Characterization of sub-6-fs optical pulses with spectral phase interferometry for direct electric-field reconstruction

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We demonstrate spectral phase interferometry for direct electric-field reconstruction (SPIDER) as a novel method to characterize sub-6-fs pulses with nanojoule pulse energy. SPIDER reconstructs pulse phase and amplitude from a measurement of only two optical spectra by use of a fast noniterative algorithm. SPIDER is well suited to the measurement of ultrabroadband pulses because it is quite insensitive to crystal phase-matching bandwidth and to unknown detector spectral responsivity. Moreover, it combines highly accurate pulse-shape measurement with the potential for online laser system diagnostics at video refresh rates. © 1999 Optical Society of America

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Optical pulses in the two-cycle regime have been generated by three different methods: external pulse compression,[1,2] optical parametric amplification,[3] and, most recently, also directly from Ti:sapphire oscillators.[4,5] Regardless of the method of generation, these two-cycle pulses exhibit a fairly complicated structure, as indicated by their strongly modulated spectra. In this situation, *a priori* assumption of a particular pulse shape for deconvolving an autocorrelation trace leads to large uncertainties in the estimated pulse parameters. For this reason it is especially important to develop reliable and robust pulse-shape-measurement techniques.

In the sub-10-fs regime two methods have been demonstrated that allow reconstruction of pulse amplitude and phase directly from measured data and do not require restrictive assumptions. The first, second-harmonic-based frequency-resolved optical gating,[6–8] was applied to the characterization of oscillators and amplifier systems. More recently, an interative phase-reconstruction algorithm using second-harmonic-generation autocorrelation and the fundamental spectrum was demonstrated.[1]

In this Letter we demonstrate a novel technique for measuring two-cycle optical pulses in the nanojoule energy regime. Our method is based on spectral phase interferometry for direct electric-field reconstruction (SPIDER),[9] a self-referencing variant of spectral interferometry.[10] This method was previously applied to the characterization of longer pulses.[9,11]

In our SPIDER apparatus two replicas of the input pulse are generated with a fixed time delay τ. These two replicas are upconverted by use of sum-frequency generation with a strongly chirped pulse derived from the same input pulse. Owing to their temporal separation, the two pulses are upconverted with two different quasi-cw slices of the stretched pulse, leading to two identical versions of the input pulse that are frequency shifted with respect to each other by a spectral shear $\delta\omega$. The resulting interferogram is recorded with a spectrometer (Fig. 1). SPIDER is a self-referencing interferometric technique; i.e., there is no need for a well-characterized reference. Note that no moving parts are required in a SPIDER apparatus and that only a single interferogram $S(\omega_c)$ has to be measured:

$$S(\omega_c) = |E(\omega_c)|^2 + |E(\omega_c + \delta\omega)|^2 + 2|E(\omega_c)E(\omega_c + \delta\omega)|\cos[\phi_\omega(\omega_c + \delta\omega) - \phi_\omega(\omega_c) + \omega_c\tau]. \quad (1)$$

Here $E(\omega)$ is the frequency-domain representation of the electric field, $\phi_\omega(\omega)$ is the spectral phase of the pulse, and ω_c is the passband frequency of the spectrometer. A fast noniterative algorithm using 2

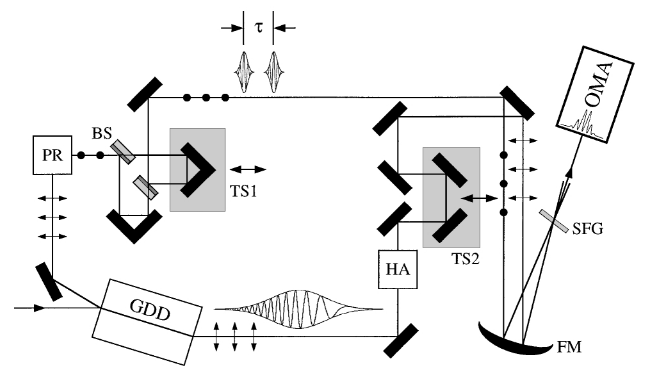

Fig. 1. SPIDER setup: GDD, SF10 glass block; PR, periscope for polarization rotation; BS, beam splitters; TS1, translation stage for adjustment of delay τ; TS2, translation stage for adjustment of temporal overlap of the short pulse pair with the stretched pulse; HA, periscope for height adjustment; FM, focusing mirror (30-cm radius of curvature); SFG, upconversion crystal [30-μm-thick type II β-barium borate (BBO)]; OMA, optical multichannel analyzer. The filled shapes represent silver-coated mirrors, and the filled circles and arrows on the beam path display the polarization state of the beam.

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one-dimensional Fourier transforms extracts the phase of the oscillatory cosine term [Eq. (1)] of the interferogram. The linear phase term $\omega_c \tau$ is separately measured by conventional spectral interferometry[10] and subtracted from the cosine phase term. This calibration measurement has to be done only once. While it can be done either with the fundamental-pulse replicas or with their second harmonic, the latter is preferable because it uses the same wavelength range for calibration and measurement and therefore avoids wavelength-calibration errors. One obtains the spectral phase $\phi(\omega)$ by adding up the appropriate phase differences $\phi(\omega + \delta\omega) - \phi(\omega)$. Finally, the time-dependent intensity and phase are calculated from the reconstructed spectral phase and an independently measured fundamental-pulse spectrum. The accuracy of reconstruction of the spectral phase is quite insensitive to the phase-matching bandwidth of the upconversion crystal and the spectral responsivity of the detector, since it only depends on the spacing of the spectral fringes. Therefore, even for ultrabroadband pulses, no complicated spectral corrections are needed, in contrast with other techniques.[7] Furthermore, the noniterative character of the evaluation procedure, together with the absence of moving parts in the experimental setup, allows for pulse measurements at video refresh rates.[11,12]

Our apparatus is shown in Fig. 1. Two pulse replicas with a delay of $\tau = 300$ fs are generated in a Michelson-type interferometer. The input pulse for the interferometer is the reflection from the surface of a 6.5-cm-long SF10 glass block. The signal transmitted through this block is used as the strongly chirped pulse for upconversion. The group-delay dispersion of the block (10^4 fs^2) together with the delay of 300 fs results in a spectral shear of 4.8 THz. This chirp is adequate to ensure that each pulse replica is upconverted with a quasi-cw field, and the spectral shear is small enough to satisfy the sampling theorem.[9] Therefore this configuration is suitable for measuring pulses up to 40 times the transform limit of our spectrum. The use of the low-cost uncoated glass block as the first beam splitter ensures a large bandwidth and an appropriate power-splitting ratio, allowing for an optimal upconversion signal. The Michelson interferometer uses two 300-μm-thick dielectric beam splitters (FABS, CVI Laser Corporation) in a symmetric dispersion-balanced configuration. The symmetry allows for maximum fringe contrast. The two delayed pulses are mixed noncollinearly with the stretched pulse in a 30-μm-thick type II BBO crystal. The phase-matching bandwidth in the ordinary axis of a type II crystal is usually much larger than in a type I crystal of the same material and thickness, whereas the bandwidth in the extraordinary axis is smaller. SPIDER takes advantage of a type II configuration, since only a small part of the bandwidth of the stretched pulse, given by the spectral shear $\delta\omega$, is actually required. Consequently, we orient the narrow-band extraordinary axis of the crystal parallel to the polarization of the stretched pulse, while the short replicas are rotated into the broadband ordinary axis by a periscope. In this configuration the upconversion efficiency in our crystal varies by less than 20% over the range from 660 nm to 1 μm (note that using the other orientation would reduce this range to 750 to 880 nm). A noncollinear mixing geometry eliminates the need for another beam splitter. Geometric smearing effects caused by this noncollinear geometry and group-velocity mismatch do not play a role, provided that the strongly chirped pulse can be considered quasi-cw for the duration of the pulse to be measured. This condition is easily fulfilled.

The upconverted pulses are detected in a 0.3-m imaging spectrograph equipped with a 1200-groove/mm grating and a 1024 by 128 pixel UV-enhanced CCD array allowing for rapid acquisition. The CCD does not cover the full bandwidth of the SPIDER interferogram for our shortest pulses. Therefore, in this case we are limited to update times of the order of 10 s. The update time can be easily improved to less than 1 s by the choice of a less-dispersive grating. Only the horizontal axis of the CCD output is needed for measurement of the SPIDER interferogram. To calibrate the apparatus we measure the linear phase term arising from the delay between the replicas, using a 10-μm type I KDP crystal instead of the BBO crystal. As an alternative one could simply rotate the BBO crystal by 45°. The reduced bandwidth of this configuration causes significant shaping of the resulting interferogram but is still sufficient for accurate measurement of the linear phase. Because SPIDER reconstructs the phase information from the position of the fringes, the delay between the two short-pulse replicas is chosen so that we obtain a large number of fringes while still being able to properly resolve the individual fringes with the spectrometer.

We used SPIDER to measure the amplitude and the phase of sub-6-fs-duration pulses from a state-of-the art semiconductor saturable absorber mirror–assisted Kerr-lens mode-locked Ti:sapphire laser.[4] Figure 2 shows the SPIDER interferogram of a pulse with a transform limit of 5.3 fs. For comparison, the individual spectra of the upconverted pulses are also displayed. Note that they are identical but shifted by the spectral shear $\delta\omega$. The spectral phase that was reconstructed from the SPIDER trace is plotted in Fig. 3, together with the independently measured pulse spectrum and the corresponding temporal intensity profile

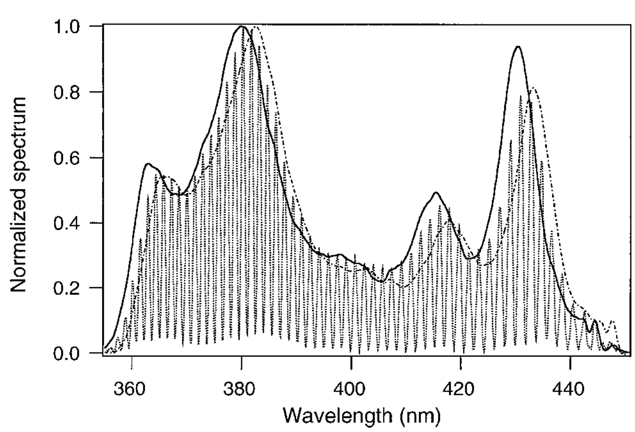

Fig. 2. SPIDER trace of a sub-6-fs pulse (dotted curve). Additionally, the spectra of the individual upconverted pulses are shown (solid and dashed–dotted curves).

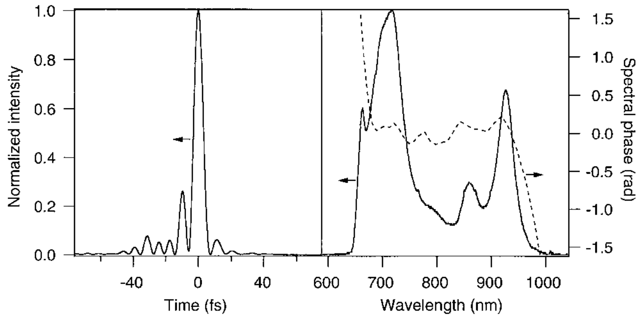

Fig. 3. Reconstructed temporal intensity profile (left) and spectral phase (right; dashed curve). The independently measured power spectrum of the pulse (right; solid curve) has a transform limit of 5.3 fs. The solid curves are referenced to the left and the dashed curves to the right vertical axes.

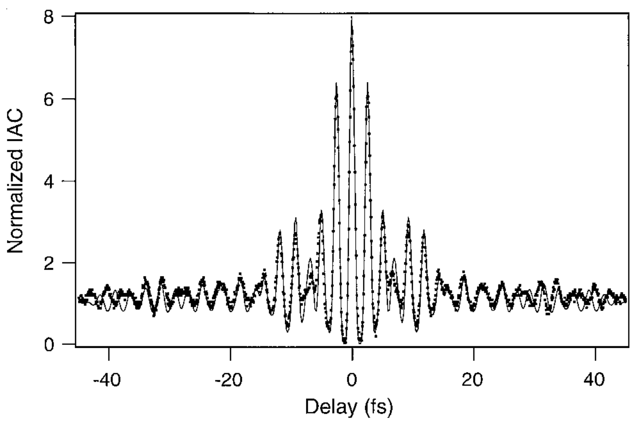

Fig. 4. Comparison of measured interferometric autocorrelation (IAC; dots) with the SPIDER-reconstructed IAC (solid curve).

with a FWHM of 5.9 fs. The oscillations in the central part of the phase are caused by the extracavity double-chirped mirrors,[13] which are used to compensate for the dispersion of the output coupler, together with the higher-order dispersion of the extracavity prism pair. Note the correspondence between the phase oscillations and the shape of the spectrum, which is expected since similar double-chirped mirrors are used in the laser cavity itself. The global S-like shape of the phase stems from residual uncompensated phase of the output coupler. This measurement clearly demonstrates that SPIDER can be used to directly reconstruct the complicated phase distortions experienced by ultrabroadband pulses.

As an independent check of the accuracy of the method, we compare the interferometric autocorrelation (IAC) calculated from the SPIDER data with a separately measured IAC (Fig. 4). The agreement is excellent even for the low-intensity structure in the wings of the IAC. The conventional but unjustified method of fitting a sech^2 pulse to the autocorrelation deceivingly yields a pulse duration of 4.5 fs. This systematic underestimation of the pulse duration affirms the need for complete characterization methods. The SPIDER measurement also confirms the analysis presented in Ref. 4 by different characterization methods, which resulted in a duration of 5.8 fs for pulses generated by this laser.

In conclusion, we have demonstrated SPIDER as a novel tool for the characterization of some of the shortest pulses available to date. The results of the SPIDER measurement show excellent agreement with those made by other methods. In contrast with those methods, however, SPIDER offers the unique advantage of providing complete spectral phase information with update times much shorter than 1 s. This suggests the possibility of using SPIDER as a complete and accurate online characterization tool for pulses in the sub-10-fs range.

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