A new single shot THz detection strategy with electro-optic sampling

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ABSTRACT

We present a new technique for single shot Terahertz detection in electro-optics sampling (EOS) with a narrowband probe pulse shaped using a Fabry-Pérot etalon. The technique allows tdetection in the frequency domain using a high-resolution CCD spectrometer. The technique is simple and sensitive. It has a high time resolution and can be simply implemented in a standard EOS scanning experiment

Keywords: Terahertz detection, single shot, electro-optics sampling, Fabry-Pérot etalon.

1. INTRODUCTION

The emergence of terahertz (THz) spectroscopy has proven useful in a broad range of fields from the study of semiconductors and metals, the identification of chemicals relevant in biological systems, and for the pharmaceutical industry, food safety, or even for the detection of explosives [1]–[4]. In THz time domain spectroscopy (THz-TDS), a short optical laser pulse generates an intense few cycles or even single cycle THz pulse. Most commonly, these picosecond THz pulses are detected in the time domain by pulses with much shorter duration through electro-optic sampling (EOS) [5].The complete THz waveform is then reconstructed by scanning many of these short pulses with a delay line. Additionally, numerous schemes have been developed to detect the full THz pulse with a single pulse increasing stability, sensitivity, and speed of detection[6].These schemes are particularly motivated by applications in transient THz absorption spectroscopy or multidimensional THz spectroscopy, where two separate delays need to be scanned simultaneously, slowing down acquisition time. Some of these schemes have allowed to speed up experiments at the cost of more complicated and expensive experimental setups.

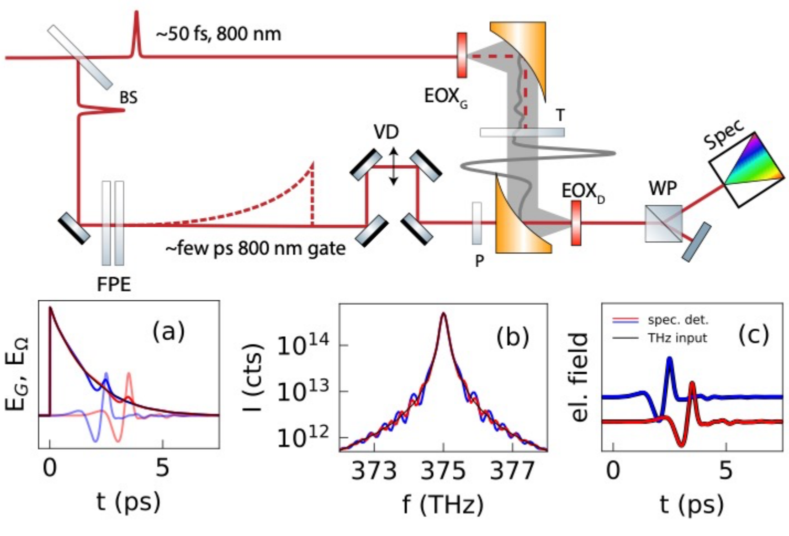

Fig. 1. Experimental setup and sketch of the measurement technique. (a) field envelope (black) of the narrowband picosecond probe pulse acting THz pulse at two different delays (light blue, red), and field envelope with mixing with the THz pulse (blue, red). (b) optical spectra of the envelopes in (a) around the carrier frequency. (c) THz input (black) and recovered THz waveform from the spectra in (b) using the retrieval algorithm following the same color code.

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In this proceeding, we demonstrate single shot THz detection by mixing the THz pulse with a picosecond narrowband probe pulse shaped using a Fabry-Perot étalon (FPE). The measurement principle is sketched in Fig.1. The narrowband picosecond probe (Fig.1.a) is overlapped in time with the THz pulse in the EOS detection crystal. This leads to a amplitude modulation of the picosecond pulse envelope in time, whose spectrum displays modulations in the wings of the original probe spectrum (Fig.1.b). The frequency and the extent of these modulations depend on the strength, spectrum and phase of the THz field, and the time delay between probe and THz pulse. We retrieve mathematically the THz waveform displayed in Fig.1.c. from the measured spectrum, which can be acquired in a single shot with a CCD spectrometer.

2. . MATERIALS AND METHODS

Our laser delivers few mJ, 50fs, 800nm pulses at 1kHz repetition rate. A small portion of the beam is used to generate single cycle THz pulse through optical rectification in a ZnTe crystal. Another portion of the beam is used as a probe for EOS. We previously used this beam for the standard scanning technique of EOS, using amplification schemes for efficient THz detection. Here we used two crossed polarizer and no waveplate in the detection beam. In standard EOS, this would result in completely distorted THz traces [7]–[11], but with our technique, we can use cross polarizer without distortion. We will speculate why this is possible in the discussion section. Instead of rastering the THz waveform by physically displacing the probe beam, we placed a FPE in the probe beam and detected the probe with a miniature high resolution CCD spectrometer (HR4000, Ocean Optics, 0.05 nm/pixel, resolution 0.2nm). When passing our short 50fs pulse into the FPE, a pulse train of pulses with exponentially decaying intensity is created [10–12]. In the limit when the thickness of the FPE is smaller than the pulse extension in space, the train of pulses becomes a continuous pulse with a sharp rise and an exponentially decaying tail which extensions depends on the free spectral range and finesse of the FPE. Our FPE (TecOptics). has a thickness of 11um, (FSR), and a finesse of 80. The spectrum of the outcoming pulse is then defined by the overlap of the input pulse spectrum and the transfer function of the FPE which corresponds to a series Lorentzians separated by the FSR and extended wings connecting them that depends on the finesse. Overlapping the probe with the THz in time and space within the detection crystal results in a polarization modulation of the probe imprinting the THz field's sign and strength. This polarization modulation is transformed into an amplitude modulation by the polarizer placed after the detection crystal. The probe is then detected in the frequency domain with a spectrometer. Depending on the acting THz field, the probe modulations are apparent in the wings of the spectrum as demonstrated in Fig.1.b. From two spectra, with and without the THz acting on the probe we are able to reconstruct the acting THz field by reversing the imprinted amplitude modulation on the picosecond probe (Fig.1.c).

3. MATHEMATICAL DESCRIPTION

The signal field envelope E_{sig} is the probe field E_{probe} modulated in amplitude by the THz field E_{THz}. It follows:

$$E_{sig}(t) = E_{probe}(t)\big(1 + mod(t)\big) = E_{probe}(t) + E_{probe}(t).mod(t) \qquad (1)$$

with

$$mod(t) \propto E_{THz}(t)$$

This modulation in time corresponds to a modulation of the spectrum on both side of the center frequency of the probe. These oscillations detected in the spectrum in Fig(1)b. correspond to a Difference Frequency Generation (DFG) and a Sum Frequency Generation (SFG) effect between the probe and the THz on the low and high frequency side of the center spectrum respectively. The amplitude of these modulations depends on the probe spectrum in the overlaping region between the DFG/SFG and the probe spectrum, the amplitude of the THz and the delay between the probe and the THz pulse. It is an interference effect between the 2 terms on the right hand side of Eq.(1). The consequence of the rapid decay of the probe spectrum with frequency on both side of the probe central frequency is that the high frequency of the THz spectrum will be more affected by noise.

We detect the intensity of the probe in the frequency domain after passing through a spectrometer which yields the square of the absolute value of the Fourier transform of the envelope shifted by the carrier frequency.

$$I_{sig}(\omega) = \left|\mathcal{F}\left[E_{sig}(t)\right]\right|^2$$

We can recover the time domain field $E_{sig}(t)$ inverting the previous equation and keeping only the real part of the inverse Fourier Transform, as fields in the time domain are real:

$$E_{sig}(t) = \Re\left(\mathcal{F}^{-1}\left[\sqrt{I_{sig}(\omega)}\right]\right)$$

Note that this assume that the spectral phase is well behaving and that no dispersion affects the time domain signal, which appear reasonable as our pulse is narrowband. We can do the same for the probe field $E_{probe}(t)$ in absence of THz.

$$E_{probe}(t) = \Re\left(\mathcal{F}^{-1}\left[\sqrt{I_{ref}(\omega)}\right]\right)$$

And the THz field can be simply recovered from eq.(1):

$$E_{THz}(t) = \frac{\mathrm{E_{sig}(t)}}{\mathrm{E_{probe}(t)}} - 1$$

The probe is decaying exponentially in time, so that the delay between the THz and the probe has a strong effect on the modulation signal in the time domain. Also, the tail of the time domain THz pulse will overlap with less intense probe, so that it will be more affected by noise. Moreover, a good knowledge of the probe in the time domain is crucial for a correct recovery of the THz. For the proof of concept presented here, we assumed that the probe duration was Fourier transform limited, but it might be necessary to have an experimental measurement of the phase an amplitude of the probe for a more accurate recovery of the THz pulse.

4. RESULTS AND DISCUSSION

In Fig(2a) we present the measured spectrum for three different delays between the THz and the probe, making sure the overlap in time is satisfactory to recover the full THz trace. These data are averaged over 1400 shots. We used a log scale for th y-axis, as the spectral intensity of the probe decays fast with frequency on both side of the probe central frequency. The signal to noise ratio is still very good thanks to the high dynamic range of CCD detectors. We must highlight the fact that we symmetrized the spectra by mirroring only the low frequency side to the high frequency side of the spectrum. That lead to better THz recovery for a reason that is not clear at the current state of our knowledge. Note that mirroring the high frequency side would also work properly, with slight discrepancies in the THz recovery between the two methods.

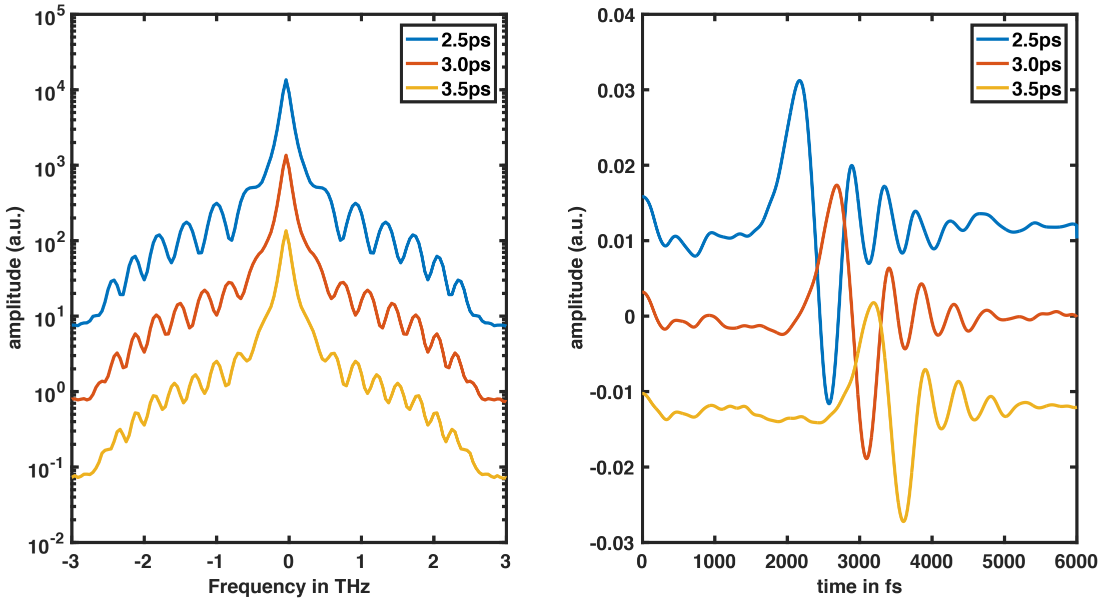

Fig. 2: a) symmetrized measured spectra for three different delays between the probe and the THz pulse, the frequency has been shifted to the center frequency of the probe pulse. b) time trace recovered from the spectra in a). In both graphs, the curves are shifted for clarity.

On Fig (2b) we plotted the recovered THz traces in the time domain for the three measured spectra of Fig(2a). The traces are consistent, and we observe that we are sensitive to the absolute delay between the THz and the probe. The three traces should be identical but, we observe a decay in amplitude, which is an indication that the the probe field is certainly longer than the simple Fourier transform of the spectrum that we used. This phase effect has not been investigated at the time being, and as mentioned before, a better knowledge of E_probe (t) would certainly make the method more accurate.

We also want to highlight the fact that this method is very sensitive to small delays or phase changes of the THz. The method being interferometric, a small change in delay is easily detectable. In the standard EOS scanning method, the signal at a definite stage position is convoluted with a 40fs pulse with a stage accuracy in the order of a few fs (in our case) making the absolute accuracy in the THz phase hardly better than 10fs. Here, there is not such limitations, and we could indeed measure very small delay changes (on the order of 1fs): This is for us a crucial advantage as we are usually limited by the poor phase sensitivity with the standard EOS scanning method, and we usually work around this limitation by making thicker samples.

Finally, we want to show the recovered THz traces for three randomly selected single shot measurements in Fig.3. To perform these measurements, we had to chop 3 pulses over 4 as our spectrometer can not integrate for less than 4ms (4 shots). We can see that the recovery is consistent even for single shot measurements when we compare the three single shot traces with the one averaged over 100 shots. The experimental conditions were slightly change in this experiment, compared to what is presented in Fig2., which explains the discrepancy between the THz waveform of Fig 2 and 3.

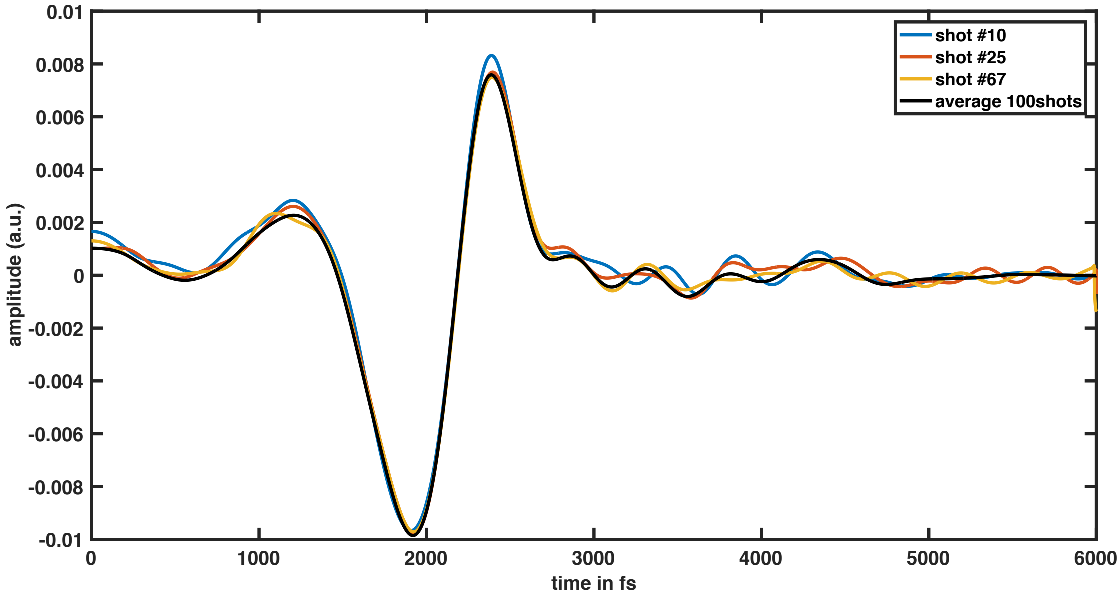

Fig. 3: collection of three recovered single shot THz traces together with the average over 100shots (black)

5. CONCLUSION

In conclusion, we presented a new single shot THz measurement technique that is very simple to realize. The method is particularly sensitive to the phase which is of great interest when measuring on thin samples like the conductive polymers we use in our research [12]–[14]. The reliability of the recovery could be improved with a better knowledge of the pulses, and with more adapted optics and detection system: in fact the FPE used in this work was not design for the purpose presented in this proceeding, and the specifications of the FPE could be better adapted to THz single shot detection.

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