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Time-gated spectral characterization of ultrashort laser pulses

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Abstract

We present a novel time-gated characterization technique that allows to directly monitor the time evolution of the angular spectra within femtosecond laser pulses. We show an application of the technique to the case of a 160-fs chirped pulse.

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Keywords: Ultrashort pulses; Optical measurement technique

Femtosecond laser pulses are now widely available in many laboratories and are routinely used in various research fields. One of the main difficulties associated with such short pulses is a correct and precise characterization of the pulse in both space and time domains (i.e. in the near field, NF) as well as in both k-vector and wavelength domains (i.e. in the far field, FF). Indeed, many applications require more than a simple measurement of the time-integrated spatial profiles or spatially integrated temporal profiles. This is the case, for example, of experiments associated with pulse filamentation in Kerr media in which strong space–time coupling occurs, i.e. the pulse presents a temporal profile that has a strong dependence on the transverse spatial coordinate. In order to overcome the shortcomings of standard (time or space) integrated measurements some of the present authors have introduced a new 3D-mapping technique [1,2]. This is based on a non-linear optical gate obtained by mixing in a $\chi^{(2)}$ crystal the pulse under investigation with an ultrashort gate pulse. The

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generated sum frequency (SF) signal reproduces the pulse spatial intensity distribution within the ultrashort gate, so that by changing the relative delay of pulse and gate it is possible to obtain a full 3D intensity map. This method was applied with success to the characterization of spontaneously generated X-waves in $\chi^{(2)}$ media [3], of pulse filaments [4] and of spontaneous X-waves formation [5] in Kerr media. We have also recently proposed another technique [6] based on the use of an imaging spectrograph so as to obtain the θ–λ angular spectrum (AS). The observation of the FF structures gives a large amount of information also on the spatio-temporal structure of the pulse, due to the direct relationship between large-scale features in the FF and small, localized structures in the NF.

Here, we propose a fusion of these two techniques in what we call a gated angular spectrum (GAS) measurement. By measuring the AS of the SF generated by mixing the wave-packet (WP) under investigation with a short gate, we obtain detailed information on the AS of each temporal slice of the WP. The technique is particularly relevant for the case of WPs with broad AS (i.e. far exceeding the transform limit). In this case, the GAS allows to establish which temporal portion of the WP originates the different AS components. The main difference with respect to the spatio-temporal characterization technique described in [7], is that, in our case, we have direct access to information on the time-resolved FF angular spectra evolution, and that our technique is not limited to moderate amounts of spatial chirp. Another interesting feature of the method proposed here is that we can exploit the experimental data to retrieve also information on the time-dependent phase of the pulse. In this paper, we introduce the GAS method and test it by characterizing amplitude and phase of a non-transform-limited fs laser pulse.

The experimental layout is shown in Fig. 1. At the input we had a 800-nm, 160-fs pulse delivered by a Ti:sapphire laser system (Spitfire, Spectra-Physics) at 1-kHz repetition rate, which was divided in two parts. One beam is used as the laser WP under investigation, while the other is used to pump a non-collinear optical parametric amplifier (TOPAS White, Light Conversion, Ltd.) generating the 10-μJ gate pulse with wavelength

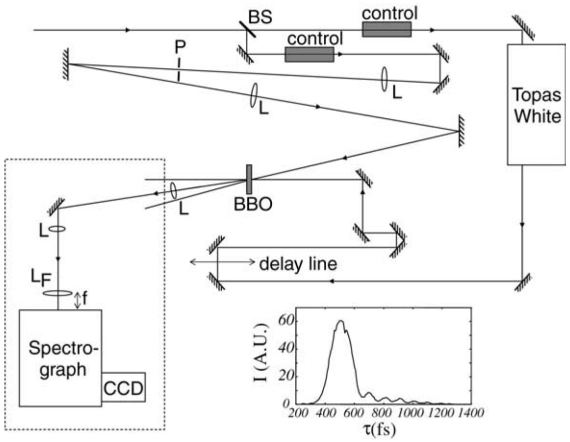

Fig. 1. Experimental layout for the GAS measurements. L indicates lenses, BS are beam-splitters, control stands for the feedback control system, P is the spatial filter pin-hole. In the inset, we show a cross-correlation between the laser pulse and the gate pulse.

centered at 710 and ~40-nm bandwidth, which would correspond in the case of a transform-limited Gaussian pulse to a ~20-fs temporal duration. Moreover, the laser WP was tightly focused in order to have a nearly 100-μm FWHM diameter, while the gate had a fairly constant fluence distribution over a much larger area (1-mm FWHM diameter), in order to guarantee that the generated SF signal reproduces the laser WP spatial intensity distribution. The non-linear gating was then performed by mixing the gate and the laser WP, the second with energy set at 3.3 μJ, by means of a half-wave plate and a Glan Polarizer. We used a thin (20 μm) type-I-phase-matching β-barium borate crystal under slightly non-collinear geometry in the horizontal plane, so as to spatially separate the two input beams from the generated SF signal at 376 nm. We ensured that the SF process was performed in the low conversion limit so as to avoid any back-conversion processes that could lead to features in the SF spectrum which are not present in the actual laser WP. The output facet of the crystal was then imaged with a 4-f telescope onto the back focal plane of a 5-cm focal length lens L_F. The entrance slit of the imaging spectrograph was then placed in the focal plane of the lens L_F and aligned in the vertical plane so as to avoid any additional tilting of the pulse front due to non-collinear interaction geometry. At the output plane of the spectrograph the frequency and angle resolved FF of the SF were recorded by a high-dynamic-range (16-bit) CCD camera (DU420, Andor Technology). The setup includes also two feedback control systems that were used for energy stabilization. The inset in Fig. 1 shows a cross-correlation trace between the laser WP and the gate pulse obtained by measuring the power of the SF signal as a function of delay. The trace presents a main peak, corresponding to the laser WP, with a duration of 160 fs FWHM, followed by a series of trailing peaks of lower intensity (less than 5% of laser WP intensity). By spanning the delay line in 26.6-fs steps, we recovered the evolution of the angular spectrum of the input pulse.

In Fig. 2 we show, as an example, the AS of the SF for three different time slices of the pulse under study. What we can see from these graphs is that by means of this technique we are able to monitor the evolution of the angular spectrum within the laser pulse. In particular we see that increasing the delay between the laser WP and the gate pulse the peak intensity wavelength experiences a blue-shift without any appreciable change in the θ coordinate. So we have a direct visualization of the laser WP temporal chirp.

In Fig. 3, we represent in a different manner the characterization of the laser WP. Graph (a) shows the (angular-integrated) temporal spectrum versus the delay τ, between the two pulses, whereas (b) shows the (wavelength-integrated) angular spectrum as a function of τ. In Fig. 3(a), the tilt of the lobes clearly indicates the presence of a strong temporal chirp in the input pulse. It is possible to directly evaluate the value of the temporal chirp parameter from Fig. 2 or from Fig. 3(a). Indeed, approximating the main intensity peak with a linearly chirped Gaussian pulse [8], $I \propto \exp[-(1+i\alpha)(t^2/\tau^2)]$, we can calculate the chirp parameter of the SF signal as

$$\alpha_{SF} = \frac{\Delta\lambda}{\Delta t}\frac{\pi c \tau^2}{\lambda^2} \tag{1}$$

from which we find a value $\alpha_{SF} = -1.39$. Note that, under the assumption of transform-limited gate the same chirp value has to be attributed to the laser WP. Fig. 3(b), instead, shows a bell-shaped, symmetrical, angular distribution of the WP fluence, peaked in the axial direction, with a slight apparent broadening in correspondence of the WP peak intensity, due simply to the higher measured intensity, so that the low intensity wings rise above the noise level. This is indeed what is expected in the case of a Gaussian pulse for which

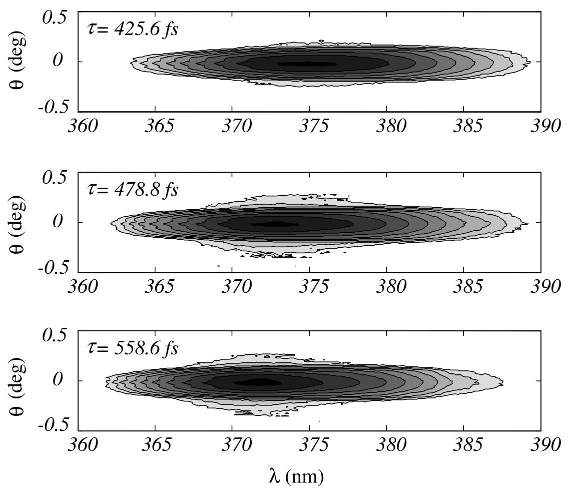

Fig. 2. Example of measurement of the angular spectrum of the SF field at three different delays between the laser WP and the gate pulse. Gray-level contour plots are in logarithmic scale.

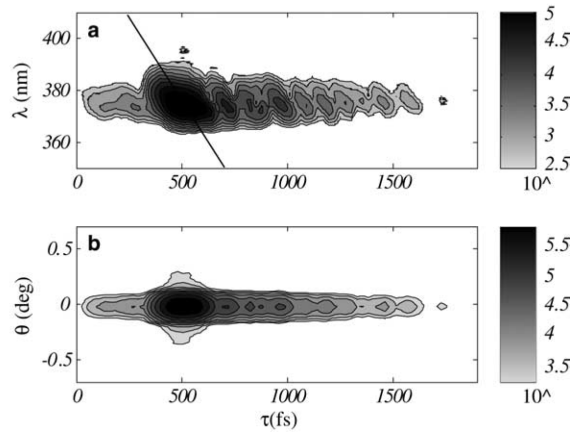

Fig. 3. Experimental gated angular spectrum (GAS) characterization of the input femtosecond pulse. (a) Logarithmic intensity distribution of wavelength versus time. (b) Logarithmic intensity angular distribution of k-vectors versus time.

the k-vectors are all directed on-axis. We would like to underline that this kind of results becomes particularly important in the case of conical emission. Indeed since this plot shows the variation of the angular distribution of frequencies, or, in other words, the direction of the k-vector of the new emitted frequencies, it enables to see which slices of the pulse are originating conical emission.

We note that, exploiting the AS data of Fig. 3(a), it is possible to obtain information on the phase of the pulse under the assumption of negligible angular dependence of the phase profile. Indeed Fig. 3(a) represents the dependence of intensity on wavelength and time, $I(\lambda, \tau)$, which is the quantity usually called spectrogram and measured in traditional frequency resolved optical gating (FROG) techniques [9]. We are using two extremely different pulses, and, for this reason, we applied to our results the FROG trace inversion retrieval algorithm described in [10]. By means of this algorithm, we are able to retrieve intensity and phase of the input pulse with good accuracy. Fig. 4(a) shows the recovered intensity and phase of the laser WP, while Fig. 4(b) shows the same quantities for the gate pulse. Note that also the retrieved gate pulse presents a parabolic time-dependent phase. By numerically performing the cross-correlation between the recovered laser and gate pulse profiles, we obtained the results in Fig. 5, which are in good agreement with the directly measured cross-correlation profile.

The time dependence of the laser WP phase profile in the time region around the pulse peak can be approximated by a parabolic function, with a maximum phase shift of nearly $\pi/2$. Fitting the phase curve with a quadratic term, i.e. accounting for a linear chirp, we found a value of $\alpha = -1.04$ for the chirp value of the laser WP, which differs from α_{SF} deduced from Fig. 3(a), owing to the chirp of the gate pulse.

In conclusion, we have described a novel technique for measuring the time-resolved angular spectrum of amplitude and phase modulated pulses. This kind of measurement, since it is not integrated in time nor in space, will be useful for the characterization of pulses in which spatio-temporal couplings play an important role as is the case, for example, for femtosecond pulse filamentation [6] and non-linear X-waves generation [5] in Kerr media. In particular, the GAS technique as is presented here can be used for the cases of filamentation in solids and liquids or, in general, in media for which very high pulse energies are not needed. We believe that, with some modifications to the set-up, it will be possible to overcome this limitation and to extend it to cases in which higher energies are involved, such as, for example, in the case of filamentation in air. Moreover, besides

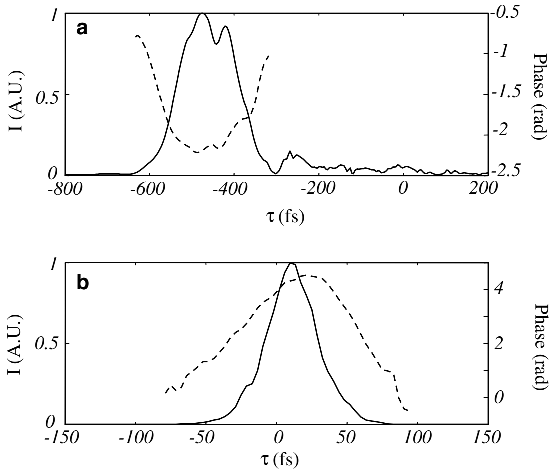

Fig. 4. Laser WP (a) and gate pulse (b) retrieved by means of the trace inversion algorithm, amplitude (solid line) and phase (dashed line).

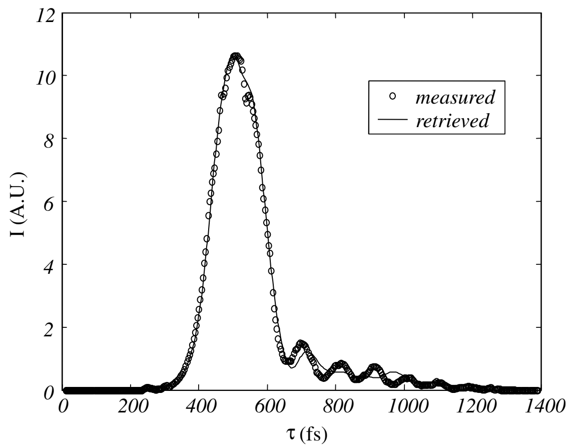

Fig. 5. Comparison between the measured (circles) cross-correlation and that calculated using the retrieved pulses (solid line).

information on time evolution of angular spectra, we showed that in the case of a transform-limited gate, the technique allows direct access to the chirp of the pulse under investigation.

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