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Phase-matching free pulse retrieval based on plasma-induced defocusing

Pierre Béjot*, Rishabh Bhalavi, Olivier Faucher, Franck Billard, and Edouard Hertz

Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR CNRS 6303 Université de Bourgogne 21078 DIJON CEDEX – France

Abstract. A phase-matching free pulse retrieval technique based on plasma-induced defocusing in a rare gas is presented. Based on a pump-probe setup, this technique uses a moderately intense pump laser pulse for ionizing the medium, creating in turn an ultrafast defocusing lens. While a coronagraph blocks out the probe pulse in absence of ionization, the plasma lens leads to increase the probe beam size in the far field. By measuring the spectrum of the probe propagating around the coronagraph as a function of the pump-probe delay τ , a bi-dimensional trace (ω, τ) is obtained. This enables to fully characterize the temporal and spectral characteristics of the probe pulse through a method that is free of phase matching constraints. Demonstrated both in the near-infrared (800 nm) and in the ultraviolet (266 nm), the present technique is potentially suited for characterizing pulses in the whole transparency region of the used gas, i.e., from the deep-ultraviolet to the far-infrared.

1 Introduction

The advent of ultrashort laser sources several decades ago has opened a real breakthrough for observing ultrafast phenomena taking place at femtosecond and picosecond timescales and also for studying the behaviour of matter submitted to very intense electromagnetic fields. The production of such ultrashort optical events, the shortest timescale ever produced at this time, has immediately raised the question of their measurements. Indeed, for many applications, the precise knowledge of the time-dependent phase and amplitude of the ultrashort laser pulse is of prime importance.

Many self-referenced techniques, with varying experimental complexity and limitations, aiming at characterizing ultrashort laser pulses, have thus been developed [1-7]. Recently, a phase-matching free pulse characterization technique exploiting transient absorption in solids as an ultrafast optical switch has been developed [8,9]. Briefly, this frequency-resolved optical switching technique (FROSt) consists in measuring the spectrum of a probe that propagates through a transparent dielectric medium. When an intense pump pulse photo-excites the medium, long-living free-carriers are generated, strongly decreasing the probe transmission. By measuring the transmitted probe spectrum as a function of the pump-probe delay, a bi-dimensional signal (ω, τ) is obtained. Using a retrieval algorithm, the spectral and temporal probe pulse characteristics can then be retrieved with this temporal knife-edge technique. Demonstrated in the near- and

mid-infrared, this method is nevertheless not well suited for ultraviolet (UV) pulses.

In this context, we present here another frequency-resolved optical switching technique that breaks the UV limitation of the aforementioned method. The ultrafast optical switch is based here on the generation of an ultrafast rise time long-lived plasma-induced defocusing lens. The proposed technique is free from phase-matching issue and potentially works over an extremely broad spectral region, ultimately limited by the gas absorption in the UV (≈ 120 nm for argon) and by the plasma frequency in the far-infrared ($\approx 100 \mu\text{m}$).

2 General concept and experimental setup

Atoms and molecules exposed to a non-resonant intense ($10\text{-}100 \text{ TW/cm}^2$) laser field exhibit highly nonlinear dynamics that can lead, among other phenomena, to their photoionization. Assuming that K photons are needed for ionizing the medium and neglecting recombination, the electrons density ρ evolves as

$$\rho(t) \propto \int_{-\infty}^t I^K(t') dt', \quad (1)$$

where I is the pulse intensity. The produced plasma tends to locally decrease the refractive index of the medium as

$$\Delta n = -\frac{\rho}{2\rho_c}, \quad (2)$$

* Corresponding author: pierre.bejot@u-bourgogne.fr

where $\rho_c = \epsilon_0 m_e \omega_0^2 / q^2$ is the critical electrons density, with ϵ_0 the vacuum permittivity, m_e (resp. q) is the electron mass (resp. charge), and ω_0 is the laser pulsation. Accordingly, a pump beam with a Gaussian spatial profile ionizing a medium will create a defocusing lens until the plasma recombination (few hundreds of picoseconds for argon). A probe pulse propagating through the plasma will then be defocused, increasing its size in the far field [10]. As shown in Fig. 1, this phenomenon can be used as a switch if a coronagraph is inserted in the probe path that lets some part of the probe passing around only when the medium is ionized. The signal spectrum, obtained as a function of the pump-probe delay, is then redirected to a spectrometer. Note that the implemented temporal knife-edge then acts reversely as compared to the technique based on transient absorption since, in our case, no signal is recorded before the pump ionizes the medium. After the record of the bi-dimensional trace $S(\omega, \tau)$, a retrieval algorithm allows to recover the probe spectral phase, while its spectral amplitude is simply measured when the probe propagates well after the pump.

Experiments were carried out for characterizing both near-infrared (800 nm) and UV (266nm) pulses. All experiments have been carried out with a Fourier-transform limited 40 fs, 800 nm, 40 μ J pump beam. Pump and probe beams are linearly, cross-polarized for minimizing the Kerr-induced cross-focusing effect contribution when they temporally overlap. When needed, the UV laser pulses have been generated with a commercial third-harmonic generator module placed in the probe path. The pump and probe beam are focused by an aluminium parabolic mirror ($f=20$ cm) with a slight angle ($\approx 3^\circ$) in a static cell filled with argon (1 bar) closed with 1 mm thick fused silica windows, inducing a supplemental dispersion of 36 (resp. 200) fs² at 800 (resp. 266) nm. After the interaction, the probe beam is collimated with a plano-convex fused silica lens and the coronagraph is placed on the probe path. The signal diffracted by the plasma lens is then redirected in a spectrometer (Ocean Optics, USB-4000). The pump-probe delay is varied by using a motorized translation stage placed in the pump path. The probe energy is set to approximately 1 μ J.

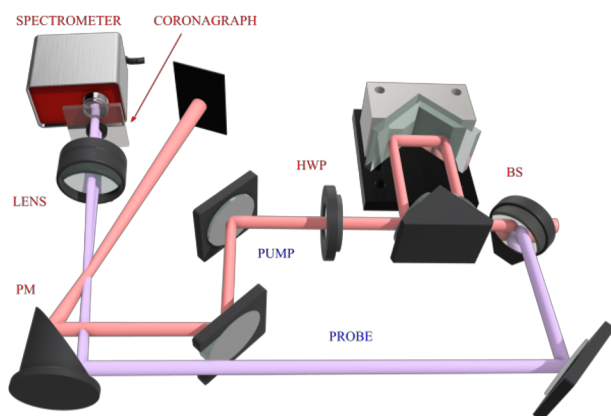


Figure 1. Experimental setup. BS: beam splitter, HWP: half-waveplate, PM: parabolic mirror

3 Results and discussion

As shown in figure 2(a) that displays both experimental (left) and retrieved signals (right) for compressed pulses at 800 nm, a slight residual cubic phase still remains. The retrieved pulse duration is 42 fs. For validating our setup, flat windows with calibrated thicknesses have been placed in the probe path. Figure 2(b) shows the typical signal obtained with a 10mm thick SF11 window. All experimental results obtained for the different applied phases are in very good agreements with the expectations.

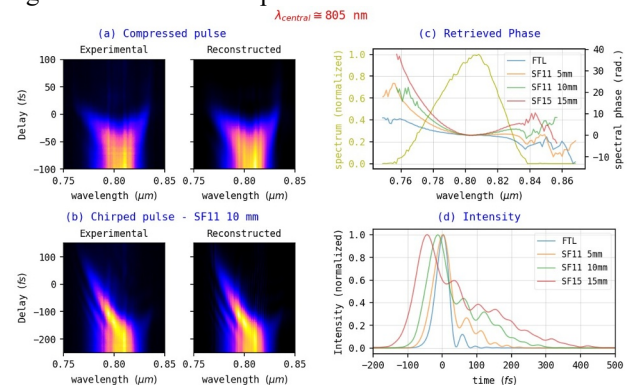


Figure 2. Experimental results obtained at 800 nm for (a) FTL and (b) chirped pulses. Panel (c) [resp. (d)] shows both the spectral amplitude and phases (resp. temporal intensity distribution) for different SF11 windows inserted in the probe path.

After a thorough presentation of the techniques, experimental results obtained both in the infrared and in the UV will be presented. Limitations and potential improvements will then be discussed.

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