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A Single-shot Terahertz Time-domain Spectroscopy Instrument for Intense Laser System

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Abstract. A single-shot terahertz time-domain spectroscopy method is developed using an echelon-pair. Terahertz waveform is encoded to a beamlets array by electro-optic effect, with a total time window of 37.7 ps and a time step of 94.3 fs. Comparing with spectral encoding methods, this technique directly encodes terahertz waveform to spatial resolution, which is more suited as a terahertz diagnosis for high power ultra-short laser systems with inherent spectral fluctuations.

1. Introduction
Terahertz time-domain spectroscopy (TTDS) is a widely used diagnosis tool of various Terahertz (THz) sources. Traditional TTDS is using a multi-shot scanning method to obtain the temporal waveform of THz wave, which limits its applications in high power laser and THz source experiments as those sources are usually of low repetition rates or have shot-to-shot fluctuations. Recently, single-shot TTDS is of interests to many researches such as intense THz generations, ultrafast relativistic electron beam diagnostics [1-3], etc. Most of the schemes for single-shot detection of THz fields exploit the spectral encoding with a chirped probe pulse [4], which requires a rather stable output spectrum of the probe laser. For those widely used short pulse Chirped Pulse Amplification (CPA) laser systems, spectral shaping methods, like a birefringent filter [5] or an acousto-optic programmable gain control filter [6], are often used to obtain a broadband spectrum so that the pulses can be compressed to tens of femtosecond duration, as the limit of Fourier transform. These spectral shaping components meanwhile increase the instability of laser spectrum, making the spectral encoding TTDS more difficult. In this paper, we present a direct "spatial encoding" single-shot TTDS scheme by using an echelons pair proposed by Kim et.al. [7]

2. Experiments and results
The two reflective echelons used in our experiments are made of aluminum with a surface flatness better than λ/5. The reflective surfaces are designed with 20 steps each and step heights of 400 μm (echelon 1) and 20 um (echelon 2). As shown in figure 1, 400 (20×20) beamlets can be produced with a total size of 10 mm ×10 mm, a time step of ~94.3 fs and a total time window of ~37.7 ps.
A preliminary experiment was performed at the P3 laser system of the Graduate School of Engineering, Osaka University. The experimental configuration is shown as figure 2. A 10mJ, 800nm, 60fs laser beam is set up as a typical pump-probe electro-optic (EO) sampling system [8]. The pump beam is focused into ambient air by a lens with a focal length f=200 mm. A type I beta barium borate (BBO) crystal is placed after the focal lens to generate a second harmonic (2\(\omega\)) laser pulse together with the fundamental one (\(\omega\)). A polymer filter is used to transmit THz wave from the 2-color laser generated plasma channel [9] to be collected by an off-axis parabola (OAP), while blocking the residual \(\omega\) and 2\(\omega\) pulses. The probe arm after passing the reflective echelons pair is sent through a half-wave plate and a polarizer to change the beam polarization to be same with the THz wave. The beam is then collinearly focused onto a 1mm thick <110> ZnTe crystal with the synchronized THz pulse. The THz electric field is encoded to the different position of the beamlets, which is detected by a 16 bit CCD camera after passing another polarizer with a cross polarization. The two lenses (lens 1 and lens 2) are set as an image-relay to reproduce the image of the echelons pair to the camera while keeping the collinear focus with the OAP on the ZnTe.

A typical CCD image of the beamlets is shown as figure 3a. Note that the shape of each beamlet will be square when well imaged, which is difficult to be separated, as they are quite close to each other. When we shift the CCD off the image plane slightly, the beamlets’ shapes change to circles with a much more clear boundary, while the relative intensity remaining similar.
Figure 3. (a) Typical beamlets image without the cross polarizer P2. (b) Beamlets image obtained by comparing the difference of with and without the presence of THz field.

A sample image of the compared difference measured with and without the THz pulse clearly shows the intensity modulated by the THz field, as shown in figure 3b. The intensities of each beamlet are integrated and read out row-by-row following the time step. The single-shot THz waveform is then obtained with a signal-to-noise ratio better than 3 orders, as shown in figure 4a. The measured waveform shifts as we adjust the delay between the pump and probe beams, which agrees well with the designed time steps.

Figure 4. (a) Measured THz waveforms with different delay times between pump and probe beams. (b) The corresponded amplitude spectra. The numbered peaks give the absorption lines from the water vapor in the air.

The corresponded THz spectrum is shown as figure 4b, by performing the Fourier transform of the temporal waveform. Multiple absorption peaks can be found which are mostly contributed from the water vapor in the ambient air. The numbered peaks between 0.2 THz to 2.4 THz show good consistence with the results from Ref. 10.

This single-shot TTDS method was also used to diagnose the THz wave generated in laser-solid interaction experiment. The experimental setup is shown as figure 5a. The P3 laser works at high-
power single-shot mode, outputting 600 mJ, 27 fs pulses before target. The pump laser is focused by an OAP to a solid copper target with a focal spot diameter of 5 μm and a peak intensity of ~1×10^20 W/cm². The laser-accelerated electron beam coupling with a periodic metal structure excites a coherent radiation in the THz range by a scheme similar with Smith-Purcell radiation [11]. The THz wave, after passing a Teflon window, is then collected and focused onto the ZnTe crystal. The probe beam reflected out from the beam transportation chamber by a pellicle beam splitter with 3% of the total laser energy is then collimated with the same setup as the air-plasma experiment. Figure 5b gives a typical single-shot measurement result of the multi-cycle THz waveform generated when electron beam swapping the periodic target surface.

As a direct spatial encoding method, the measurement noise is mostly from the fluctuations of the beam pattern and the beam pointing stability. With careful controls of the laser parameters and system vibrations, the stability of our P3 laser’s far field focal spot is better than few micrometers, and the RMS laser power stability is within 5%. However, with spectral encoding methods, an additional spectral instability will also be induced. In our case, to achieve an ultra-short laser pulse lesser than 30 fs, an acousto-optic programmable gain control filter (Mazzler) is installed inside the regenerative amplifier cavity, which controls the gain of the cavity to obtain an output laser spectrum broader than 70 nm. This spectral shaping optics also increases the instability of the spectrum to be worse than 20%, which is not easy to be reduced. We have tried to use spectral encoding measurement in our system. The THz waveform can’t be clearly revealed, as the noise level is too high.

3. Conclusion

In conclusion, using a reflective echelons pair, we have demonstrated a single-shot TTDS method, which encodes the THz field directly to the spatial distribution, allowing a stable THz waveform measurement with high power ultra-short laser systems. With this scheme, we succeeded in the diagnosis of the THz wave generated by two-color laser ionized air-plasma with a 0.16 TW laser power and by laser-solid interaction with a high laser power of more than 20 TW inside vacuum system.

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