A new method to measure the shape of short THz pulses: Differential Electronic Gating

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Abstract **- A simple experimental method has been developed to determine the shape of repetitive picosecond THz pulses in the presence of jitter in the trigger signal. This method, a modification of the recently reported Differential Optical Gating (DOG) method, is based on the femtosecond electronic gating of a high-frequency sequential oscilloscope. Preliminary tests have been performed on pulses from the free electron laser FELIX as well as on pulses from a mode locked p-Ge laser.**

I. INTRODUCTION

In the visible and near infrared spectral region many non-linear detection techniques are used to determine the shape of picosecond optical pulses by measuring the pulse intensity auto-correlation. At THz frequencies, some work has been done in this field. For instance, using two-photon absorption in p-type $Hg_xCd_{(1-x)}Te$, the width of picosecond pulses of the free electron laser FELIX for a wavelength range from 20 μm to 40 μm has been studied [1]. Recently, it was demonstrated that a GaAs/AlAs superlattice detector could be used as an autocorrelator for intense THz pulses in the 1 – 7 THz frequency band [2, 3]. However, the intensity auto-correlation has, in principle, the disadvantage that any asymmetry in the pulse shape can not be determined. Also, general use of non-linear detection techniques at THz frequencies is not feasible due to the small optical susceptibilities of materials and /or low pulse intensities in this wavelength region.

Two *linear* techniques to analyze short THz pulses already exist. These use high intensity femtosecond optical pulses to *create* as well as to *detect* - through optical or electronic gating - broadband THz pulses [4, 5]. The intrinsic synchronization between a THz and a gating pulse results in a very good time resolution. Other sources for the creation of short THz pulses, such as the free electron laser and the mode locked p-Ge laser, however, do not rely on optical pumping. The use of a gating technique, therefore, causes serious problems to synchronize the THz and gating pulses, strongly detoriating the temporal resolution with which the THz pulse can be determined.

Recently, Rella et al. [6] developed the "Differential Optical Gating" (DOG) method, that enables the study of THz pulses with a good time resolution, *also* in the absence of an adequate synchronization between THz and gating pulse. A disadvantage of this technique is that, in order to obtain a time resolution of the order of picoseconds, a mode-locked Ti:Sapphire laser system is needed.

We have developed a simple technique, based on the DOG principle, that does not rely on optical, but on *electronic* gating. This work was started in order to determine the precise pulse width of our mode-locked p-Ge THz laser, which, until now was impossible because

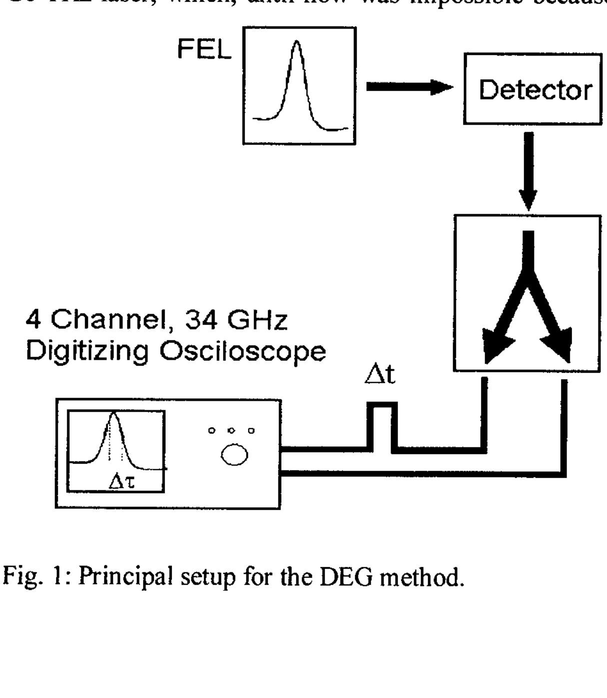

Fig. 1: Principal setup for the DEG method.

of the limited bandwidth of the 6 GHz single-shot oscilloscope used. We show that, with this "Differential Electronic Gating" (DEG) method together with an ultrafast room temperature detector, a time resolution in the picosecond range is possible.

II. PRINCIPLE OF THE DIFFERENTIAL TECHNIQUE

In the DEG technique the THz pulse is detected by one fast detector. The signal is *electronically* gated and recorded at two slightly different times t and $t + \Delta t$. In that way, both the average intensity $\bar{I}$ = [I(t+Δt)+I(t)]/2 and the time derivative of the intensity $F(\bar{I})$ = [I(t+Δt)-I(t)]/ Δt are determined. For a series of THz pulses, this yields a set of derivative *versus* intensity data, $\{F(\bar{I})\text{-}\bar{I}\}$, which is *not* influenced by jitter in the trigger, as time as explicit variable has been eliminated. The actual pulse intensity as a function of time can now be reconstructed by integration: $\int_{\bar{I}_0}^{\bar{I}_1} d\bar{I} / F(\bar{I}) = t(\bar{I}_1) - t(\bar{I}_0)$. It must be noted that this integral is only well defined, if $F(\bar{I})$ does not contain any zeros. But at the pulse maximum the derivative will always be zero. Therefore, without additional assumptions it is only possible to reconstruct rising and falling edges of a pulse shape. In order to obtain the pulse duration, one can take advantage of the fact that the density of data points indicates the relative amount of time spent in a given part of the F-$\bar{I}$ curve. By comparing the density in the peak region ($\bar{I}$ = max. and F = 0) with the density in the region, where F ≠ 0, the time duration of the pulse peak can be inferred.

III. EXPERIMENTAL

We have tested the DEG technique (the principle of our experiment is shown in Fig.1), using either pulses at a wavelength of 150 μm from the free electron laser "FELIX", set at a 4 μs long macropulse and a micropulse repetition frequency of 1 GHz, or pulses at 175 μm from our mode-locked p-Ge THz laser. The light is focused on a fast room temperature superlattice detector [3] consisting of a GaAs/AlAs superlattice mounted in a corner cube reflector with a long wire antenna. The video output of the detector was amplified with a 28 ps rise time amplifier and split by a Picosecond Pulse Labs. Model 5335 high frequency power splitter. One signal is delayed with respect to the other, using two coaxial lines with a slightly different length.(see fig. 1) The signals I(t+Δt) and I(t) are measured at the same time on two different channels of a HP 54120B gating oscilloscope with 54123A front-end, featuring a 34 GHz bandwidth and a 200 fs electronic gate width. Pulse shapes have also been studied using a single shot 6 GHz bandwidth Tektronix 7250 oscilloscope. The time delay between the channels, that determines the time scale of the reconstructed pulse, is measured by sending the scope's TDR pulse into the power splitter, and comparing the time delay of the signals on the two channels. At the

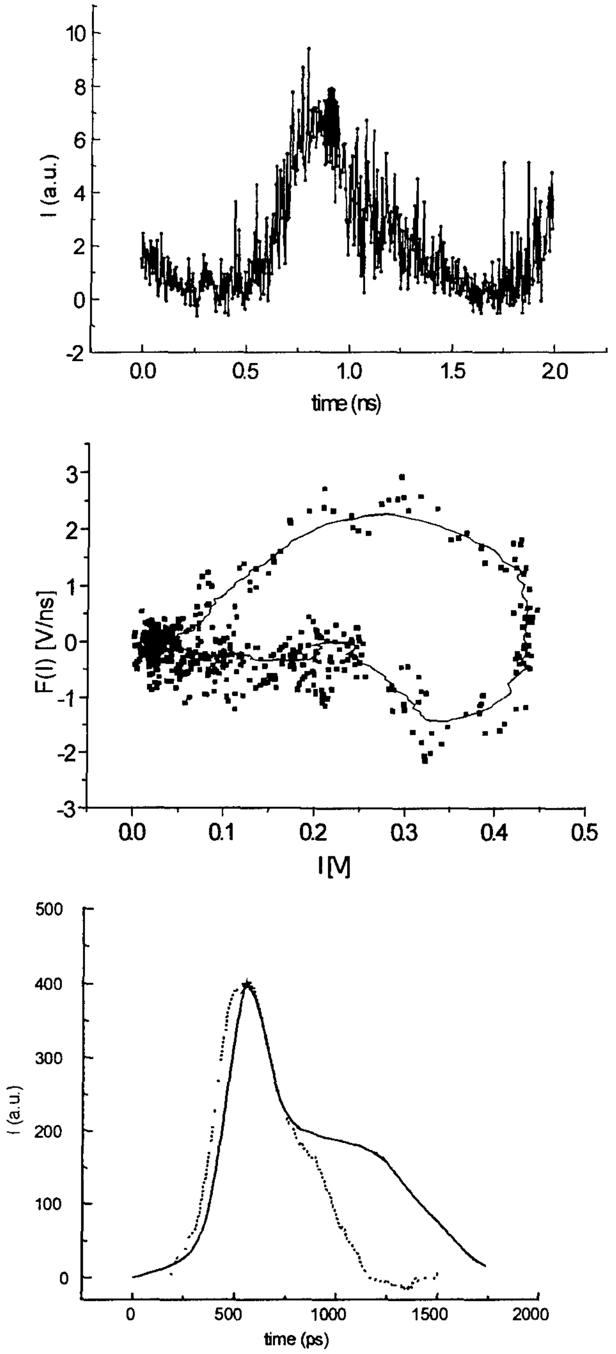

Fig. 2: Mode-locked p-Ge laser output:

a: Sequential data with optical trigger.
b: F *versus* I plot with Δt = 40 ps.
c: Reconstructed pulse (solid line) and averaged sequential signal (dotted line).

same time the accuracy of the power splitting is checked. Using the normal sequential data collection routine of the oscilloscope, a set of data {I(t+Δt), I(t)} is taken at each macropulse, with a 0.2 ps stepwise increase of the time delay between external trigger and electronic gate.

IV. RESULTS

The first experiment was performed using the output of our mode-locked p-Ge Thz laser [8]. Earlier experiments using a 6 GHz bandwidth single shot oscilloscope proved that that source was able to produce 60 ps FWHM pulses. In view of the 50 ps overall rise time of that electronic system, clearly a way to improve the time resolution had to be found! In this experiment we used a 40 ps time delay between the two channels, and the optical signal itself was used as a trigger. In fig. 2^a the sequential data from two channels are shown, whereas in fig. 2^b the F *versus* I plot of a large data set is given. The reconstructed shape is shown in fig. 2^c, together with a pulse shape obtained from an averaged sequential scan. Although the FWHM value of the reconstructed pulse is slightly smaller, the overall shape is even worse than that obtained from the direct scan. Clearly this method does not work properly in this case. The reason for that is the strong shot to shot variation of the intensity and shape of the pulse resulting from strong mode beating of the laser.

To test the technique with a well controlled source with a reproducible pulse shape, experiments were started at the FELIX free electron laser. For this experiment, the laser was slightly detuned to create a double pulse structure [9]. In a first test we used Δt=13 ps and the optical signal itself was taken as a (very good) trigger. In fig.3^a the resulting data sets for the two channels show a well defined double pulse structure. Fig. 3^b gives the same data set, but now plotted as F *versus* I; a double loop curve is seen, characteristic for pulse structure with two unequal pulses. The reconstructed shape is given in fig.3^c and compared to the direct signal of fig.3^a. Because of the finite overlap between the two pulses, no zero intensity region in between the pulses occurs, and thus the distance between the pulses can be unambiguously determined from the experimental data. The two shapes match quite well and the FWHM value of the first peak in both cases is about 50 ps, mainly set by the amplifier rise time. For the second test Δt=7 ps was taken and the macropulse trigger was used with a jitter of about 1 ns; two orders of magnitude larger than the FWHM of the pulse . In the data from the first channel given in fig. 4^a, therefore, no pulse shape can be distinguished at all. In Fig.4^b the full data set F-$\bar{I}$ plot is shown and the reconstructed double pulse is given in Fig. 4^c. The FWHM of the largest pulse is about 40 ps, slightly smaller than before, due to the smaller value of the time delay Δt used.

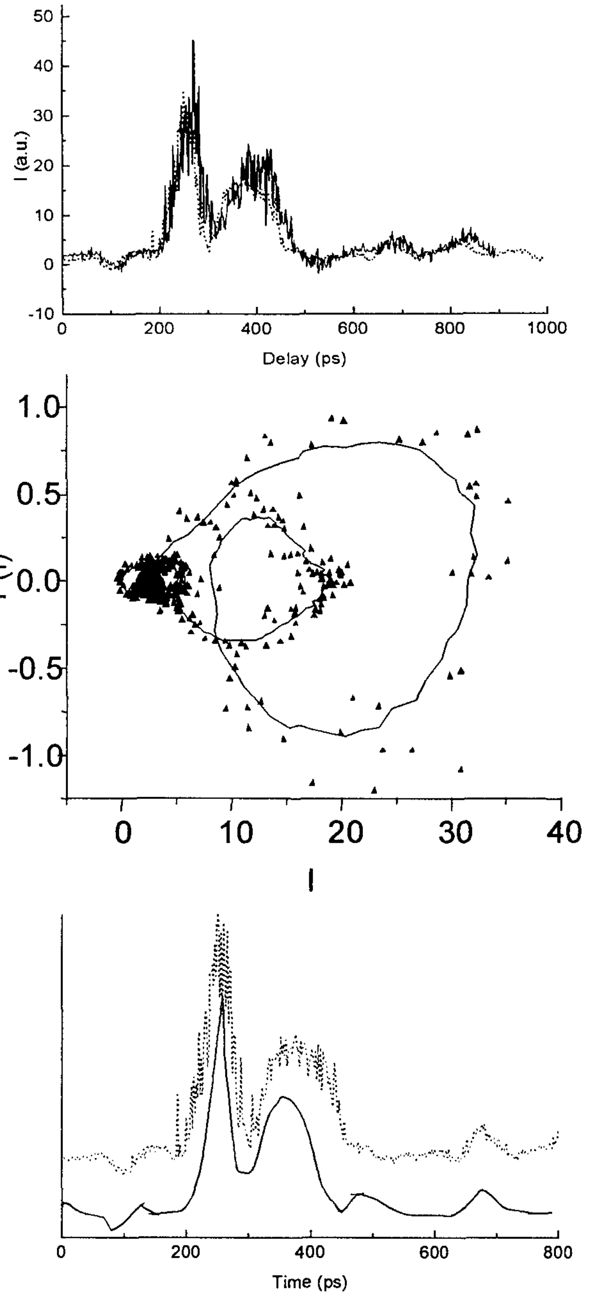

Fig. 3: FELIX double pulse:

a: Sequential data with optical trigger: two chanals with Δt = 13 ps.
b: F *versus* I plot with double loop contour.
c: Reconstructed pulse (solid line) compared with sequential pulse shape.

V. CONCLUSIONS

We have shown that the use of the differential electronic gating (DEG) method enables the detection of repetitive picosecond THz pulses, even when the jitter of the synchronization signal is much larger than the width of the pulse. The time resolution of this method is limited by the electronic rise time of optical detector and electronics. The shot to shot reproducibility of the pulse shape, however, has to be good - like in all sequential recording techniques – in order to obtain an optimal result.

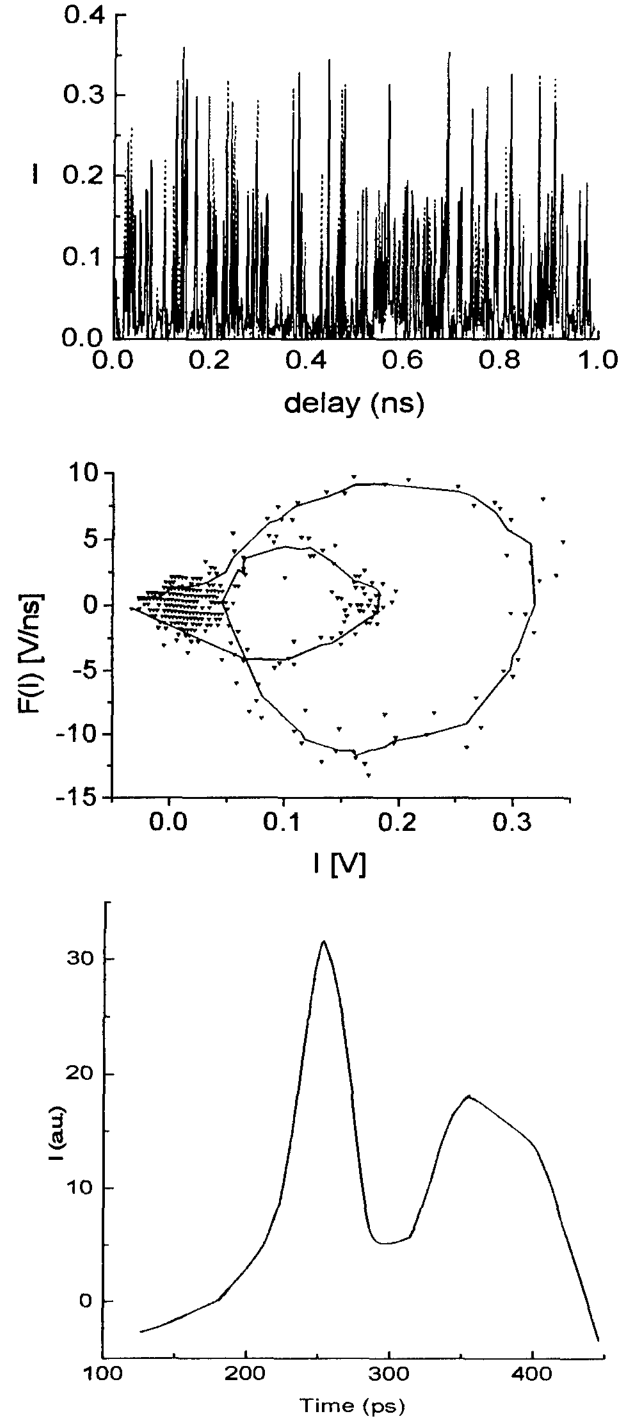

Fig. 4: FELIX double pulse:
a: Sequential data with macropulse trigger; two channals with $\Delta t = 7$ ps.
b: F *versus* I plot.
c: Reconstructed pulse with 40 ps FWHM.

Acknowledgments

The authors thanks M.J.W. Vermeulen from the Delft Interfaculty Reactor Institute for the use of the 6 GHz oscilloscope and W.Wegscheider for the sample growth.

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