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Self-referenced spectral interferometry cross-checked with SPIDER on sub-15 fs pulses

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ABSTRACT

We characterized 11.7 fs nearly perfect Fourier Transform pulses with self-referenced spectral interferometry (SRSI), a new recently demonstrated technique. These pulses were first precisely optimized with three feedback loops between the SRSI setup and an AOPDF. An inherent control criterion to confirm that the measurement quality is theoretically derived and experimentally demonstrated. Each experimental result was cross-checked with SPIDER.

1. Introduction

Complete and self-referenced temporal characterization of femtosecond pulses requires a nonlinear or nonstationary filter [1]. The most popular pulse measurement techniques, frequency resolved optical gating (FROG) [2] and spectral phase interferometry for direct electric field reconstruction (SPIDER) [3], indeed rely on three-wave or four-wave mixing processes to extract a signal from which the spectral phase can be retrieved.

The existence of a reference pulse with a known spectral phase hugely simplifies the measurement setup and algorithm by using spectral interferometry. This method is linear, analytic, sensitive and precise [4,5].

Self-referenced spectral interferometry (SRSI), a recently demonstrated ultrashort pulse measurement technique [6,7] is based on the spectral interferometry between the pulse to characterize and a reference pulse generated from the pulse to characterize ("self created") by a frequency-conserving nonlinear optical effect. For reasons of compactness, simplicity, colinearity and achromaticity, the nonlinear effect used here is Cross-polarized Wave Generation (XPW) [8].

After a brief reminder of the principle of spectral interferometry and its Fast Fourier Transform (FFT) implementation, the condition to get an adequate reference pulse from the pulse itself by XPW is introduced. The self-referenced spectral interferometry technique is then described theoretically and experimentally. Optimization of a 12 fs pulse with an Acousto-Optic Programmable Dispersive Filter (AOPDF) [9] illustrates the ability of this method to accurately determine the spectral phase.

To further assess its accuracy, this SRSI device is compared in the validity range of the measurement with a custom SPIDER specifically designed for ultrashort pulses (sub-35 fs).

2. Spectral interferometry

Mixing an unknown pulse with a reference pulse separated by a time delay τ creates spectral interferogram. Spectral interferometry consists of analyzing this fringe pattern in order to characterize the unknown pulse. Let $E(\omega)$ be the complex spectral amplitude of the pulse and $E_{ref}(\omega)$ the complex spectral amplitude of the reference pulse. The signal measured by the spectrometer can then be expressed as:

$$S(\omega)=\left|E_{ref}(\omega)+E(\omega)e^{i\omega\tau}\right|^2=S_0(\omega)+f(\omega)e^{i\omega\tau}+f^*(\omega)e^{-i\omega\tau} \quad (1)$$

where $S_0(\omega)=\left|E_{ref}(\omega)\right|^2+\left|E(\omega)\right|^2$ is the sum of the spectra of the unknown and reference pulses; $f(\omega)=E^*_{ref}(\omega)E(\omega)$ is the interference term between the two pulses.

The spectral amplitudes, $|E(\omega)|$ and $|E_{ref}(\omega)|$, and the spectral phase difference between the two pulses $\varphi(\omega)-\varphi_{ref}(\omega)$ are directly retrieved from this signal by Fourier Transform Spectral Interferometry (FTSI) [10].

FTSI starts by taking the inverse Fourier Transform of the measured spectrum, which is as follows:

$$FT^{-1}[S](t)=E^*_{ref}(-t)\otimes E_{ref}(t)+E^*(-t)\otimes E(t)+f(t-\tau)+f^*(-t-\tau) \quad (2)$$

In this expression, the first two terms correspond to the field autocorrelation functions of each pulse and are thus centered around $t=0$. The third and fourth terms are the correlation functions shifted by τ, respectively, centered at $t=\tau$ and $t=-\tau$. If the value of τ is large enough to avoid any overlap between the terms and small enough to avoid aliasing, $f(t-\tau)$ can be extracted

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by numerically filtering out the other terms. Fourier Transforming back into the frequency domain then yields $f(\omega)e^{i\omega\tau}$. The phase and amplitude of this interference term are then:

$$\arg f(\omega)+\omega\tau=\varphi(\omega)-\varphi_{ref}(\omega)+\omega\tau \quad (3)$$

$$|f(\omega)|=|E_{ref}(\omega)||E(\omega)|. \quad (4)$$

If the condition $|E_{ref}(\omega)|>|E(\omega)|$ is fulfilled for each angular frequency ω, the spectral amplitude of both pulses are given by

$$|E_{ref}(\omega)|=\frac{1}{2}\left(\sqrt{(S_0(\omega)+2|f(\omega)|)}+\sqrt{(S_0(\omega)-2|f(\omega)|)}\right)$$
$$|E(\omega)|=\frac{1}{2}\left(\sqrt{(S_0(\omega)+2|f(\omega)|)}-\sqrt{(S_0(\omega)-2|f(\omega)|)}\right) \quad (5)$$

And both spectral amplitudes are reconstructed independently.

Moreover, if the reference pulse phase is known then the spectral phase of the pulse is directly given by

$$\varphi(\omega)=\varphi_{ref}(\omega)+\arg f(\omega). \quad (6)$$

3. Reference pulse "self-creation"

For a self-referenced characterization, the reference pulse has to come from the pulse itself. This reference pulse must exhibit a broader spectrum than the pulse to measure, and a known spectral phase. The question is how to generate such a reference pulse. In the spatial domain, it is well known that a Fourier filtering flattens the phase. Applying the same concept for ultra-short pulses in the spectral domain, a temporal filter can be used to obtain the reference pulse. Working with ultrashort pulses, only a nonlinear filter can be used. To interfere with the pulse itself, it has to be a frequency-conserving nonlinear optical effect such as Cross-Polarized Wave generation (XPW) (Fig. 1). The input pulse with a linear polarization is focused into a 1 mm (1 0 0) oriented BaF_2 crystal (Fig. 1a). An orthogonally polarized wave is generated by the third order nonlinearity anisotropy. At the output of the crystal, after recollimation, the XPW generated pulse is selected by a polarizer. The relationship between the input pulse and the XPW generated pulse can be approximated by a pure cubic effect on the temporal electric field as long as there are no significant dispersion and depletion of the pulse in the crystal. This cubic effect on the temporal electric field corresponds to applying a temporal filter whose profile is the temporal intensity of the pulse.

The limitation of this filtering depends upon the temporal intensity of the pulse. If the pulse is coarsely compressed as shown in Fig. 1b, the filtering is very efficient (Fig. 1c). The output spectral phase is flat and the spectrum broader than the input one (Fig. 1d). On the contrary, if the pulse is stretched, the nonlinear time filtering is less efficient or even totally inefficient depending on the chirp value. The filtering characteristics determine the validity and quality of the reference pulse and hence of the measurement.

For chirped gaussian pulses, it can be analytically found that the spectral half-width (σ) and chirp (ϕ'') of the input and XPW signal are linked [11] by:

$$4\sigma^2_{XPW}=(4\sigma^2)\left[3\left(1+\left(\sigma^4\phi''^2/9\right)\right)/(1+\sigma^4\phi''^2)\right]$$
$$\phi''_{XPW}=\phi''\left[\frac{1}{9}\left(1+\sigma^4\phi''^2\right)/\left(1+\left(\sigma^4\phi''^2/9\right)\right)\right]. \quad (7)$$

For a nearly compressed pulse, the spectrum is $\sqrt{3}$ broader than the input pulse spectrum and the chirp is nine times smaller. Even when the XPW spectrum is as broad as the input pulse, its chirp is a third of the input chirp. The chirp value reconstructed with spectral interferometry ($\arg f(\omega)$, Eq. (3)) is then two thirds of the input chirp. In this case, the XPW spectral phase is not flat enough to give a precise direct measurement, but still gives an order of magnitude of the input chirp.

Second order phase temporally enlarges a pulse whereas higher-order phase mainly creates side-lobes on the pulse temporal profile. As the XPW filtering consists in filtering the pulse by its own temporal intensity, small amplitude side-lobes are easily removed. Therefore, the XPW spectral phase flattening is much more efficient for higher-order phase than for second order phase [12].

4. Self-referenced spectral interferometry

Implementation of the SRSI combines spectral interferometry with nonlinear filtering on one arm. A compact and collinear setup is shown in Fig. 2 below. The input pulse is first filtered by a polarizer to perfectly define its polarization direction. The precision on this polarization direction is essential for the XPW filter quality. After the polarizer, the pulse passes through a birefringent plate. At the output, two temporally delayed pulses aligned on the XPW crystal principle axes are obtained. Depending upon the orientation of the birefringent plate with respect to the polarizer axis, the energy ratio between the two pulses can be adjusted. The first pulse (polarized linearly in the plane of the paper in Fig. 2) is used to generate the XPW reference pulse in a BaF_2 crystal as previously shown in Fig. 1a. As the XPW pulse polarization is orthogonal to the input one, a second polarizer used as analyzer selects only the XPW pulse. The second replica at the output of the birefringent plate propagates through the

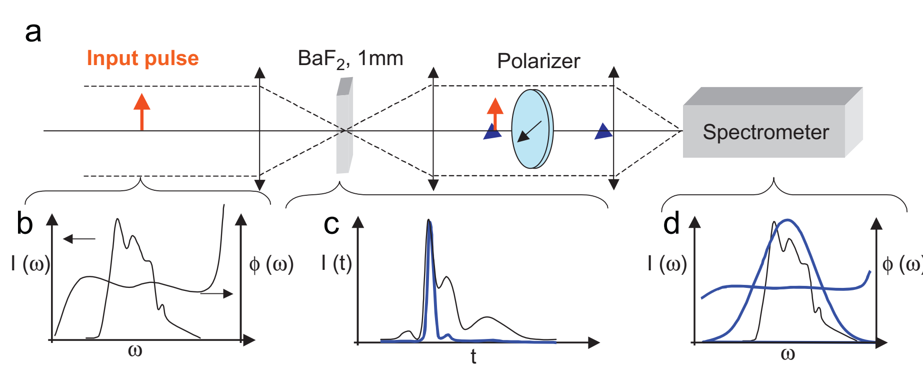

Fig. 1. (a) XPW optical setup. Arrows indicate polarization directions, (b) spectral intensity and phase of the input pulse, (c) temporal intensities of the input pulse (black curve) and the XPW pulse (blue), (d) spectral intensity and phase of the XPW pulse (blue), as compared to input pulse spectrum (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)