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SPECIAL TOPIC — Terahertz physics

Single-shot measurement of THz pulses*

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Terahertz (THz) waves have shown a broad prospect in the analysis of some dielectric materials because of their special properties. For the ultrafast irreversible processes, the THz single-shot measurement is a good choice. In this paper, a single-shot system is investigated, where a pump beam is used to generate THz pulses with high electrical field by optical rectification in $LiNbO_3$, the probe beam with wavefront tilted by a blazed grating is used for single-shot measurement. The time window is up to 90 ps, the signal to noise ratio is 2000 : 1, the spectrum covers from 0.1 THz to about 2.0 THz, and the spectral resolution is 0.011 THz. The single-shot measurement result agrees well with that of a traditional electrical-optic sampling method.

Keywords: terahertz waves, tilted wavefront, single-shot measurement

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1. Introduction

Terahertz (THz) wave is in the range of 0.1 THz–10 THz, it is being widely used in many applications because of its special properties and wide spectral range, such as security,[1] biomedical imaging,[2,3] tomography,[4,5] etc. The traditional terahertz time-domain spectroscopy system (THz-TDS) based on electro-optical (EO) sampling technique or photoconductive detector uses a mechanical delay line[6,7] to obtain a THz time domain waveform, and this process usually takes several seconds to several minutes. When the traditional system is used, the performance of the sample should be stable. But some typical ultrafast events are irreversible, which are very difficult to be reproduced, such as material irreversible damage, protein denaturation, and some life process.[8] Hence, many single-shot measurement techniques were development in order to study these ultrafast irreversible processes, such as spectra encoding,[9] crossed detection,[10] and reflective echelons.[11] Recently, some researchers developed a THz single-shot technique based on pulse front tilting by a blazed grating.[12–14]

In this article, we improved the THz single-shot technique and obtained better experimental results. First, the experiment setup and the principle of the system are introduced. Then, we demonstrate the time domain waveform and frequency spectrum of the THz pulse acquired by the single-shot system, which are consistent with the results from a traditional EO sampling technique. Finally, we discuss the reasons for differences in waveform details and the factors contributing to the signal-to-noise ratio (SNR).

2. Experiment setup

Figure 1 shows the schematic of the THz sight-shot measurement system used in our experiment. A femto-second (fs) laser amplifier (Spitfire Ace-100F, Spectra-Physics, USA) generates the laser pulses with the time duration of 100 fs, the repetition rate of 1 kHz, the central wavelength of 800 nm, and the average output power of about 4.5 W. The fs laser beam is split into pump beam and probe by a 70/30 beam splitter.

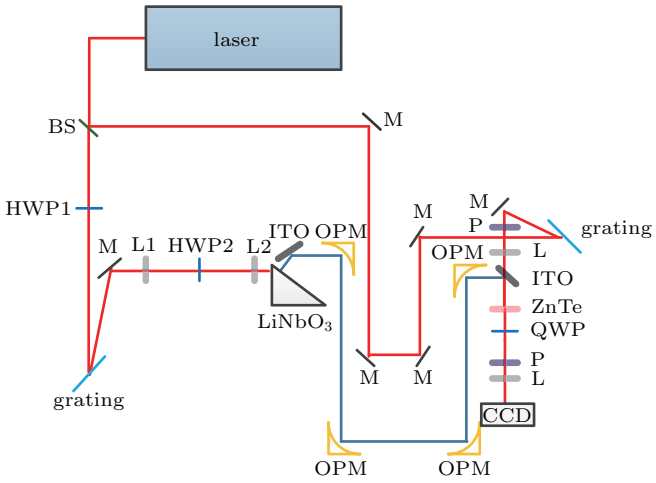


Fig. 1. Schematic of terahertz single-shot measurement system based on tilted wavefront. BS: beam splitter; HWP: half wave plate; ITO: indium tin oxide; OPM: off axis parabolic mirror; P: polarizer; M: mirror; QWP: quarter wave plate; CCD: charge coupled device; L: lens.

$MgO:LiNbO_3$ is pumped by the pump pulse with a tilted wavefront to generate a THz pulse with high electrical field.[15–17] The principle of generation of tilted wavefront using a blazed grating is shown in Fig. 2.

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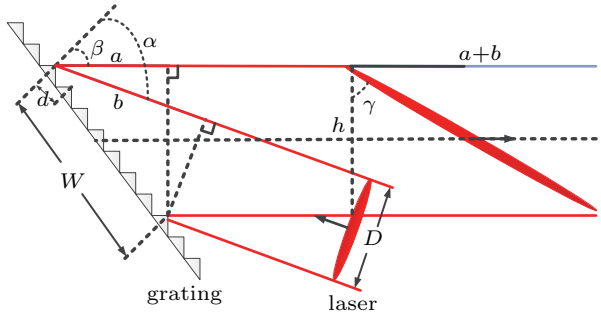


Fig. 2. Schematic of generating tilted wavefront using grating.

The probe beam is also treated in the same way to generate a tilted wavefront. In Fig. 2, the laser with the beam diameter of D illuminates on a blazed grating (1200/mm, GR50-1208, Thorlabs, USA) with the incident angle of α, the first order diffraction beam is used as the probe light, according to the grating equation

$$\sin\alpha + \sin\beta = \frac{\lambda}{d}, \tag{1}$$

where β is the diffraction angle, λ is the wavelength of the laser beam, d is the grating constant. $a+b$ is the optical path difference between the upper edge and lower edge of the laser beam reaching the same phase plane h, the probe generates a titled wavefront, γ is the tilting angle. As shown in Fig. 2, W is the beam diameter on the grating, so

$$W = \frac{D}{\cos\alpha}, \tag{2}$$

$$a = W\sin\beta = \frac{D\sin\beta}{\cos\alpha}, \tag{3}$$

$$b = W\sin a = \frac{D\sin\alpha}{\cos\alpha}, \tag{4}$$

$$h = W\cos\beta = \frac{D\cos\beta}{\cos\alpha}. \tag{5}$$

According to Eqs. (1)–(5), the expression of γ is

$$\gamma = \arctan\left(\frac{a+b}{h}\right) = \arctan\left(\frac{\sin\alpha+\sin\beta}{\cos\beta}\right) = \arctan\left(\frac{\lambda}{d\cos\beta}\right). \tag{6}$$

The single-shot measurement of THz pulse based on pulse-front tilting converts the time measurement in time domain to a space measurement, as shown in Fig. 3. Here we used a blazed grating to generate the tilted wavefront of the probe pulse as shown in Fig. 2. When a THz pulse and the probe pulse are collinearly incident on the ZnTe crystal simultaneously, the EO effect reflects the time varying information of the THz pulse across the diameter of the probe pulse, and this information is then recorded by a charge coupled device (CCD, BEAMAGE-3.0, gentec-eo, Canada) behind a confocal lens. A pair of polarizers before and after the ZnTe crystal are used to analyze the polarization state change of the probe pulses. A quarter-wave plate (QWP) before the second polarizer compensates the strain-induced birefringence and makes linear measurement of THz trace instead of quadratic measurement.

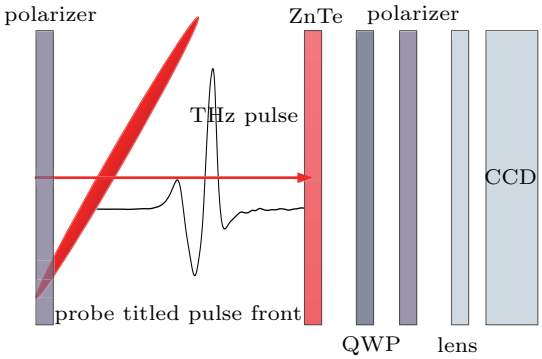


Fig. 3. Schematic of single-shot measurement of THz pulse by probe pulse with titled wavefront.

3. Results and discussion

During the experiment of THz single-shot measurement, a probe pulse without THz pulse was taken as a background image, then the probe pulse with THz information was taken as a signal image. When the signal image subtracted the background image, the result showed the polarization state change of the probe pulses caused by the electric field of the THz pulses. Figure 4 shows the raw image of single-shot measurement of the THz pulse. Here the units of x axis and y axis are pixels. To obtain the relationship of space (pixel in CDD) and time (time interval in time domain waveform), we moved the stage and made the THz pulse meet with the probe pulse with a tilted pulse front at different position and the results are shown in Figs. 5(a)–5(f). The x axis has 2048 pixels, the amplitude of the electric field of the THz pulses is given by vertically accumulating the date of the y axis. Figure 5(g) shows the temporal waveforms extracted from Figs. 5(a)–5(f). In Figs. 5(a)–5(f), the mechanical delay line interval between two adjacent images is 0.4 mm, the delay time is 2.67 ps, and then the peak position of the THz pulse waveform shifts is 60 pixels, so the temporal resolution is 44.4 fs/pixel, therefore, the temporal waveform can be obtained.

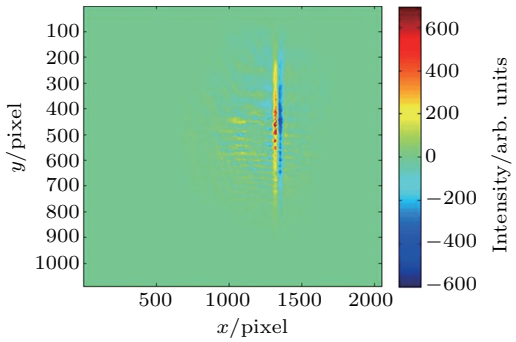


Fig. 4. The raw image of single-shot measurement of the THz pulses.

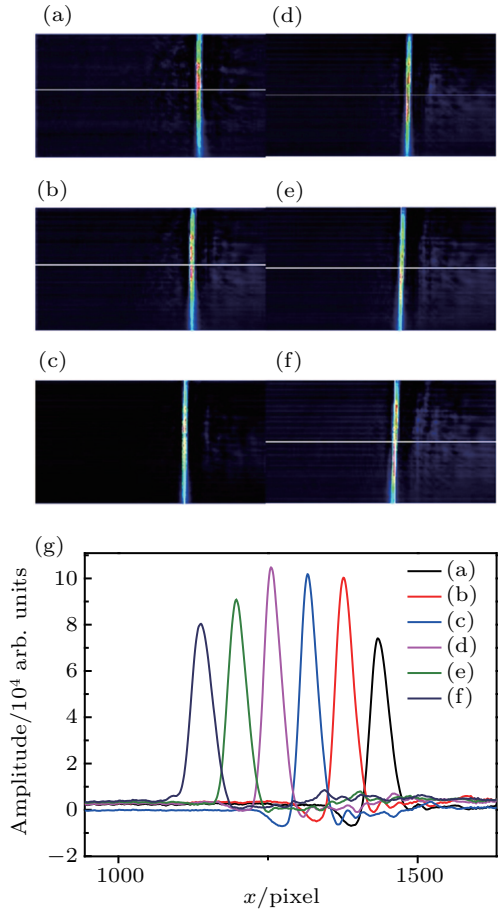


Fig. 5. (a)–(f) The raw images of single-shot measurement of THz pulses at different positions (the step size of the time delay is 2.67 ps). (g) Temporal waveforms extracted from (a)–(f).

Figure 6 shows the time-domain waveform extracted from Fig. 4, and a time-domain waveform obtained from the traditional EO sampling method for comparison. By fast Fourier transform, the spectrum is obtained. Figure 7 presents their power spectra from Fig. 6.

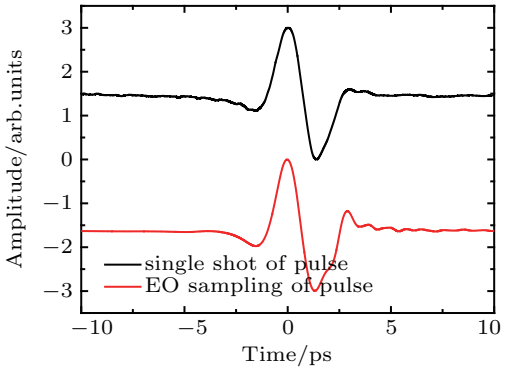


Fig. 6. The time domain waveform of the THz pulses with single-shot measurement (upper), along with EO-sampling (lower).

The single-shot measurement results agree well with those of the traditional EO sampling method. The SNR of the single-shot measurement THz time-domain waveform is 2000:1, but that of the traditional EO sampling result is 10000:1 under the same conditions. The spectra cover from 0.1 THz to about 2.0 THz and the spectral resolution is 0.011 THz. The SNR of the single-shot measurement result is lower than that of EO sampling, which is caused by the following five main factors. First, the CCD exhibits a broadband spectral response in the wavelength of 350–1150 nm, but the central wavelength of the laser is 800 nm, and the responsivity of the CCD at 800 nm is only 65% of its maximum. Second, the image quality of the probe pulse with a tilted pulse front on ZnTe and CCD is very important, the image blurring and geometric distortion can lead to signal distortion, the perfect position of the lens and the better quality of the ZnTe crystal can improve the image quality. Third, the single-shot measurement is based on the background subtraction method, the more stable the laser power, the smaller the background noise. Fourth, the polarization state of the probe pulses is modulated by the THz pulses, which is defined as the electric-optical modulation degree. According to the previous studies, the EO modulation degree is positively related to the thickness of the EO-crystal at the same THz electric field intensity. So, a thicker crystal can be used for higher SNR. Finally, the THz power increases with the increasing pump power, so the SNR of the system will be higher if a stronger pump laser is used. The system will be more practical, if the above question can be solved.

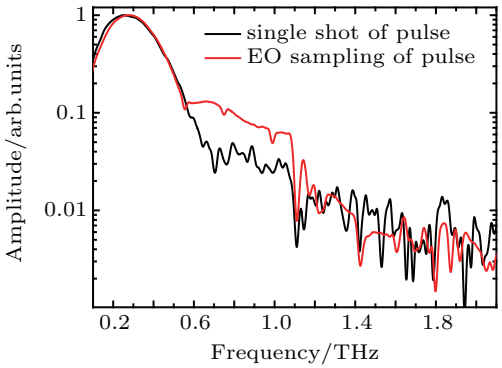


Fig. 7. The THz power spectra with single-shot measurement (black line), along with EO-sampling (red line).

4. Conclusion and perspectives

In summary, a THz single-shot system was demonstrated, and its performance was measured. Its spectrum covered from 0.1 THz to about 2 THz with a spectral resolution of 0.011 THz, and the SNR of the time domain waveform was $\sim 2000:1$. The main factors affecting the SNR of the system were discussed in detail. Reduce the background noise or increase the THz electrical field, a higher SNR can be obtained, which is help to improve the practicability of the system.

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