Optics Communications 284 (2011) 3785–3794

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Single-shot multiple-delay crossed-beam spectral interferometry for measuring extremely complex pulses

Jacob Cohen [a], Pamela Bowlan [b], Vikrant Chauhan [a], Peter Vaughan [a], Rick Trebino [a,*]

[a] Georgia Institute of Technology, School of Physics, 837 State St, Atlanta, GA 30332, USA
[b] Max-Born-Institute, Max-Born Straße 2A, 12489 Berlin, Germany

ARTICLE INFO

*Article history:*
Received 15 December 2010
Received in revised form 26 February 2011
Accepted 27 February 2011
Available online 12 March 2011

*Keywords:*
Pulse measurement
Spectral interferometry
Complex pulses
Arbitrary waveforms

ABSTRACT

We demonstrate a single-shot measurement technique based on spectral interferometry (SI) for measuring the complete intensity and phase vs. time of extremely complex ultrashort laser pulses. Ordinarily, such a method would require an extremely-high-resolution spectrometer, but, by temporally interleaving many SI measurements, each using a different reference-pulse delay, our method overcomes this need. It involves introducing a transverse time delay into the reference pulse by tilting its pulse front transversely to the spectrometer dispersion plane. The tilted reference pulse then gates the unknown pulse by interfering with it at the image plane of a low-resolution imaging spectrometer, yielding an effective increase in the delay range and spectral resolution—by a factor of 30 in our proof-of-principle implementation. Our device achieved a temporal resolution of ~130 fs and a temporal range of 120 ps. This simple device has the potential to measure even longer and more complex pulses.



## 1. Complex ultrafast waveforms and their measurement

Recently there has been significant effort in the field of optical arbitrary-waveform generation [1], where a goal is to generate ~10 ns-long pulses with <100 fs structure. At the same time, this effort is also driving the field of optical metrology to develop new high-temporal- and high-spectral-resolution techniques [2–8] to measure such extremely complex waveforms.

The challenge in such measurements is attaining a large enough temporal range to measure the large temporal extent of the pulse, while simultaneously achieving a high temporal resolution to measure the fine temporal structure of the pulse. Alternatively, analogous spectral range and resolution conditions must be met if the measurement is performed in the frequency domain. Unfortunately, no measurement technique exists that can accomplish this—and to do so on a *single shot*, an additional requirement for measuring a true arbitrary waveform.

The measure of the complexity of a pulse is the time-bandwidth product, TBP = $\Delta t\ \Delta\nu$, where (in this work) $\Delta t$ is the FWHM of the pulse temporal intensity and $\Delta\nu$ is the FHWM of the pulse spectrum. Using the above numbers, arbitrary-waveform generation can yield pulses with TBPs of ~100,000. For their measurement, commonly used self-referenced methods do not suffice, as they can characterize only very simple ultrashort pulses directly out of lasers. Of such methods, to our knowledge, only frequency-resolved optical gating (FROG) can measure pulses with time-bandwidth products greater than ~10. But self-referencing is unnecessary for most complex pulses, as complex pulses are usually generated from simpler pulses using an additional apparatus, so that an easily measurable reference pulse is available to assist in measuring the complex pulse.

When such a pre-characterized reference pulse is available, cross-correlation FROG (XFROG) has measured (continuum) pulses with TBPs up to 5000 [9]. Alternatively, sonogram methods [10–12]—mathematically equivalent to the spectrogram generated in XFROG [9]—are capable of similar-complexity measurements. But it would be difficult to extend these methods to pulses with much larger TBPs due to the very large data sets involved ($N^2$ points, where $N$ is the length of the pulse field vector).

Additionally, several time-domain techniques based on temporal imaging can measure the temporal intensity of ps pulses [6,7] by stretching them to many ns in length, where detectors and oscilloscopes can accurately measure their intensities vs. time for potentially very complex pulses. In addition, high-bandwidth oscilloscopes and streak cameras can also measure the temporal intensity of longer, ps and ns, pulses. Heterodyning with a delayed version of the pulse or with another known pulse can yield the phase. Several techniques use this approach, including a variety of additional processes, such as four-wave-mixing in fibers [12]. However, these techniques involve a complex apparatus and/or expensive and fragile electronics.

In general, FROG and sonogram techniques have the great advantage that they involve two-dimensional data traces, which provide redundancy and internal corroboration of the measurement. But in the effort to measure extremely complex pulses, sacrifices must

* Corresponding author.
*E-mail address:* rick.trebino@physics.gatech.edu (R. Trebino).

0030-4018/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2011.02.078

be made, and this otherwise attractive feature is expendable. One technique that makes this sacrifice and has the potential to measure very complex waveforms is spectral interferometry (SI) [13]. In its simplest form, SI involves measuring the spectrum of the sum of two fields, that of a reference pulse and an unknown pulse. The result is a spectral interferogram from which both the amplitude and phase of the unknown pulse can be retrieved, provided that the reference pulse is known.

Although in principle SI is simple and high spectral resolution, in practice it is neither. Because it requires collinear pulses, it is very difficult to align and maintain aligned. And because it typically requires the reference pulse to be separated in time from the unknown pulse in order to make the spectral fringes required for pulse retrieval, its spectral resolution is limited to a factor of about five worse than that of the spectrometer used [14].

There have been numerous variations of SI, and some have improved its spectral resolution. For example, dual-quadrature SI (DQSI) [3,15], and even quadruple-quadrature SI (FQSI) [3], eliminate the pulse separation, but at a price of additional complexity and alignment sensitivity. Recently, Fontaine et al. demonstrated a "spectral interleaving" DQSI using multiple high-bandwidth oscilloscopes [3], which measure multiple spectral pieces of the pulse and concatenate them together. This technique offers a large temporal range: several microseconds. However, the temporal resolution is limited by that of the photo-detector and oscilloscope to about ~20 ps and so is inapplicable to ultrafast arbitrary waveform measurement. Alternatively, Asghari et al. demonstrated a time-domain variation of DQSI with 400 fs temporal resolution and 350 ps temporal range and used it to measure pulses with TBPs ~900. They achieved this by linearly chirping the pulse under test by a known (and large) amount, thereby mapping the individual spectral components of the pulse to time at an oscilloscope. Although this technique can be scaled to measure longer pulses with very fast update rates and high temporal resolution, it requires very accurate characterization of the dispersive medium in order to accurately map frequency to time.

It has also been proposed to significantly increase the finesse (and hence the measurable pulse complexity) of SI by using a variation of an echelle-type spectrometer that consists of a highly dispersive etalon with its dispersion orthogonal to that of the spectrometer diffraction grating [16], which yields a rectangular array that raster-scans the spectrum across the rectangular camera—a promising approach for measuring very complex pulses on a single shot. Its spectral resolution and accuracy are only limited by higher-order spectral variations of the dispersive elements, which could perhaps be compensated either optically or numerically.

Alternatively, it has been asserted that "time interleaving" [17] (measuring temporal pieces of the pulse separately and then concatenating them) could be the solution to the problem of measuring complex pulses on a single-shot. In previous work, we demonstrated a multi-shot time-interleaving technique that we call MUD TADPOLE. It has the ability to measure pulses with extremely large TBPs, and we have used it to measure pulses with TBPs of 65,000 [8]. MUD TADPOLE is a simple temporal scanning version of SEA TADPOLE [18–23], which is an experimentally simplified variation of SI that involves crossing *at an angle* the pulse to be measured with the previously measured reference pulse, which greatly simplifies alignment. The crossed beams generate a *spatial* interferogram [24,25]—unlike standard SI, which generates a *spectral* interferogram (the cause of the loss of spectral resolution), from which the unknown pulse's intensity and phase can be retrieved by *spatially* filtering the measured interferogram without loss of spectral resolution.

In this paper, we demonstrate a *single-shot* version of MUD TADPOLE, to our knowledge, the first single-shot technique for measuring complex waveforms that temporally interleaves many measurements with sub-ps temporal resolution and potentially nanosecond temporal range.

## 2. SEA TADPOLE and MUD TADPOLE

As mentioned, MUD TADPOLE shares a simple, yet powerful, feature with SEA TADPOLE and other crossed-beam SI methods: the required numerical filtering is accomplished using spatial fringes, rather than spectral fringes. Thus rather than separating the unknown and reference pulses in *time*, these methods separate them in *angle*. While SEA TADPOLE requires that the reference pulse at the output of the spectrometer (which expands inside the spectrometer to the reciprocal of its spectral resolution) be longer than the pulse to be measured, MUD TADPOLE does not make this assumption and instead takes advantage of the fact that the reference pulse generates spatial fringes *only* with the temporal piece of the unknown pulse with which it temporally overlaps. This allows multi-shot MUD TADPOLE to temporally scan the delay of the reference pulse, making numerous SEA TADPOLE measurements, something not possible in standard Fourier transform SI (FTSI), in which a large delay is required between the reference and unknown pulses.

We continue to exploit this advantage in single-shot MUD TADPOLE, making multiple SEA TADPOLE measurements at multiple delays—but on a single shot. We accomplish this by crossing the unknown pulse with a reference pulse with significant *pulse-front tilt* (PFT), generating a spatial interferogram similar to that obtained in SEA TADPOLE, except that now the delay varies spatially in the direction perpendicular to the spectral dispersion plane (see Fig. 1). Then a lens images the grating, mapping time to position at the camera.

Imaging the face of the grating onto the detector of the imaging spectrometer ensures that spatial dispersion (spatial chirp) is absent there and the main spatio-temporal distortion in the reference pulse is PFT (assuming the reference pulse was free of spatio-temporal distortions to begin with). This permits the use of a simple Fourier filtering technique [8] to retrieve the data.

The result is $N$ SEA TADPOLE measurements of the electric field of the unknown pulse, each delayed in time by an amount proportional to the PFT, $\eta$ (the time delay of the pulse front per unit transverse distance across the beam). Provided that the range of delays generated—the product of the PFT and the size of the camera at the output of the imaging spectrometer, $\Delta x_c$—is greater than or equal to the temporal length of the unknown pulse, $\tau_{unk}$, or $\eta \cdot \Delta x_c \geq \tau_{unk}$, then the full temporal electric field of the unknown pulse can be

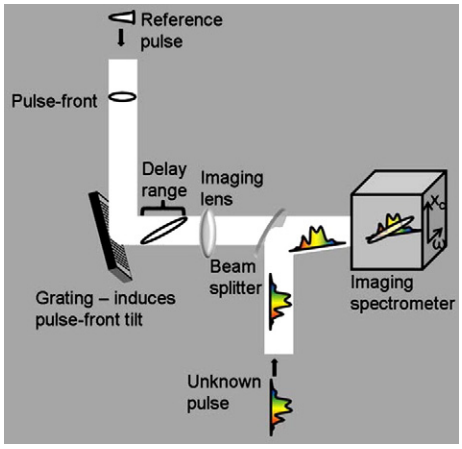


**Fig. 1.** Experimental setup for single-shot MUD TADPOLE. The pulse front of the spatially uniform reference pulse is tilted along the horizontal dimension by a grating. The imaging lens images the plane of the grating onto the detector of the imaging spectrometer, ensuring that spatial dispersion is absent and the main spatio-temporal coupling in the reference pulse is PFT. The unknown pulse is incident on the imaging spectrometer at a slight angle, $\theta$, with respect to the reference pulse. This crossing of the two pulses results in a spatial interferogram with spatial fringes along the $x_c$ dimension at the camera at the output of the imaging spectrometer.