Two-dimensional spectral shearing interferometry for few-cycle pulse characterization

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We present a new method for measuring the spectral phase of ultrashort pulses that utilizes spectral shearing interferometry with zero delay. Unlike conventional spectral phase interferometry for direct electric-field reconstruction, which encodes phase as a sensitively calibrated fringe in the spectral domain, two-dimensional spectral shearing interferometry robustly encodes phase along a second dimension. This greatly reduces demands on the spectrometer and allows for complex phase spectra to be measured over extremely large bandwidths, potentially exceeding 1.5 octaves. © 2006 Optical Society of America

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As few- and single-cycle optical pulses have become more common, spectral phase interferometry for direct electric field reconstruction[1] (SPIDER) has emerged as one of the principal methods for determining the electric field of such pulses,[2] with variants specialized for low-power pulses[3] and spatiotemporal characterization,[4] among others. SPIDER applies the technique of Fourier transform spectral interferometry to a pair of frequency sheared pulses. Two significant benefits of spectral shearing interferometry are its insensitivity to noise[5] and the fact that it directly measures spectral phase. In contrast, indirect methods such as interferometric autocorrelation[6] and frequency-resolved optical gating[7] require the solution of ill-posed inverse problems.[8,9] Nonetheless, there are a few issues with conventional SPIDER that are particularly cogent for large bandwidths. Most notably, the delay τ between the pulses must be calibrated and maintained to within interferometric precision.

In Fourier transform spectral interferometry, the measured pulse width error for a given delay error $\delta\tau$ can be shown by Gaussian analysis to be approximately

$$\delta t \approx \delta\tau(\Delta\omega/\Omega), \tag{1}$$

where $\Delta\omega$ is the pulse bandwidth and Ω is the shear frequency. For few- and single-cycle pulses, the dimensionless ratio $\Delta\omega/\Omega$ is typically of the order of 100 (see Ref. 10, for example). For few-cycle pulses, then, the SPIDER delay error $\delta\tau$ must be of the order of 10 as to achieve even 10% accuracy in the measured pulse width. Such calibration accuracy is not trivial for delays of the order of picoseconds and requires mechanical stability to within a few nanometers and beam pointing to within a few milliradians (assuming perfect alignment to begin with). Unfortunately, there is no self-consistency check available in SPIDER; any error in τ is simply manifest as an additive quadratic phase. This is especially relevant when one is optimizing a laser: Given the coupling between beam alignment and τ, it is probable that any tuning of the laser will be, to some extent, optimization of spurious delay to minimize the pulse width as measured.

A second issue with conventional SPIDER is the use of a Michelson interferometer to split the measured pulse. This invariably introduces phase distortion, especially for broadband pulses, as it is difficult to build a beam splitter that is dispersionless over more than an octave of bandwidth.

Zero-additional-phase SPIDER[11] addresses this issue by using two noncollinear chirped pulses. However, it still suffers from the SPIDER delay calibration issues discussed above. Furthermore, the multiple path geometry results in inefficient coupling into the spectrometer, making the method most appropriate for externally amplified chirped pulses.

In the course of writing the present Letter we were made aware of spatially encoded arrangement (SEA) SPIDER,[12] which was recently demonstrated on 100 fs pulses. SEA-SPIDER uses an arrangement similar to zero-additional-phase SPIDER, though no interpulse delay is introduced and a spatial interference fringe is imaged orthogonally to the spectral axis.

In common with SEA-SPIDER, our method also performs shearing interferometry with zero delay, though we use a collinear geometry and encode the fringe over time rather than space (as discussed in what follows). A benefit of SEA-SPIDER relative to our method is that the former is capable of single-shot operation. However, where power limitations render single-shot measurements impossible, two-dimensional spectral shearing interferometry (2DSI) may hold advantages in terms of stability and signal strength, owing to the collinearity of 2DSI and the fact that the fringe is decoupled from the spatial structure of the beam. Furthermore, expression (1) still applies to any shearing interferometry, even if the delay is nominally zero. Thus the separate paths taken by the pulses in SEA-SPIDER mean that even subwavelength imaging aberrations or nanometer intersection misalignments of the auxiliary pulses could become an issue for extremely short pulses.

In 2DSI, two highly chirped (quasi-cw) signals are created by dispersing a portion of the pulse to be measured and splitting the result in a Michelson interferometer (see Fig. 1). The two chirped pulses are mixed with the original short pulse in a type II $\chi^{(2)}$ nonlinear crystal. The two upconverted pulses that result are sheared spectrally but are collinear (neglecting the small difference in transverse photon momentum caused by the shear) and with identical envelopes, forming a single pulse. To observe the phase difference between the pulse's two components, the delay of one of the chirped auxiliary pulses is scanned over a few optical cycles by oscillating its corresponding mirror in the interferometer. This is tantamount to scanning the zeroth-order phase of one of the upconverted pulse components. The spectrum of the upconverted signal is recorded as a function of this phase delay, yielding a two-dimensional intensity function that is given by

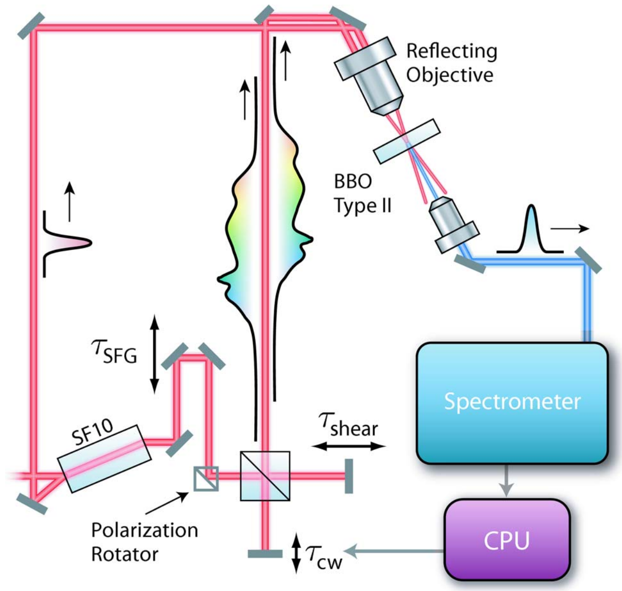

Fig. 1. (Color online) Schematic of 2DSI optics: SF, SF10 glass (Schott glass); BBO, β-barium borate.

$$I(\omega,\tau_{\mathrm{cw}}) = |A(\omega)|^2 + |A(\omega-\Omega)|^2 + 2|A(\omega)A(\omega-\Omega)| \times\cos[\omega_{\mathrm{cw}}\tau_{\mathrm{cw}} + \underbrace{\phi(\omega)-\phi(\omega-\Omega)}_{\tau_g(\omega)\Omega+O[\Omega^2]}], \tag{2}$$

where τ_{cw} and ω_{cw} are the delay and the local frequency, respectively, of the quasi-cw signal being shifted, $A(\omega)$ is the upconverted pulse spectrum, and $\phi(\omega)$ is its spectral phase. As in SPIDER, the phase difference between the two sheared components is a first-order approximation for the group delay multiplied by the shear frequency.

A two-dimensional raster plot of $I(\omega,\tau_{\mathrm{cw}})$ reveals the shifted pulse spectrum along the ω axis, with fringes along the τ_{cw} axis that are locally shifted in proportion to the group delay at a given frequency. See Figs. 2(a) and 2(b) for an example (in the wavelength domain). The user can immediately ascertain the rough qualitative properties of the complex spectrum simply by looking at the raw spectra; each spectral component is vertically shifted in correspondence to its actual shift in time. The ability to interpret the spectra directly is valuable when one is optimizing a laser, yielding information not available with processed data from an inversion algorithm alone.

Precise quantitative determination of the group delay spectrum can be effectively extracted by computing one-dimensional fast Fourier transforms along the τ_{cw} axis and taking the phase of the dominant spectral component. It is not necessary to know the length or rate of the delay scan, so long as the scan is relatively linear and sufficiently long. Only the relative phase of the fringes matters in Eq. (2), so the technique is highly robust to perturbations to the delay scan. In contrast to SEA-SPIDER (which requires knowledge of the nominal fringe spacing to deconvolve the spatial envelope), the only calibration needed with 2DSI is for the upconversion frequencies

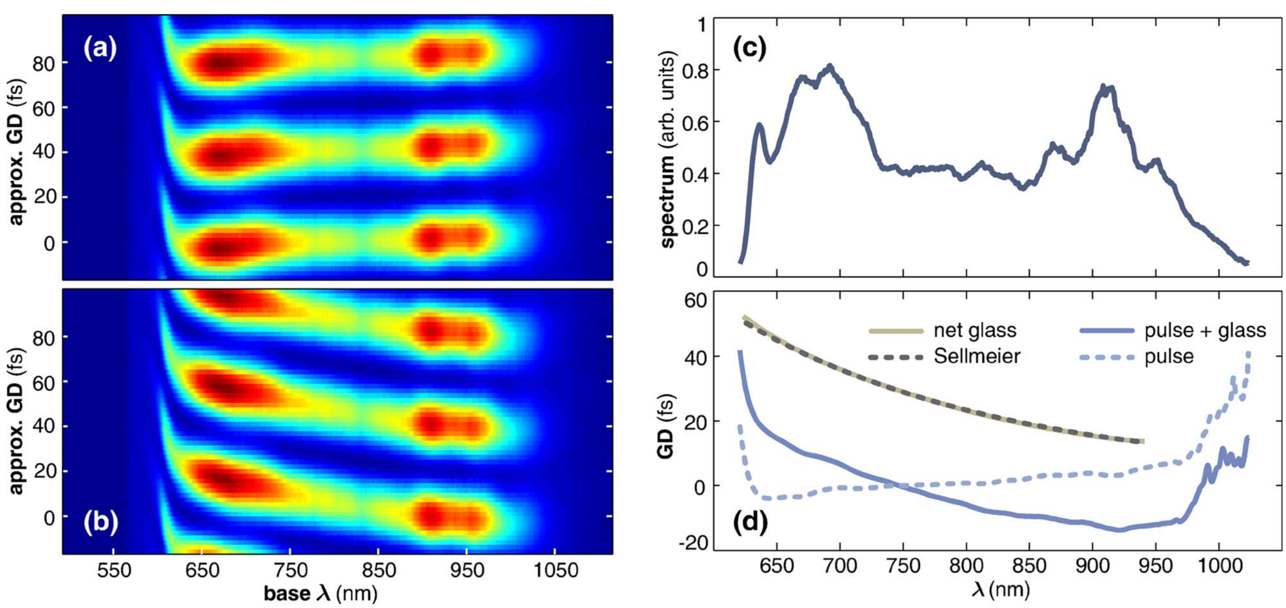

Fig. 2. (Color online) Raw 2DSI data from (a) a 5 fs laser pulse and (b) a pulse dispersed by 1 mm of fused silica. The spectrum is shown in (c) with the extracted group delay (GD) curves shown in (d) alongside the measured and Sellmeier-derived glass group delay.

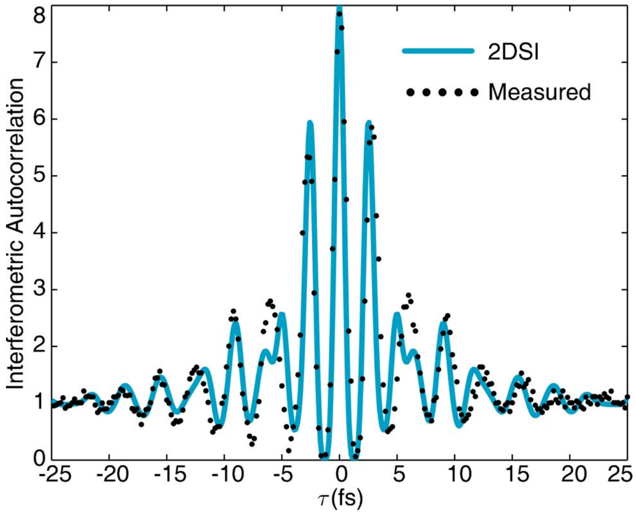

Fig. 3. (Color online) 2DSI predicted and measured interferometric autocorrelation of a 5 fs pulse.

that determine the shear. Furthermore, this is a relatively noncritical calibration, as demonstrated in Ref. 1, and changes in incoming beam alignment will have a negligible effect.

While the requirement for scanning prohibits single-shot operation, scan rates up to a few hertz were possible in this first implementation, limited by the speed of the computer interface to the piezoelectric amplifier. With further optimized hardware, scans well above video rates should be possible, given the extremely short distances involved.

The sensitivity to the spurious interpulse delays common to spectral shearing methods is mitigated with 2DSI, as the upconverted pulses originate from the same point in space and time (the intersection of the quasi-cw beam and the short pulse) and are then paraxially imaged into a spectrometer. Given the stationary phase condition of imaging and the lack of aberrations on axis, the zero delay between the pulses should remain stable even with changes in incoming beam alignment. Multiple shears can nonetheless be used as a self-consistent verification that no phase errors have occurred.

As with SEA-SPIDER, the ability to arbitrarily set the shear allows for optimal selection of Ω for a given situation, subject to sampling requirements. A given setup may thus be used to measure a wide variety of pulse bandwidths and chirps. This is in contrast to conventional SPIDER, for which the need to spectrally resolve a dense fringe limits the time–bandwidth product that can be tolerated.

To gauge the relative accuracy of the method, a few-cycle (5 fs FWHM) pulse from a prismless Ti:Sa laser[13] was measured, with 2DSI used both before and after dispersion by a 1 mm fused-silica plate [Figs. 2(a) and 2(b), respectively]. It is apparent from the raw spectrum in Fig. 2(a) that the pulse is initially slightly negatively chirped, and the positive dispersion introduced by the glass plate is evident in Fig. 2(b). The net measured group delay matches the Sellmeier predicted curve well, as shown in Fig. 2(d). To enhance the fringe tilt, a shear of 18 THz was used. No averaging was done, and the shear was calibrated independently by cross correlation of the upconverted spectra with the base spectrum.

To qualitatively demonstrate the absolute accuracy of the system, an IAC was performed on the same 5 fs pulse and compared with that predicted by the reconstructed pulse from the 2DSI measurement. The predicted and experimental IAC traces are shown in Fig. 3. The traces conform reasonably well, with some deviation that we attribute largely to limitations in the IAC technique for few-cycle pulses (note that the IAC is not exactly symmetric, as it ideally should be). As a measure of the precision and repeatability of 2DSI, we achieved the same pulse width prediction to within a few hundredths of a femtosecond for shears ranging from 4 to 20 THz.

Two-dimensional spectral shearing interferometry involves a relatively simple optical setup with little calibration required, yet is capable of extremely accurate measurements over a large bandwidth. The lack of dispersion on the pulse to be measured, the stable absence of delay between the sheared pulses, and the relaxed spectrometer resolution requirements make 2DSI extremely well suited for the measurement of wide-bandwidth pulses, including those with potentially complicated phase spectra. Further work is under way to increase the scanning frequency to video rates.

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