# Two-dimensional spectral shearing interferometry (2DSI) for ultrashort pulse characterization

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**Abstract**: We present a new pulse characterization method based on two-dimensional spectral shearing interferometry with zero delay. It features simple calibration, greatly relaxed spectrometer resolution, and is well suited for few-cycle laser pulses.

**OCIS codes**: (320.7100) Ultrafast measurement; (120.5050) Phase measurement

## 1. Overview of Method

As few-cycle pulses have become common, spectral shearing interferometry (SPIDER [1]) has become a proven method for measuring the spectral phase of such pulses [2, 3]. Here, we present a two-dimensional spectral shearing (2DSI) technique which, in contrast to SPIDER, requires only the non-critical calibration of the shear frequency and does not perturb the pulse before up-conversion. Rather than encode phase as a sensitively calibrated fringe in the spectral domain, this method robustly encodes phase along a separate dimension, greatly reducing demands on the spectrometer and allowing for complex phase spectra to be measured with high accuracy over extremely large bandwidths, potentially exceeding an octave.

In the present scheme, the pulse under test is up-converted with two chirped pulse copies. The two chirped quasi-CW signals are created in an interferometer and mixed with the short pulse in a Type-II $\chi^{(2)}$ crystal (see Fig. 1). The two up-converted copies are sheared spectrally, but are collinear and temporally identical (they essentially form a single pulse). The delay of one of the chirped pulses is scanned over a few optical cycles by vibrating the corresponding mirror in the interferometer. This is tantamount to scanning the zeroth-order phase of one of the pulse copies. The spectrum of the output pulse is recorded as a function of this phase delay, yielding a 2-D intensity spectrum that is given by

$$I(\omega,\tau_\phi) = 2A(\omega)A(\omega-\Omega)\cos[\omega_{\rm cw}\tau_\phi + \underbrace{\phi(\omega)-\phi(\omega-\Omega)}_{\tau_{\rm g}(\omega)\Omega+O(\Omega^2)}] + \text{D.C.} \tag{1}$$

where $\tau_\phi$ and $\omega_{\rm CW}$ are the delay and local frequency, respectively, of the quasi-CW signal being scanned, $A(\omega)$ is the magnitude of the up-converted pulse spectrum, and $\phi(\omega)$ is the spectral phase. The under-bracketed term is the first-order finite difference of the spectral group delay multiplied by the shear frequency.

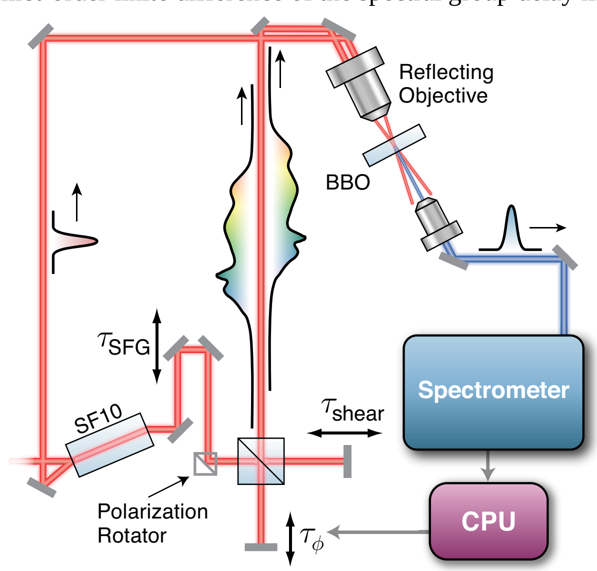


Fig. 1. Schematic of 2DSI optical setup.

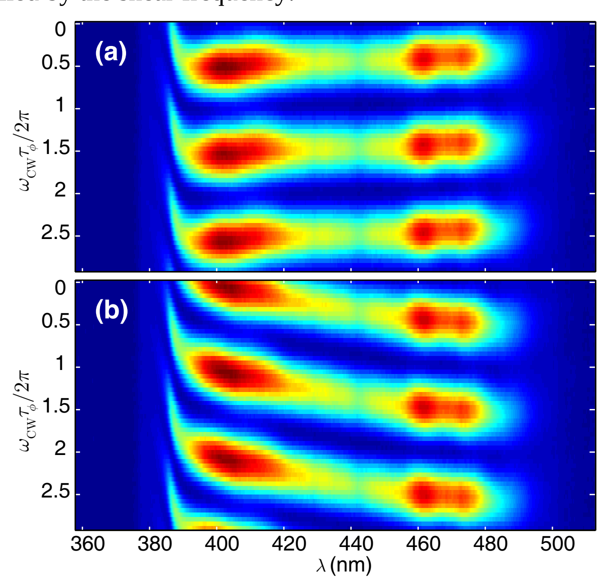


Fig. 2. Raw output of 2DSI for: (a) 5 fs pulse and (b) the same pulse dispersed by 1 mm of fused silica.

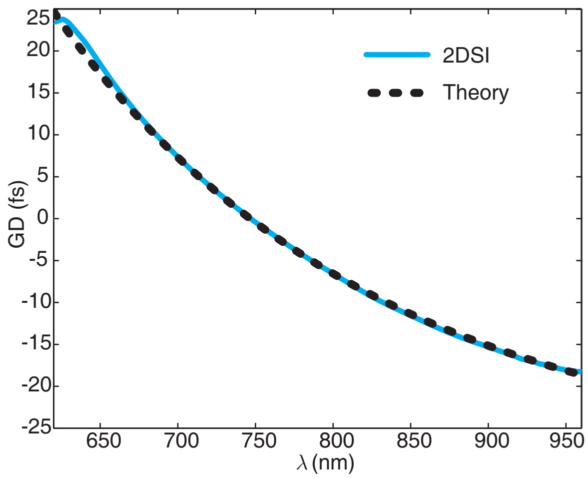


Fig. 3. Group delay measurement of 1 mm of fused silica.

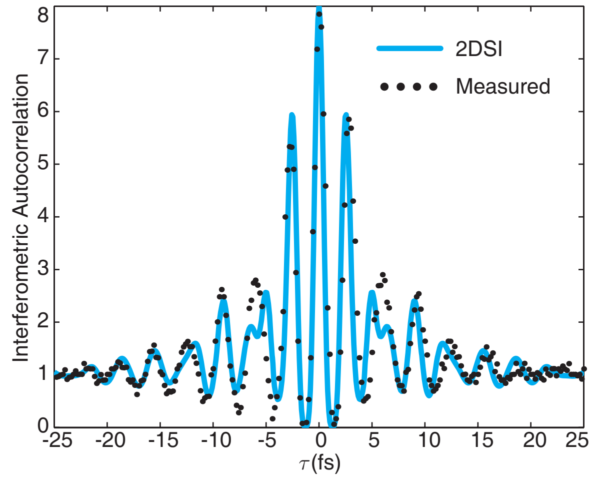


Fig. 4. Predicted interferometric autocorrelation for 5 fs pulse.

A simple two-dimensional raster plot of the raw spectra (see Fig. 2) reveals the shifted pulse spectrum along the $\lambda$-axis, with fringes along the $\tau_\phi$-axis that are shifted by an amount proportional to the group delay at the corresponding wavelength. The user can thus immediately ascertain the salient properties of the complex spectrum simply by looking at the raw output of the measurement: each spectral component is vertically shifted in proportion to its actual shift in time. Precise quantitative determination of the fringe phase (and thereby group delay spectrum) can be directly obtained from the output with FFTs taken along the phase axis, with no iterative processing or filtering required.

The only calibration needed is for the shear, $\Omega$. This calibration can be done very accurately and easily by measuring the pulse before and after transmission through a known dispersive element. Multiple shears can be used to measure a given pulse as a self-consistent verification that no spurious absolute phase errors have occurred. This ability also allows for a wide range of pulse widths to be measured by the same setup.

It is not necessary to know the length or rate of the scan, so long as it is relatively linear over the measurement and long enough to determine a phase. Only the relative phase of the fringes matters in (1) and so the technique is robust to experimental noise. This fact also greatly simplifies the implementation and analysis of 2DSI.

## 2. Experimental Results

To gauge the relative accuracy of the method, we measured a few-cycle (~5 fs FWHM) pulse from a prismless Ti:sa laser [4]. We then introduced a 1 mm fused silica plate and measured the dispersed pulse. Raw output of the scans is shown in Fig. 2. The resulting group delay, obtained by directly subtracting the computed group delays from two measurements, matches the theoretical value well (Fig. 3). The difference curve is smooth despite significant group delay ripple in the individual pulses (caused by the chirped mirrors in the laser) evidenced in Fig. 2. The fused silica plate was *not* used to calibrate the shear for this experiment.

To demonstrate the absolute accuracy of the system, we performed an interferometric autocorrelation (IAC) on the same 5 fs pulse and compared it to that predicted by the spectral phase obtained from our 2DSI measurement and a separately measured spectrum. The predicted and experimental IAC traces are shown in Fig. 4. They conform well, though with slight deviations that we attribute largely to limitations in the IAC technique for few-cycle pulses (note, for example, that the IAC is not absolutely symmetric, as it ideally should be).

In summary, 2DSI does not require the dispersive splitting of the measured pulse that is characteristic of SPIDER, nor the associated highly sensitive calibration of pulse delay. This, together with the significant relaxation on spectrometer resolution, renders 2DSI extremely well suited for the measurement of wide-bandwidth pulses, including those with potentially complicated spectral phase. Further work is underway to optimize the sensitivity and to increase the scanning frequency to video rates to enable online laser optimization. We are also investigating the possibility of single-shot 2DSI using tilted wavefronts and a 2-D CCD sensor.

## References


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