Complete characterization of weak ultra-short near-UV pulses by spectral interferometry

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ABSTRACT We present a method for a complete characterization of a femtosecond ultraviolet pulse when a fundamental near-infrared beam is also available. Our approach relies on generation of the second harmonic from the pre-characterized fundamental, which serves as a reference against which an unknown pulse is measured using spectral interferometry (SI). The characterization apparatus is a modified second harmonic frequency resolved optical gating setup which additionally allows for taking SI spectra. The presented method is linear in the unknown field, simple and sensitive. We checked its accuracy using test pulses generated in a thick nonlinear crystal, demonstrating the ability to measure the phase in a broad spectral range, down to 0.1% peak spectral intensity as well as retrieving π leaps in the spectral phase.

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1 Introduction

Techniques allowing for a complete characterization of the instantaneous intensity and frequency of a femtosecond pulse were first introduced in the 1990s. The FROG (frequency-resolved optical gating) [1], SPIDER (spectral interferometry for direct e-field reconstruction) [2] and sonographic techniques [3] are the most popular. These techniques are usually based on sum-frequency generation of an unknown near-infrared (NIR) pulse with a modulated copy of itself. The resultant ultraviolet (UV) radiation is registered as a function of modulation. Finally, the pulse envelope and phase are retrieved from acquired data. It is crucial for those methods to filter out the fundamental components from the sum-frequency signal. Fortunately, it can be easily accomplished by inserting a colored glass or spatial filter. Moreover, the UV signal is measurable with inexpensive silicon-based photodetectors.

Frequently, one faces the need to characterize the second harmonic (SH) of nanojoule pulses of Ti:sapphire lasers. This is the case in ultra-fast spectroscopy [4, 5], micromachining [6] or downconversion-based photon-pair sources [7–9]. Directly generalized FROG and SPIDER techniques suitable for characterization of the UV pulses are based on upconverting or downconverting the unknown second-harmonic pulse using the fundamental beam [10, 11]. The resultant radiation, which carries information about the unknown pulse, is difficult to detect. In the case of using upconversion the detected signal is centered around 266 nm where the silicon detectors are inefficient. On the other hand using downconversion produces weak pulses at the fundamental wavelength that are easily overwhelmed by the stray background. Moreover, the nonlinear up- or downconversion process requires substantial intensity of the measured beam. The latter requirement has recently been diminished by an application of an optical parametric amplification based conversion process [12]; however, these new approaches are complicated in use. Whereas for sub-µJ pulses other nonlinear processes can be used to characterize the pulses as in self-diffraction FROG [13] and zero additional phase SPIDER [14], the method described below could be useful also in those cases.

In this paper we present a method for a complete characterization of SH pulses when the fundamental beam is also available. This is a typical experimental situation, which can be exploited to avoid nonlinear conversion of a SH beam. It is assumed that the fundamental pulses are characterized prior to the measurement, for example using the well-established second harmonic generation frequencyresolved optical gating (SH FROG) technique [1]. The scheme of our method is presented in Fig. 1. The idea of measurement is analogous to TADPOLE [15], but extended to near-UV pulses. A portion of the fundamental beam is converted into a reference second harmonic. Thanks to application of a very thin crystal in this step the complex spectral field of the reference pulse can be precisely calculated. Then, the reference pulse and the unknown pulse are brought to interfere on a slit of a spectrometer and spectral fringes are registered. The phase of the unknown pulse is retrieved from this signal using the Fourier filtering technique [16]. We demonstrate this method for a pulse generated in a 1-mm-thick beta barium borate (BBO) crystal oriented for type I phase matching. We were able to reconstruct the phase in a spectral range where the pulse intensity is above 0.1% maximum, including the π phase leaps.
2 Method

The first step in our measurement method is registering a FROG trace for the fundamental beam [1]. Next, we run the standard retrieval procedure using FROG software (Femtosoft Technologies) and obtain complete information on the electric field of the fundamental pulses. In particular, we learn about their complex spectral field $E_{\text{ref}}(\omega)$:

$$E_{\text{ref}}(\omega) = \sqrt{I_{\text{ref}}(\omega)} e^{i \phi_{\text{ref}}(\omega)}, \quad (1)$$

where $I_{\text{ref}}(\omega)$ is the spectral intensity and $\phi_{\text{ref}}(\omega)$ is the spectral phase. Note that $I_{\text{ref}}(\omega)$ can be measured directly with a spectrometer. This gives us a possibility to check the consistency of the data retrieved from FROG. Next, we double the known fundamental pulses in a BBO crystal. We choose a thin crystal because of negligible group-velocity mismatch between NIR and UV bands and large conversion bandwidth.

We take advantage of this fact to calculate precisely the output second harmonic and use it as a reference. Its complex spectral field $E_{\text{unk}}(\omega)$ is given by the usual convolution formula

$$E_{\text{unk}}(\omega) \propto \int d\omega' E_{\text{ref}}(\omega') E_{\text{ref}}(\omega - \omega'). \quad (2)$$

In particular, we learn about the spectral phase of the reference pulses $\phi_{\text{ref}}(\omega)$. The above formula is a reflection of the fact that the second-harmonic field in time is the fundamental field squared: $E_{\text{unk}}(t) = E_{\text{ref}}^2(t)$. Note that FROG retrieves the reference pulse including the phase acquired during propagation through the FROG setup. Also note that even if the crystal narrows down the bandwidth of the reference pulse, it contributes a negligible phase to it.

We exploit the spectral interferometry method in order to retrieve the phase difference between the unknown second-harmonic pulse $E_{\text{unk}}(\omega)$ and the reference pulse $E_{\text{ref}}(\omega)$. This is accomplished by directing them with a relative delay $\tau$ into the spectrometer slit, where they interfere. Hence, we measure the interference spectrum $I_{\text{SI}}(\omega)$ of the form

$$I_{\text{SI}}(\omega) = \left| E_{\text{ref}}(\omega) e^{-i \omega \tau} + E_{\text{unk}}(\omega) \right|^2$$

$$= I_{\text{ref}}(\omega) + I_{\text{unk}}(\omega) + 2 \sqrt{I_{\text{ref}}(\omega) I_{\text{unk}}(\omega)} \cos[\phi_{\text{ref}}(\omega) - \phi_{\text{unk}}(\omega) - \omega \tau]. \quad (3)$$

An exemplary interference spectrum $I_{\text{SI}}(\omega)$ is shown in Fig. 2. The key information about the unknown phase $\phi_{\text{unk}}(\omega)$ is contained in the $\cos[\phi_{\text{ref}}(\omega) - \phi_{\text{unk}}(\omega) - \omega \tau]$ term. First, we retrieve $\phi_{\text{ref}}(\omega) - \phi_{\text{unk}}(\omega)$ using the Fourier filtering technique [16]. The interference spectrum can be separated into three distinct elements: the sum of spectral intensities $I_{\text{ref}}(\omega) + I_{\text{unk}}(\omega)$, which is slowly varying with $\omega$, and the fringes described by the last term in (3), which consist of positive and negative frequency parts varying as $e^{+i \omega \tau}$ and $e^{-i \omega \tau}$.

We calculate the Fourier transform of the interference spectrum, which splits those parts in the Fourier domain, provided that the delay $\tau$ is large enough. A typical result is shown in Fig. 3. Next, the Fourier transform is multiplied by a supergaussian filter function $F(\tilde{t})$:

$$F(\tilde{t}) = \exp \left[ - \left( \frac{\tilde{t} - \tau}{\Delta \tilde{t}} \right)^8 \right], \quad (4)$$

where $\tilde{t}$ denotes time in the Fourier domain and $\Delta \tilde{t}$ is the filter width. $F(\tilde{t})$ is non-zero near the $\tilde{t} = \tau$ point and zero elsewhere. Thus, the product of the filter function $F(\tilde{t})$ and the interference spectrum in the Fourier domain $I_{\text{SI}}(\tilde{t})$ contains only the term originating from the part of $I_{\text{SI}}(\omega)$ which varies as $e^{+i \omega \tau}$. It is transformed back into the frequency domain,