Single Shot Temporal Contrast Measurement of Subpicosecond Pulses

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Abstract. We propose a new single-shot third order correlator to measure the temporal contrast of pulses in the picosecond range of high power chain lasers. We use time-to-angular coding to transfer the temporal contrast information to a $3\omega$ probe pulse. We determine the temporal window with the resolution obtained from this technique and predict via simulations the time-to-space coding as well as the time-to-frequency coding. We demonstrate the concept experimentally. The image acquisition is performed with a simple 16 bit CCD camera. An amplitude mask can easily improve the dynamics.

1. Introduction

In general, the ultra short laser pulses from a Chirped Pulse Amplification (CPA) laser suffer from amplified spontaneous emission (ASE) background and pre- and post-pulses associated with the main laser pulse. The pre-pulses combined with ASE will modify the target and thus significantly alter the physics of the laser-matter interaction. In Ultra High Intensity (UHI) physics\cite{1} the contrast ratio between the main pulse, the pre-pulse and ASE must be between $10^7$ and 100 femtoseconds up to the nanoseconds scale. In the context of the French Aquitaine Petawatt project\cite{2}, the ranged contrast is $10^{10}$. Another characteristic of UHI laser is their low repetition rate. So to obtain the contrast ratio of a UHI laser, we need to measure the contrast ratio with a single shot measurement.

Direct measurement of the contrast ratio with an electro optics device utilizing a fast integrator is typically limited to 100 picoseconds resolution. Below this resolution, an optical method is used. To acquire the temporal profile in a single shot configuration, the time must be coded in another dimensionality includes space, wavelength and angular dispersion. Space, wavelength and angular domain can be used. Since the final detector is a CCD spatial detector, the wavelength and angular domain must be converted into spatial domain using a spectrometer and a lens respectively. In 1998, Sirutkaitis et al\cite{3} demonstrate the first single shot third order correlator using time-to-space coding. The third-order correlation was registered over a 3 ps temporal range. A dynamic range of $10^3$ was demonstrated and limited only by the photodiode array detector. Collier et al\cite{4} presented a simple linear design. In 2001, Geindre at al.\cite{5} demonstrated a method for obtaining the time-resolved measurement. Based on spectral interferometry, the time-to-wavelength technique allows for single-shot measurements and keeps the temporal resolution consistent with the full bandwidth of the probe pulse. Surville in his thesis\cite{6} demonstrated a time-to-wavelength coding method to measure the spatio temporal evolution of a smoothed laser pulse.
We demonstrate a single-shot third order cross-correlator based on time-to-angular coding [7-8]. Upon presentation of an analytical study of this coding technique, we compare the three different coding methods. In a third part we demonstrate experimentally the time-to-angular coding.

2. Comparison between the different time coding.

To enable us to compare the time-to-angular coding to another encoding method, we performed an analytical study of vectorial coding. An acousto-optic device is typically used for this purpose. However this technique is too slow to enable picosecond resolution. A diffraction grating (N grooves/mm) creates an angular dispersion of the spectral components of the input pulse. In this way the temporal stretch is linked to angular dispersion [7]. To overcome this limitation we used a two step coding method: in a first step we create a time-to-wavelength coding using a simple grating stretcher (F stretching factor). In a second step, a diffraction grating creates a wavelength-to-angular coding. Hence the temporal stretch and the angular dispersion are freely adjusted.

The addressable number of points in single shot diagnostic correspond to independent points that can be acquired. In a time-to-angular coding cross correlator the addressable number of points is the ratio between the dispersion, $\theta_d$, induced by the grating and the natural full angle diffraction, $\theta_d$, of the beam: 

$$N_{\text{points}} = \frac{\theta_d}{\theta_d}.$$ 

The dispersion is $\theta_d = N \Delta \lambda / \cos \alpha_0$, the divergence is $\theta_d = 2 \ln 2 \lambda / \langle d \pi \rangle$, $\lambda$ is the central wavelength, $\Delta \lambda$ is the spectral bandwidth of the pulse, $d$ is the Full Width Half Maximum size of the beam on the diffraction grating and $\alpha_0$ is the grating diffraction angle. The same results are obtained using a temporal approach and taking into account the ratio between $\tau_R = d N \lambda / (c \cos \alpha_0)$ the transverse time delay induced by the grating and $\tau_0$ the duration of the transform-limited pulse. However, the input pulse on the diffraction grating is not Fourier Transform limited. When the input chirp pulse, $\tau = F \tau_0$, is longer than the transverse delay time, the number of points is limited by: 

$$N_{\text{chirp,points}} = \frac{F \tau_0}{\tau_R}.$$

The optimum corresponds to the maximum of the two numbers of addressable points. The maximum number of addressable points is $N_{\text{points}} = \sqrt{F}$ when $\frac{d}{\sqrt{F}} = \frac{2 \ln 2 \lambda}{\pi \Delta \lambda N \tau_0}$. In this case the resolution is equal to the delay time induced by the dispersion grating: 

$$\tau_{\text{resolution}} = \tau_R = \sqrt{F} \tau_0.$$

| Coding methods: | Spatial | Spectral [6] | Angular |
|----------------|---------|-------------|---------|
| Resolution     | $\tau_0$ | $F \tau_0$ | $\sqrt{F} \tau_0$ |
| $\frac{n \tan \phi/2}{2c} d$ | $\frac{2 \sqrt{2}}{\sqrt{c}} \tau_0$ | $F \tau_0$ | $F \tau_0$ |
| Number of points addressable | $\frac{2c \tau_0}{n \tau_0}$ | $2 \sqrt{2}$ | $\sqrt{2 \ln 2} \sqrt{F}$ |

a With $\tau_0$ is the FWHM duration of the fundamental input pulse, $n$ the refractive index and $\phi$ the angle between the two beams.

The table 1 summarizes the descriptors for each coding method in this investigation. One of them is the very low number of points addressable in the time-to-wavelength coding. This result can be understood because, firstly, the spectral bandwidth of the second harmonic corresponds to the total temporal width of coding and secondly the spectral bandwidth of the second harmonic is roughly equal to the spectral bandwidth of the fundamental beam. Since the number of addressable points is
the ratio between the spectral bandwidth of the third harmonic and the spectral bandwidth of the fundamental beam, the number of points is very low. To perform a high number of usable points, the spectral bandwidth of two beams must be very different. The time-to-space coding has a good resolution but a temporal probe domain width limited by the transverse spatial size of the beam or the third harmonic crystal. The time-to-angular coding has a limited resolution but a freely adjustable temporal domain width.

A more complete analytical evaluation of the electric field demonstrates that the number of addressable points is:

\[
N_{\text{analytical points}} = \left\{ \left[ 1 + 2 \left( \frac{T_R}{T_0} \right)^2 \right] \left[ 1 + 2 \left( \frac{T_R}{T} \right)^2 \right] \left[ 1 + 4 \left( \frac{T_R}{T} \right)^2 + 4 \left( \frac{T_R}{T_0 T} \right)^2 \right] \right\}^{1/2}
\]

This expression is in good agreement (figure 1 – full line) with the previous approach and with a complete simulation performed under Miro [9] (red dot). Moreover, the limitation induced by the diffraction grating for small beam size (dot line) and by the chirp are plotted (dash line).

![Figure 1. Number of addressable points induced by diffraction grating (dot line), chirp of pulse (dash line), calculated with a complete analytic approach (line) and with simulation under Miro code (red dots).](image1.png)

![Figure 2. Experimental setup. SHG: second harmonic generation, THG: third harmonic generation.](image2.png)

### 3. Experimental results

#### 3.1. Experimental setup

This diagnostic is a single-shot third order cross correlator based on a time-to-angular coding. The third order correlation is done between a fraction of the input pulse and the major part second harmonic converted input pulse. After the second harmonic conversion, the time-to-angular coding is realized in two steps: a first one creates a time-to-wavelength coding with a double pass grating compressor. A second step creates a wavelength-to-angular coding using a simple diffraction grating. The experimental setup is sketched on Figure 2. The input pulse is split into two arms with a half wave plate and a polarizer. Less than 10% of the energy input is sent through the first arm for the pulse being tested. The ratio between the two arms is slightly adjusted to perform the best Third Harmonic Generation (THG) efficiency. The pulse in the second arm is frequency doubled with a type I BBO crystal. The SHG pulse goes across a double pass compressor. This chirped pulse is sent to 2400 lines/mm diffraction grating with an angle of incidence angle close to Littrow angle. Beams of two arms are mixed in the THG BBO type I crystal with a lens of focal length \( f_1 \) located a distance \( 2f_1 \) away from the diffraction grating. The angular coding is transformed in spatial coding on a 16 bit...
CCD camera with a lens of focal length $f_2$ located a distance $f_2$ from the THG crystal. Spatial and $3\omega$ filters are located in front of the camera to remove the fundamental and second harmonic beams.

![Figure 3. Correlation between the $2\omega$ spectrum and the THG along the temporal interval available.](image1)

![Figure 4. Single shot contrast measurement without amplitude correction (dot) and with an amplitude correction (line).](image2)

3.2. Experimental results and discussion

Optical pulses from CPA Titanium: Sapphire regenerative amplifier were used to demonstrate the cross correlator. The amplifier delivers a 200 fs, 500 µJ pulse at 1053 nm at 10 Hz. To validate the cross correlator we insert before the diagnostic a Michelson interferometer with an unbalanced energy and delay arms. Therefore, we can adjust the energy and the delay of the second pulse. We have verified the linearity of the temporal calibration for the CCD camera at 200 fs/pixel with resolution of 600 fs. The Figure 3 plots the variation of THG main pulse along the temporal window moving the delay line. This figure demonstrates the correlation between the $2\omega$ spectrum profile of the probe pulse and THG amplitude signal along the time interval. Therefore, we can define a Gaussian profile amplitude correction using the 23 picoseconds time interval. Using this amplitude correction on a measured single shot contrast measurement (dots on Figure 4) we can calculated the corrected single shot amplitude (line on Figure 4). Only the central part of the two curves are superposed where the corrections is very small, while on the edge of the time interval correction the difference between the two curves is very important. Thus demonstrate the very low contrast quality of the input laser pulse.

4. Conclusion.

We have demonstrated for the first time a single-shot third order cross correlator based on time-to-angular coding. We have made comparison between the different coding methods. The amplitude dynamic is limited by the very low contrast of the laser used. Nevertheless the dynamic of the 16 bit CCD camera can be improved using a spatial amplitude mask.

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