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

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Abstract. We demonstrate a new pulse measurement technique, two-dimensional spectral shearing interferometry, which is particularly amenable to the optimization of few-cycle lasers. The method only requires the calibration of the spectral shear and is stable to incoming beam perturbations. We show initial results of measurements from a 5 fs Ti:sa oscillator.

1. Introduction

Spectral shearing interferometry (typified by SPIDER [1]) is unique among pulse measurement techniques in that it directly and unambiguously measures the spectral phase of an optical signal by interfering adjacent frequency components. Consequently, it has joined frequency resolved optical gating [2] as one of the principal methods used to measure few-cycle pulses [3, 4]. There are, however, a few challenges with SPIDER relevant for the measurement, and especially optimization, of ultrahigh bandwidth pulses.

Chief among these issues is the fact that SPIDER requires interferometric calibration and stability of the delay between the up-converted pulses. An uncertainty of $\delta\tau$ in the delay creates a dispersion error $\delta\phi''$ that results in a temporal uncertainty in the measured pulse (roughly the potential pulse width error) of approximately

$$\delta t = \delta\phi'' \Delta\omega \approx \delta\tau \left(\frac{\Delta\omega}{\Omega} \right). \tag{1}$$

For few- and single-cycle pulses, the dimensionless ratio $\Delta\omega/\Omega$ (essentially the number of phase samples) must be on the order of 10–100 [4]. Thus, achieving even one femtosecond of temporal accuracy requires knowing and stabilizing the delay to on the order of ten attoseconds. Since this delay is typically around a picosecond, this is a non-trivial task. For example, even with initially perfect alignment, roughly one femtosecond of error will be introduced with only two milliradians of beam deviation. It is thus probable that any tuning of the laser will be, to some extent, simply optimization of spurious SPIDER delay to minimize the pulse width as measured.

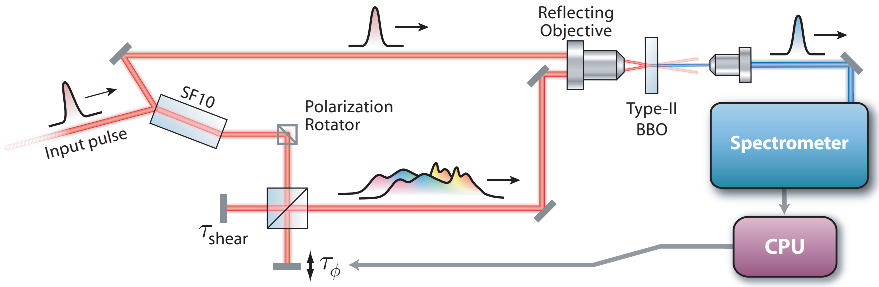

Fig. 1. Schematic of 2DSI optics.

2. Overview of 2DSI Technique

In 2DSI, two chirped (quasi-CW) pulse copies are mixed with the short pulse to be measured in a type II $\chi^{(2)}$ crystal (see Fig. 1). The two up-converted 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 in time. The zeroth-order phase of one of the upconverted pulses is scanned over several cycles by vibrating the corresponding mirror in the interferometer a few microns. The spectrum of the up-converted signal is recorded as a function of this phase delay, yielding a 2-D intensity function that is given by

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

where τ_ϕ and ω_{cw} are the delay and local frequency, respectively, of the quasi-CW signal being scanned, $A(\omega)$ is the up-converted pulse spectrum, and $\phi(\omega)$ is the spectral phase (delay invariant terms are omitted). The under-bracketed expression (the fringe phase) is, to first-order, the group delay multiplied by the shear frequency. A simple two-dimensional raster plot of (2) reveals the shifted pulse spectrum along the ω-axis, with fringes along the τ_ϕ-axis that are locally phase shifted in proportion to the group delay at a given frequency (as illustrated in Fig. 2). Since only the relative fringe phase matters, the delay scan does not need to be calibrated in any way, so long as it's reasonably linear. In fact, the only required calibration is for the shear Ω, a relatively insensitive parameter [1].

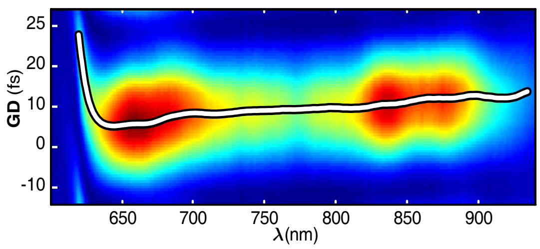

Fig. 2. A single 2DSI fringe from a 5 fs Ti:sapphire pulse, with the extracted spectral group delay superimposed, demonstrating the simple interpretation of the fringes.

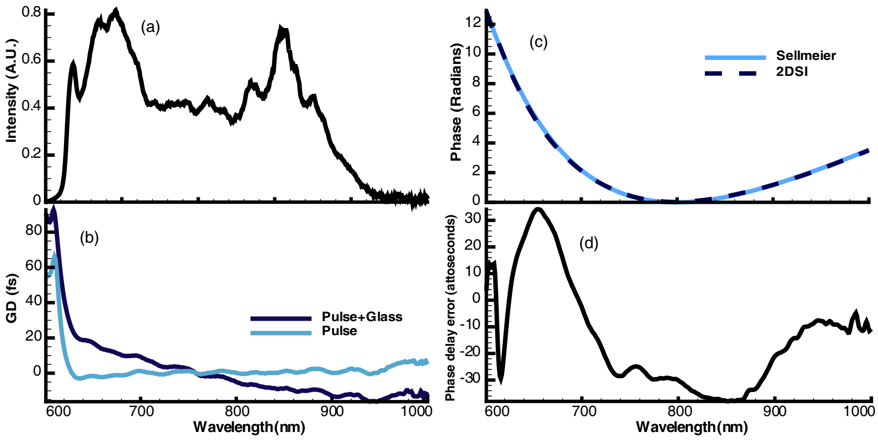

Fig. 3. Few-cycle pulse characterization: (a) spectrum of pulse; (b) spectral group delay of pulse before and after dispersion by glass plate; (c) extracted phase difference (dashed) and theoretical (solid) prediction for fused silica; (d) phase delay error computed from (c).

3. Experimental Results

We measured a few-cycle (~5 fs FWHM) pulse from a prismless Ti:sa laser (Venteon UltraBroad, NanoLayers GmbH) both before and after dispersion from a 1 mm fused silica plate. The data are shown in Fig. 3. The small group delay oscillations caused by the chirped mirror satellite pulses are evident in the individual curves, as is significant phase distortion due to output coupler roll-off in the wings. Nonetheless, subtracting them results in a smooth phase curve that closely matches that predicted by the Sellmeier equation for fused silica; the phase delay error over the 400 nm bandwidth remains within ±35 attoseconds.

4. Conclusions

2DSI does not require the dispersive splitting of the measured pulse that is characteristic of SPIDER, nor the associated highly sensitive calibration and maintenance of interpulse delay [5]. It is thus relatively robust to any beam perturbations that occur during laser tuning. These factors render 2DSI well suited for the measurement and optimization of single- and few-cycle pulses.

References

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