Simplified spectral phase interferometry for direct electric-field reconstruction by using a thick nonlinear crystal

Aleksander S. Radunsky, Ellen M. Kosik Williams,* and Ian A. Walmsley

Institute of Optics, University of Rochester, Rochester, New York 14627 and Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

Piotr Wasylczyk and Wojciech Wasilewski

Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland

Alfred B. U'Ren

Centro de Investigación Cientifica y Educación Superior de Ensenada (CICESE), Baja California, 22860, Mexico

Matthew E. Anderson

Department of Physics, San Diego State University, San Diego, California 92182

Received November 7, 2005; accepted November 29, 2005; posted December 21, 2005 (Doc. ID 65850)

We propose and demonstrate a novel implementation of spectral-shearing interferometry (SSI) for reconstructing the electric field of ultrashort pulses by utilizing asymmetric group velocity matching in a long nonlinear crystal. The proposed configuration eliminates the requirement for a linearly chirped auxiliary pulse that is in common in all existing SSI methods, relying on nonlinear conversion to produce a spectral shear. © 2006 Optical Society of America

OCIS codes: 320.7160, 320.7100, 190.4360.

All schemes for measuring the electric-field envelope of ultrashort optical pulses that rely on square-law detectors must incorporate at least two filters, one with a time-shift-invariant response function and one with a time-shift-variant response function.[1] The order in which the test pulse encounters these filters and the method of reconstruction of the pulse field from the measured data allow the techniques to be separated into fundamentally distinguishable classes: interferometric and noninterferometric. Spectrographic methods, i.e., those in which the spectrum of the time-gated test pulse is measured for several relative delays between the pulse and the time gate, and tomographic methods, i.e., those in which the spectrum of the pulse is measured for several different phase modulations, fall into the latter category.

Although it is possible to synthesize appropriate filters by using linear (including active) optical elements, for a complete characterization of pulses with durations of less than 100 fs it is necessary to use nonlinear optical processes to affect a time-shift-variant filter with the appropriate bandwidth. Recently it has been shown how for several noninterferometric schemes a single thick nonlinear crystal enables the combined action of both types of filters to be achieved simultaneously, leading to important practical device simplifications. In spectrography, for example, the narrow phase-matching bandwidth of a thick second-harmonic-generating crystal can be used as a spectral filter, thereby enabling the sum-frequency generation (SFG) process to act simultaneously as a time gate and a spectrometer.[2] This idea has been incorporated into a compact format for frequency-resolved optical gating[3] (FROG) as well as for sonogram measurement.[4]

In this Letter we show how a thick nonlinear crystal with an appropriately tailored phase-matching function can be utilized in spectral-shearing interferometry (SSI). In this application, too, the nonlinear interaction performs two functions (though different from those in spectrography and sonography) and leads to considerable simplification of the measurement instrument.

An important example of SSI is spectral phase interferometry for direct electric-field reconstruction (SPIDER). In this method the spectral phase of the test pulse is extracted from the spectral interference of a pair of spectrally shifted and time-delayed replicas of the pulse by a simple, noniterative processing of the recorded spectral interferogram (shearogram).[5] In conventional SPIDER, a relative spectral shift (the shear) between the two pulse replicas is produced when they upconvert with different quasi-monochromatic time slices of a highly chirped ancillary pulse in a thin nonlinear crystal.[6] What is required is a nonlinear process that can mix a broadband test pulse with a narrowband ancilla.

Here we demonstrate that this functionality is available by allowing the test pulse to propagate in a single, long nonlinear crystal whose phase-matching function (PMF) is arranged so that the ordinary wave has a very large acceptance bandwidth, whereas the extraordinary wave has a narrow bandwidth. This means that there is no need to arrange for a chirped ancillary pulse since the narrowband ancilla is se-

0146-9592/06/071008-3/$15.00

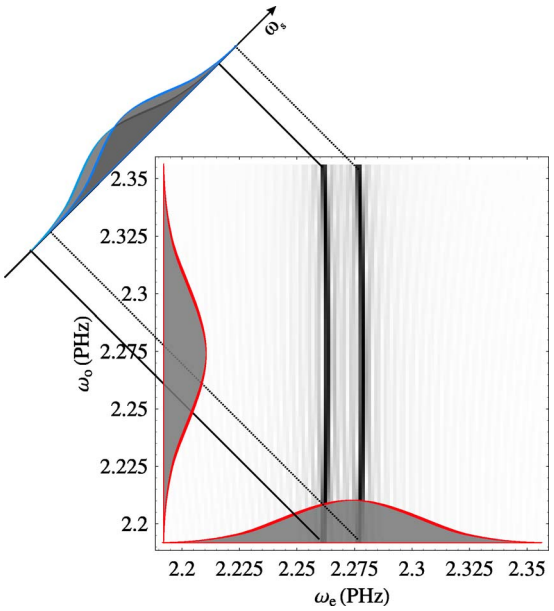

Fig. 1. (Color online) Absolute magnitudes of the collinear, type II PMF, $\mathrm{sinc}^2(\Delta kL/2)$, $\Delta k(\omega_e,\omega_0)=k_e(\omega_e+\omega_0)-k_e(\omega_e)-k_0(\omega_0)$ of a $L=2$ cm thick KDP crystal for two (different by 0.5°) values of the propagation angle, plotted as a function of frequency for ordinary ω_0 and extraordinary ω_e input polarization components (black indicating perfect phase matching). The sum-frequency signals are drawn on the diagonal axis, $\omega_s=\omega_e+\omega_0$, illustrating the shear between the outputs.

lected directly from the test pulse by the PMF of the nonlinear crystal. This scheme is known as long-crystal or LX-SPIDER. Figure 1 shows the theoretical PMF magnitude for optical fields traveling at two angles tilted ±0.25° away from the cut angle through a 2 cm long type II KDP crystal cut for maximum collinear upconversion at 830 nm. The particular combination of the crystal's material, length, and the wavelength range (Fig. 1 shows 800–860 nm) produces a nearly vertical PMF that is simultaneously very broad along the ordinary axis and very narrow along the extraordinary axis. Such a highly asymmetric PMF shape is due to a match of the group velocities of the *o*-fundamental input and the *e*-upconverted output fields and a mismatch between the *e*-fundamental and the *e*-upconverted field group velocities. The wavelength range over which pulses can be characterized using a KDP crystal is comparable to the tuning range of ultrashort Ti:sapphire lasers, while other types of crystals have been found to satisfy the above-mentioned requirement in different wavelength regions.[7] For an ultrashort pulse with the spectrum located in the 830 nm region, the unique shape of the PMF shown in Fig. 1 allows for the entire bandwidth of the *o*-wave to mix with a quasi-monochromatic portion of the *e*-wave spectrum as selected by the PMF. The precise angle of propagation relative to the crystal's optic axis (OA) determines the exact frequency of the monochromatic slice of the *e*-wave spectrum. Thus, if two copies of a pulse are directed into the crystal, altering their respective propagation angles produces a spectral shift between the upconverted outputs.

The schematic of the experimental LX-SPIDER arrangement used to prove the principle of operation is shown in Fig. 2. Our latest implementation is adapted from a Michelson interferometer, where corner-cube mirror pairs are used as the end reflectors and the output beam splitter is replaced by a mirror to collect the otherwise unused portion of the incident beam. Before entering the interferometer, the polarization of an initially horizontally polarized input test pulse is rotated by 45° (with an achromatic half-wave plate) to obtain both the *e*- and the *o*-fundamental components in the crystal whose OA is set to be horizontal. A 14 mm thick quartz plate positioned in front of the interferometer (with its slow axis oriented horizontally) delays the *e*-wave by 450 fs with respect to the *o*-wave, the general requirement being that the fundamental *e*-ray pulse upconverts both leading and trailing parts of the *o*-ray pulse in the crystal to eliminate distortions in the upconverted output.[8,9] One arm of the interferometer is translated with respect to the other to give a relative temporal delay (τ) required in the SPIDER reconstruction algorithm. The output beam of one arm is also tilted with respect to the other such that the two pulse replicas are incident at slightly different angles onto the crystal, which is placed directly behind the interferometer. We use a 2 cm KDP crystal cut at a 68° phase-matching angle at normal incidence. Each of the two pulse replicas upconverts only with itself (type II: $oe\rightarrow e$) in the crystal, and the resultant spectrally shifted and time-delayed SFG beams intersect after exiting the crystal. The spectral shearogram is resolved in a spectrometer (USB2000, Ocean Optics) with its entrance slit positioned in the beam overlap region.

Two parameters must be known for the simple, noniterative SPIDER reconstruction algorithm: the spectral shear (Ω) and the time delay between the two input replicas (τ). In our setup the shear value is easily obtained by independently measuring the blue SFG spectrum in each arm and comparing the two spectrally shifted profiles. The angle between the beams can be used to adjust the shear value, and it is typically set in the 0.2°–0.5° range in our experiments, leading to spectral shear values of

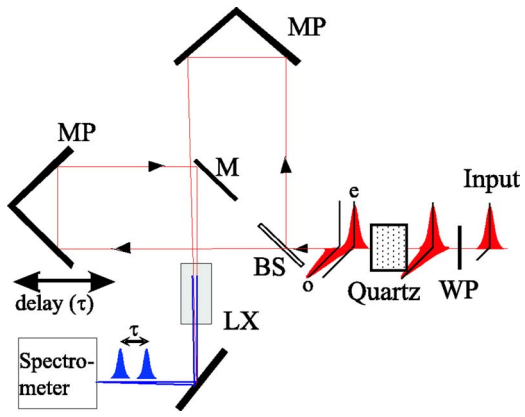

Fig. 2. (Color online) Experimental arrangement (top view) for LX-SPIDER. WP, half-wave plate; BS, beam splitter; M, mirror; MP, mirror pair; LX, crystal.

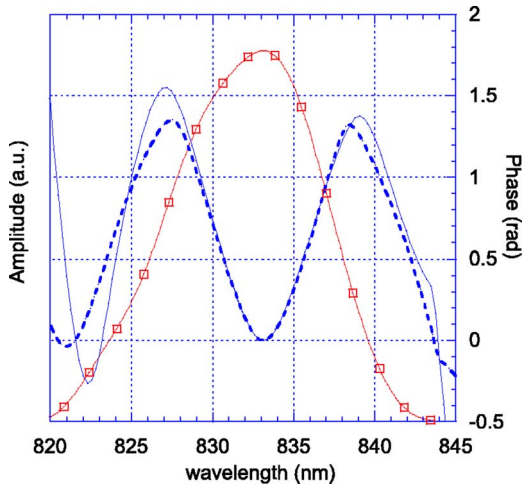

Fig. 3. (Color online) Spectral amplitude (curve with squares) of the test pulse and its sinusoidally modulated spectral phase reconstructed by conventional (solid curve) and long-crystal (dashed curve) SPIDERs.

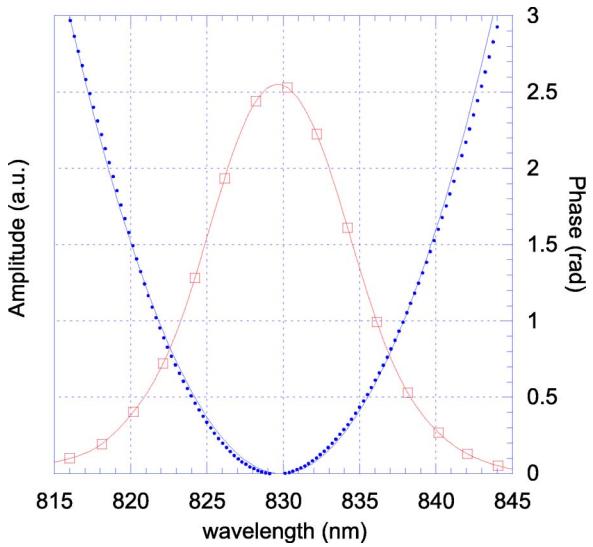

Fig. 4. (Color online) Spectral amplitude (curve with squares) and phase (dots) measured by LX-SPIDER and the theoretical spectral phase (solid curve) after propagation through 10 cm of BK7 glass.

4–10 mrad fs^{-1} (0.35–0.9 nm at 415 nm). The delay value is established by first measuring the interferogram of the horizontally polarized portions of the input test pulse that pass through the crystal without upconversion and then correcting the extracted τ by a factor that takes into account the material dispersion in the crystal experienced by the upconverted pulses. The experimental procedure requires no intermediate alignment as there is no spatial walk-off between the horizontal (extraordinary) components of the test pulse and the upconverted *e*-wave signal. The subsequent data processing is identical to that in a conventional SPIDER reconstruction.[6]

The performance of the LX-SPIDER approach was compared with a conventional SPIDER by using both devices to characterize complex pulses sculpted by a pulse shaper. Figure 3 displays the reconstruction results for a sinusoidally shaped spectral-phase profile. The recovered phases agree very well over the central bandwidth with some discrepancy appearing in the regions of middle and lower spectral density. The low signal level is responsible for the conventional SPIDER phase deviating somewhat from the ideally sinusoidal profile recovered with a more sensitive LX-SPIDER.

The accuracy of the technique has also been verified experimentally by measuring the dispersion accumulated by a 70 fs pulse (FWHM) centered at 830 nm after propagation through a test block of 10 cm BK7 glass. A comparison between the theoretical curve and the measured data is shown in Fig. 4. The spectral phases agree very well over the entire nonzero spectral-density region of the test pulse, and the measured value of group-delay dispersion of 4160 fs^2 is consistent with the theoretical value of 4175.5 fs^2 (a 0.3% discrepancy).

In summary, we have demonstrated a novel implementation of SSI for a direct electric-field reconstruction of ultrashort pulses. LX-SPIDER uses the asymmetric group-velocity-matching condition present in type II upconversion to produce spectrally sheared pulse replicas. The approach eliminates the need for an externally generated chirped pulse, leading to a simplified construction and alignment of the device with fewer components while retaining all the traditional advantages of the SPIDER reconstruction algorithm.

I. A. Walmsley, E. M. Kosik Williams, and A. S. Radunsky acknowledge the support of the NSF in conducting this research. P. Wasylczyk acknowledges the support of the Foundation for Polish Science. A. Radunsky thanks Christophe Dorrer for helpful discussions. A. Radunsky's e-mail address is alexr@optics.rochester.edu.

*Present address, Sullivan Park, Corning Incorporated, Corning, New York 14831.

References

1. V. Wong and I. A. Walmsley, J. Opt. Soc. Am. B **12**, 1491 (1995).
2. C. Radzewicz, P. Wasylczyk, and J. S. Krasinski, Opt. Commun. **186**, 329 (2000).
3. P. O'Shea, M. Kimmel, X. Gu, and R. Trebino, Opt. Lett. **26**, 932 (2001).
4. D. T. Reid and I. G. Cormack, Opt. Lett. **27**, 658 (2002).
5. C. Iaconis and I. A. Walmsley, Opt. Lett. **23**, 792 (1998).
6. C. Iaconis and I. A. Walmsley, IEEE J. Quantum Electron. **35**, 501 (1999).
7. W. P. Grice, A. B. U'Ren, and I. A. Walmsley, Phys. Rev. A **64**, 063815 (2001).
8. A. M. Weiner, IEEE J. Quantum Electron. **19**, 1276 (1983).
9. A. P. Baronavski, H. D. Ladouceur, and J. K. Shaw, IEEE J. Quantum Electron. **29**, 580 (1993).