They achieved a capture rate up to 69 frames/s with an improved signal-noise ratio using the dynamic subtraction technique. A biological sample object was first imaged by Usami *et al.* [3].

The essential components to accomplish the real-time imaging are a powerful THz source, a sensitive detection method, and a high-speed CCD camera. We used a biased photoconductive antenna to produce a high electric field. This source gives a simple output waveform, *i.e.*, almost half-cycle shape at focus, even though the peak frequency occupies the lower part of the spectrum. The pulse width was about 500 fs. The waveform severely changes a great deal along its propagation, and deviates from the half-cycle pulse at the observation plane [4]. We found out that there is a certain time window which is suitable for imaging at a fixed time delay. We adopted the optical heterodyne detection method for sensitive field image detection [5]. We used a high-speed CCD camera for capturing each optical pulse that maps the spatial distribution of one THz pulse. Our system is run at a 1 kHz repetition rate. The raw data were passed through digital imaging processes to reduce noises.

2. Waveform analysis

150-fs laser pulses were used to electro-optically sample the two-dimensional distribution of the THz field. By scanning the delay time of the probe pulse, we found that images are clearly seen only at a specific time window. Interestingly, that is not the peak time of the THz pulse. In Fig. 1, the THz field waveforms observed at the focus and on the image plane are shown. The focal length of the lens was f = 98.5 mm, and the image plane was at 1.5f from the focus. From the plot, it is seen that the main pulse shape at the focus (dotted line) is almost half-cycle having a tail with a small negative value. The negative tail is attributed to diffraction of low-frequency components before being focused. The second small pulse seen in the figure is a reflection inside the emitter wafer. At the object location, on the other hand, the pulse (solid line) is broadened. The long rise time shows diffraction of high-frequency components after focusing. The period when images were clearly observed corresponds to the time region where the THz field changes rapidly, namely at the time immediately after 0 ps in the figure, where the high frequency components dominate. By fixing the time delay in this time window, we succeeded in observing images in real time.

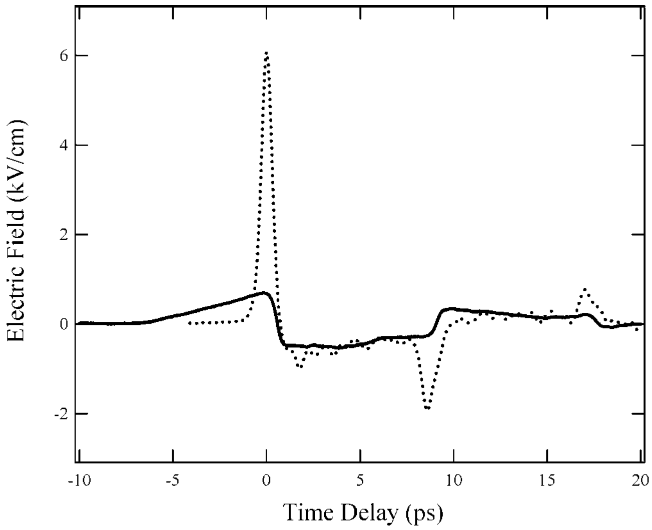

Fig. 1 On-axis temporal waveforms on the focal plane (dotted line) and on the image plane (solid line) measured using the conventional balanced detection method.

3. Imaging system

The imaging setup was similar to that as described in a previous paper [5]. The THz beam size was 30 mm, which corresponds to the emitter gap. The THz pulses passed through an object sample that was placed at distance 3*f*. The image of the object was projected to a 18 x 20 mm^2 ZnTe crystal. The probe beam was expanded, linearly polarized, and irradiated on the crystal. In this study, we applied the optical heterodyne detection method [5,6]. Using this method, we could measure the THz electric field at a high sensitivity by inserting a quarter wave plate in between the crystal and the analyzer and inducing a local oscillator field.

In experiments, the time delay was optimized by setting it at the time region where a large change in electric field was observed. In practice, the optimal time lies immediately after the peak. The timing of the laser source, a bias voltage generator, and the high-speed CCD camera were synchronized to a 1-kHz external clock. The sample object was a metal rod of 2.6 mm in diameter. The rod was hung by a string and, when at rest, placed vertically at the center of the THz beam. Real-time images of the rod, while swinging, were obtained. The electric field images were calculated and divided by the reference image obtained when the sample was removed. By this procedure, the artificial pattern attributed to the characteristics of the focused THz beam itself was removed [7]. The resulted images contained noises which originated from the CCD camera and the instability of the laser. By processing the images using a Gaussian filter, good image quality was achieved. Two images of the rod selected from a series are illustrated in Fig. 2. The spatial resolution of the images is limited by the low central frequency of the THz pulses.

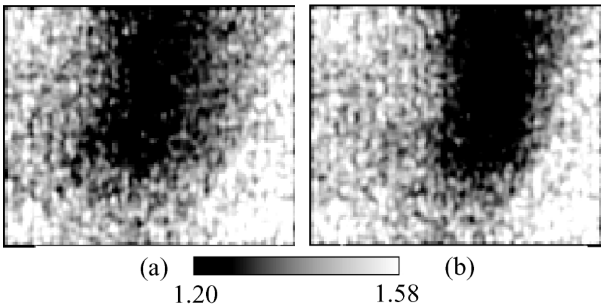

Fig. 2 Single-shot images of a metal rod which moved from left to right. Image (b) was obtained 20 ms after image (a). These images were divided by the reference image obtained without the sample object and processed using a Gaussian filter. The dimension of images is 8.8 x 7.4 mm^2. The bar indicates the gray scale. The values are mapped to percentile range 10%-90%.

4. Conclusion

Imaging with a single-shot THz pulse was achieved for the first time. A large-aperture photoconductive antenna gave a large THz beam and a large electric field. The readout pulses were set to the time where the field changes rapidly. Moving objects were imaged in real time at a rate of 1000 frames/s. Potential applications of this technique include high-speed movies and time-resolved spectroscopic studies of single-time events in the THz frequency region.

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