4-fs pulses, single-shot, high dynamic and long temporal range self-referenced spectral interferometry measurement

Thomas Oksenhendler[1], Andrea Trabattoni[2], Sunilkumar Anumula[2], Giuseppe Sansone [2], Gabriel Tempea[3], Francesca Calegari[2], Mauro Nisoli [2]

1. Fastlite, Bât 503, campus scientifique d'Orsay, plateau du Moulon, 91400 Orsay Franc
2. Politecnico di Milano, Department of Physics, Institute of Photonics and Nanotechnologies, CNR-IFN, I-20133 Milan, Italy
3. Femtolasers Produktions GmbH, Femkomgrasse 10, 1100 Vienna, Austria
Author e-mail address:thoksen@fastlite.com

Abstract: 4-fs, 1.9-mJ pulses measurement with 40-dB dynamic on +/- 500-fs temporal range was implemented by single-shot Self-Referenced Spectral Interferometry method. The experimental results agree well with pulse reconstruction from streaking with isolated attosecond pulses.
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Complete temporal characterization of few-optical-cycle light pulses is crucial for a number of ultrafast applications and for the generation and characterization of attosecond pulses. Particularly important is the implementation of experimental techniques, which allow one to measure the temporal characteristics of few-cycle pulses on a single-shot basis.

In this work we demonstrate that a technique based on Self-Referenced Spectral Interferometry (SRSI, Fastlite patented) [1] implemented with Cross-Polarized Wave (XPW) can be used to obtain a single shot measurement of sub-5-fs pulses. 25-fs pulses, with an energy of 6 mJ and 1-kHz repletion rate, generated by a Ti:sapphire laser system (Femtopower V PRO CEP, Femtolasers GmbH) were compressed by implementing the hollow-fibre technique [2]. The pulses were injected into a differentially-pumped 1-m-long hollow fibre, with an inner diameter of 320µm. A pressure gradient configuration was implemented to avoid nonlinear processes occuring before coupling the radiation in the hollow core fiber [3]: helium gas pressure increases from a few mbar at the input of the fibre to 2 bar at the output. Two wedges with a small apex angle (2.7 deg) were used to finely tune the dispersion. Compression down to 4 fs (energy: 1.9 mJ) was achieved by ultra broadband dispersion compensation (450-970 nm) with a dispersive mirror compressor (Mosaic OS, Femtolasers GmbH) [4].

Pulse optimization naturally relies on precise characterization of the pulse, information on the spectral phase being of paramount importance.

The pulse measurement by SRSI gets spectral amplitude and phase information by spectral interferometry between the pulse to characterize and a reference pulse with a broader spectrum and a flatter phase. In our implementation, the reference pulse is generated from the pulse to characterize by cross-polarized wave generation (XPW), a frequency-conserving third-order nonlinear effect compatible with few-cycle pulses [5]. In this non linear process, the input pulse is filtered by its own temporal intensity. Its spectrum tends to be broader also meaning that its spectral phase is flatter [6]. Thus the broadening of the reference pulse spectrum compare to the input one is a measurement criterion that confirms the validity of the pulse characterization:

$$Z\left(x=\frac{\phi^{(2)}}{\Delta\tau_0^{\ 2}}\right)=\frac{\Delta\omega_{XPW}}{\Delta\omega_0}>Z_{limit}=f\left(Z_0=\frac{\Delta\omega_{0,XPW}}{\Delta\omega_0}\right) \qquad (1)$$

where $\Delta\tau_0$ is the rms pulse duration, $\phi^{(2)}$ the quadratic chirp (second order spectral phase), x the normalized dispersion, , $\Delta\omega_{XPW}$ the rms XPW pulse bandwidth, $\Delta\omega_0$ the rms pulse bandwidth, Z_{limit} the estimator minimal value for the pulse to measure, $\Delta\omega_{0,XPW}$ the rms bandwidth of the XPW pulse generated from the Fourier transform pulse having the input pulse spectrum. Thus the value of Z_{limit} only depends on the input pulse spectral amplitude profile. For a Gaussian pulse profile, its value is 1.

In theory, this limit can then be expressed as a normalized dispersion range (fig.1(a)). It points out the dependence of the dispersion range upon the square of the rms duration. The dispersion constraints are doubled between 4 fs and 5.6 fs. For Gaussian pulses, the dispersion range is +/-3.46 for the normalized dispersion. Thus a 5fs (FWHM) Fourier Transform limited (FTL) (2.1fs rms) pulse can be measured if its quadratic chirp is lower than about $15fs^2$. Furthermore, the validity range is centered on the XPW compressed pulse. These dispersion constraints imply a design of the SRSI device with minimal dispersion in the beam path before the XPW generation (fig.1.(b)). The input polarizer consists of a combination of reflective Brewster incidence GaAs plates. The pulse replica is generated by reflection in a combination of quarter wave plates oriented in opposition. The reference pulse goes through the two plates without polarization rotation (+λ/4 - λ/4 =0) while the pulse replica is reflected twice in the second uncoated wave plate (+λ/4 - λ/4 -λ/4 -λ/4 =-λ/2) and then its polarization is rotated (fig.1.(c)).

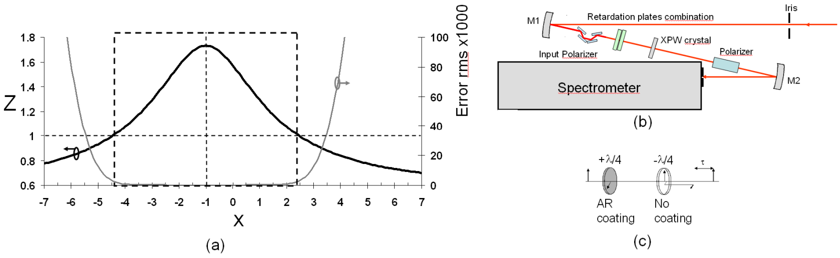

Fig. 1. (a) pulse measurement quality criteria and measurement quality versus normalized chirp, (b) schematic design of SRSI USP device, (c) pulse replica generation principle.

These elements introduce dispersion about 4fs^2 on the reference pulse and 8fs^2 on the pulse replica. The main dispersion of 4fs^2 causes the shift of the validity domain in the negative normalized dispersion direction (fig.1.(a)). The differential dispersion (difference between pulse replica and reference pulse dispersions) only affects the direct spectral phase in the data processing and can be removed after calibration without any consequence on the measurement quality. The thickness of the XPW crystal is limited to 0.2 mm to avoid any significant effect of the dispersion on the XPW generation. After the crystal, as long as the reference pulse and pulse replica experienced the same dispersion, the optics have no impact on the measurement. Thus the output polarizer used is a standard ultra broad-band calcite Glan-Thomson.

As can be seen in Fig. 2 (e) and (f), the device successfully measured 4fs optimized pulses (3.9fs FTL) on a +/- 500fs range with 40dB dynamic. The retrieved featured allow to estimate the rms pulse duration 16.5fs (10.3fs FTL) and the energy ratio contained in a temporal gate of +/- 4fs around the main pulse, 79% (94% FTL).

This experimental result has been confirmed by sampling the electric field of the pulse with isolated attosecond pulses [7]. From the streaking trace shown in Fig. 2(a) we have retrieved the electric field of the pulse (Fig. 2(c)), and the temporal intensity profile (Fig. 2(d)).

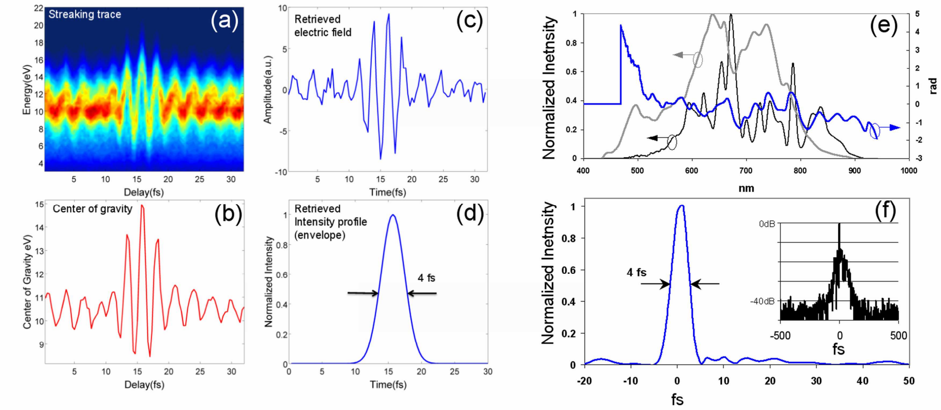

Fig. 2. (a) IR streaking image, (b) center of gravity determination, (c) Retrieved electric field, (d) Retrieved intensity profile of the pulse, (e) spectral amplitudes of XPW pulse (grey) and pulse replica (black) and spectral phase of input pulse (black) (f) Retrieved temporal intensity profile in linear scale and on log scale for the inset.

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