Beyond the fringe: SPIDER – the anatomy of ultrashort laser pulses

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Ultrashort optical pulses form an increasingly important tool for many fields. In some cases it is the ability to deliver extremely high electric field strengths that makes the pulses useful, whilst in others it is the duration of the pulse itself that is critical. In both circumstances the ability to completely characterize the pulse's electric field in time (or frequency) adds a new dimension to ultrafast science, providing the means to perform new types of experiments and extending the range and reliability of standard ultrafast optical techniques.

The widespread use of ultrafast technology in physics, chemistry, biology, medicine and its enabling role in numerous practical applications calls for the development of pulse characterization instrumentation that is at least as robust as the current generation of laser sources. This instrumentation should be extremely sensitive, easy to use, flexible and reliable. The recently developed microSPIDER shown in **figure 1** is such a device.

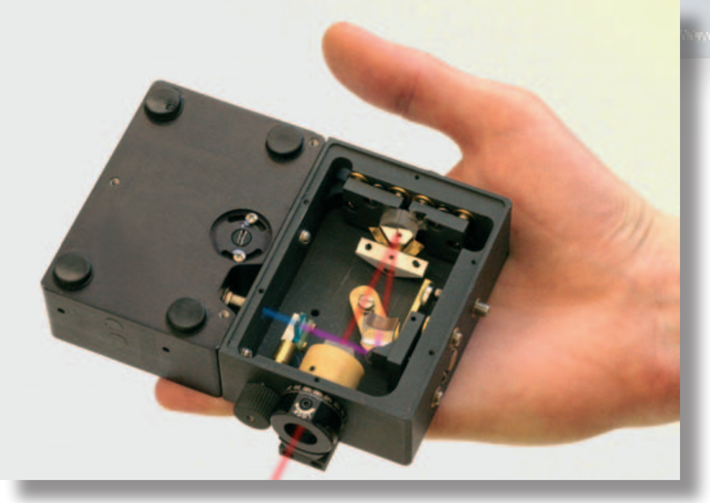

***Figure 1**: The latest generation of ultra-compact pulse characterization devices can come in handy. A micro-SPIDER for measuring the 30 fs pulses from a standard Ti:Sapphire laser system is shown*

1 Equivalence of time and frequency domain

An optical pulse may be characterized by its electric field, $E(t)$. This contains complete information about how the pulse intensity and the pulse wavelength changes in time. It is entirely equivalent to work in the frequency domain using the spectral amplitude, $\tilde{E}(\omega)$, which is the Fourier transform of $E(t)$. The energy spectrum of the pulse, as measured with a spectrometer, is then $I(\omega)=|\tilde{E}(\omega)|^2$. The problem is to determine what measurement or set of measurements should be made in order to reconstruct the pulse shape $\tilde{E}(\omega)$. Clearly a knowledge of $I(\omega)$ alone is not sufficient: the spectral phase, $\varphi(\omega)=\arg(\tilde{E}(\omega))$ is also needed. What is more, for some simple but important tasks, such as minimising the duration of a pulse with a given spectrum, knowing the phase alone is sufficient since making the spectral phase function a constant ("flattening the phase") generates the shortest possible pulse. Thus a rapid means of extracting this quantity forms the basis of pulse shape measurement and control.

2 Measuring the phase of ultrashort pulses

Ultrashort optical pulses, almost by definition, have durations shorter than the response time of any electronic instrument. Thus one can never directly measure the envelope of such an electric field by using only a photodetector. For many years it was assumed that only nonlinear optical elements were appropriate for this task, and indeed all of the early pulse characterization methods were based on either two-photon fluorescence or second-harmonic generation. But it turns out that this is not necessary. Even linear optics can be used, as long as they are active. More specifically optical elements such as shutters and phase modulators, with a response time of the same order as the measured pulse duration. The concatenation of these components with a passive linear optic, such as a spectrometer, is both necessary and sufficient for the complete measurement of a pulsed field. However, it is difficult to find active optical elements with a rapid enough response for the shortest pulses (10 fs - 30 fs) that are now generated routinely by laser systems. Thus

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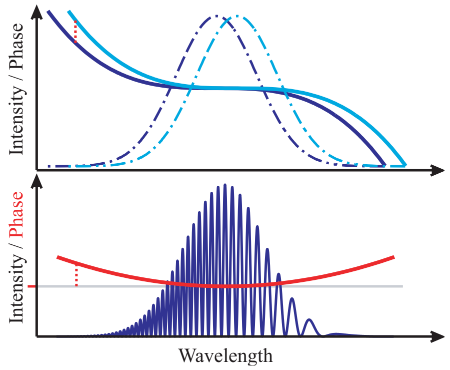

***Figure 2**: Spectral Interferometry between two spectrally sheared replica encodes the spectral phase variation across the entire pulse bandwidth. Together with the easily measured pulse spectrum, this gives a complete characterization of the input test pulse*

nonlinear optical elements are still used in commercial measurement apparatuses, and in the laboratory for pulses of duration 1 ps or less. For longer pulses, especially at telecoms wavelengths, linear modulators can be used.

Although there are several approaches to characterizing ultrashort optical pulses, in this article we concentrate on one particularly powerful method: spectral interferometry [1]. Interferometry is the natural tool for measuring the phase of optical fields. It works by superimposing two beams of light at a photodetector, thereby converting phase to amplitude. An important feature of interferometric measurement is that the phase can be extracted directly, even in the presence of noise. Spectrally-resolved interferograms in particular can be used to characterize the spectral phase of ultrashort optical pulses. In the usual case of spectral interferometry an unknown test pulse $\tilde{E}_T(\omega)$ is combined at a spectrometer with a time-delayed reference pulse.

The phase difference between test and reference is encoded in the fringe spacing. Of course this approach requires a well-characterized reference pulse, with a known spectral phase. Since this pulse must cover the same spectral bandwidth as the test pulse, characterizing the reference is just as challenging as the problem we are trying to solve! We face a dilemma.

3 Self-referencing pulse measurement using interferometry

Fortunately, there is a solution: self-referencing spectral interferometry, in which the test pulse is used to measure itself. This allows one to reconstruct the shape of a femtosecond optical pulse without the need for a separate reference pulse. One version of this technique, labelled "Spectral Phase Interferometry for Direct Electric field Reconstruction", or SPIDER [2], makes use of two frequency shifted replicas of the test pulse to generate a self-referenced interferogram, as shown in **figure 2**. The difference in the two frequency shifts is called the spectral shear.

Retrieval of the spectral phase encoded in the interferogram is fast and straightforward. Variations of the spectral phase show up as changes in the fringe spacing, and numerical one-dimensional Fourier transforms are used to extract the fringe displacements. Providing the spectral shear and the time delay between the pulses are known, the fringes spacings can be directly concatenated to extract the spectral phase versus wavelength. Phase retrieval at kilohertz pulse repetition rate has been demonstrated using this algorithm. Not only is the method insensitive to distortions of the spectral intensity but also it requires only a small dynamic range for recording the interferogram. Indeed it has been shown that one could use as low as 1 bit sampling of the interferogram signal amplitude and still retrieve the pulse field reliably in the presence of non-negligible noise.

For the most common pulse lengths of 10 fs to 1 ps in the visible or the mid infrared, generating the frequency shear usually involves nonlinear optics. Indeed, the easiest way to shift the spectrum of a pulse without distorting its phase is to sum its broad spectrum with a single frequency beam. This can easily be achieved by mixing the unknown pulse with a monochromatic wave in a sum-frequency generation (SFG) crystal.

4 American and French arachnids

In the first generation of SPIDER, a monochromatic wave is generated by sending a fraction of the unknown pulse into a dispersive optical system, which stretches this ancillary pulse in time such that each frequency occupies a different time slot. This is called chirp, by analogy to the sound of a bird song, in which the tone rises with time. Because of this, the arrival time of the unknown pulse with respect to the ancillary chirped pulse in the nonlinear crystal determines the quasi-monochromatic slice of the ancillary pulse involved in the SFG. The superposition of two delayed test pulses and the ancillary pulse in the nonlinear crystal leads therefore to the generation of two pulses, each near the second harmonic of the input pulse frequency, and each with an identical, but differently frequency shifted, spectrum (see **figure 3a**).

Recently, we have shown that one can take advantage of the properties of SFG in a long nonlinear crystal to simplify generation of the two sheared replicas [3]. In this case, known as ARAIGNEE (Another Ridiculous Acronym Involving Non-iterative E-field Extraction), the test pulse is not mixed with a monochromatic wave but with an orthogonally polarized replica

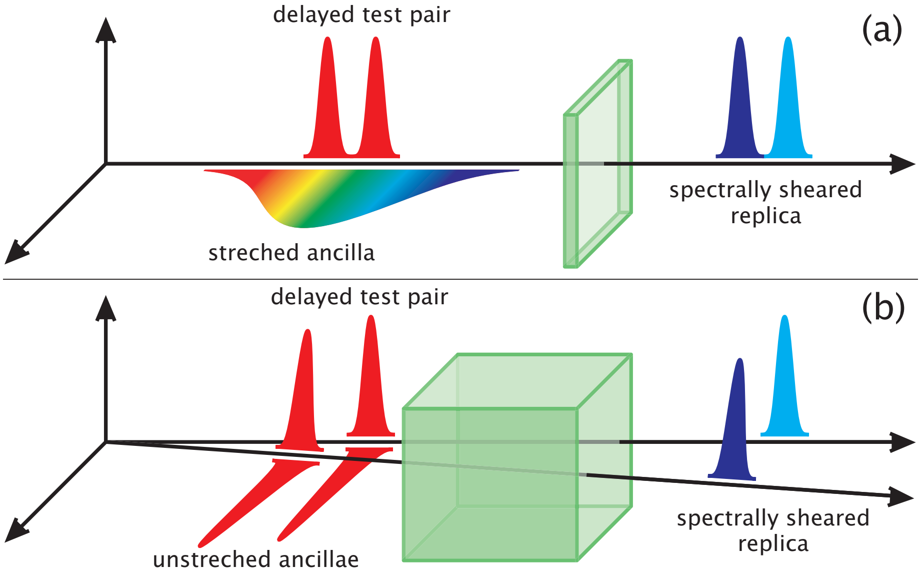

***Figure 3**: Spectrally sheared replicas can be produced using a non-linear interaction, such as sum-freqency generation. In (a) upconversion with a quasi-monochromatic section of a chirped ancillary pulse maps the test pulse field to an upshifted frequency band. In (b) the phase-matching function of the nonlinear medium itself selects a single frequency from the test pulse as the ancillary pulse*

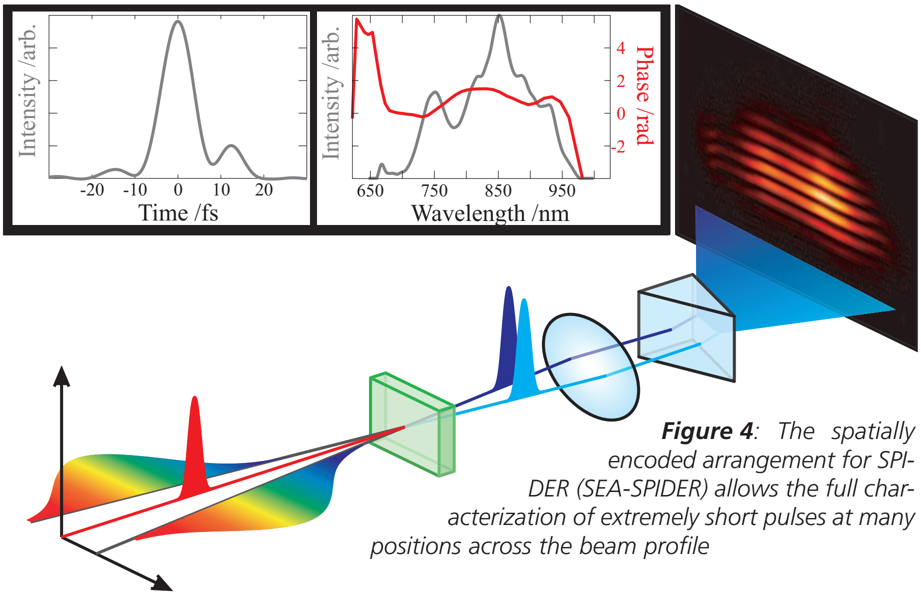

***Figure 4**: The spatially encoded arrangement for SPIDER (SEA-SPIDER) allows the full characterization of extremely short pulses at many positions across the beam profile*

of itself, as shown in figure 3b. Because of their differing group velocities in the crystal, the entire spectrum of one of the pulses is mixed with only one frequency of the other. Thus, the resulting SFG field is an undistorted replica of the unknown pulse. Since the particular frequency selected for the SFG depends on the angle of propagation of the beam in the crystal, the frequency shear between the two replicas can easily be adjusted by tilting the two beams by an angle of approximately 1° degree with respect to each other (see figure 3b).

5 The extra dimension: spatio-temporal tricks

Often it is assumed that a pulse's temporal and spatial characteristics are independent. In ultrafast optics, this assumption often fails since spatio-temporal coupling occurs in manipulations of light as simple as focusing or as complex as pulse shaping, as well as in most nonlinear interactions. One of the major challenges nowadays in pulse characterization is therefore not only to be able to measure ultrashort pulses of few optical cycles but also to characterize the dependence of the field's temporal variation for each position within the beam profile. Spectral interferometric techniques are ideally suited to this task. Indeed, all temporal information at a given point in the laser beam is coded in the spectral fringes, i.e. a one-dimensional set of data. Consequently, we can use the extra dimension of a two-dimensional sensor to good account, measuring the spatial dependence of the pulse and reconstructing the spatio-temporal electric field of a light pulse with no prior assumptions about which distortions are present.

A recent extension of this idea is to use the spatial degree of freedom to encode the spectral phase itself. In this method (Spatially-Encoded Arrangement for SPIDER, or SEA-SPIDER) the spectrally-sheared pulse replicas are arranged to have tilted wavefronts and measured using an imaging spectrometer. A typical two-dimensional fringe pattern is shown in **figure 4**. The fringes now appear in the spatial dimension, though the spectral phase can be extracted using a 2-dimensional version of the inversion algorithm. One pleasing feature of this approach is that a low-resolution spectrometer is adequate, so that very broadband pulses are easily measured. And the interferogram is itself very intuitive: the contours of the space-frequency fringes directly map the phase variation, and can therefore be used to easily optimize the pulse duration. For example, a positive chirp shows up as a tilt in the fringes, whereas a properly compressed pulse has all fringes parallel to the frequency axis of the interferogram. Furthermore, space-time coupling is extracted by measuring the pulse shape at each point across the beam.

6 SPIDER diversity

The concept of spectral shearing as an application of self-referencing interferometry is both simple and versatile and applicable to a broad range of pulses. The generality of the underlying concept has proven fruitful in addressing new needs.
The class of ultrafast optical arachnids has several orders, and a taxonomy that continues to grow. SPIDER variants use different nonlinear and linear processes to enable femtosecond pulse characterization across the whole visible, near IR and UV [4]. Other methods of coding the spectral phase have also been developed. Besides SEA-SPIDER, which has already been used to measure pulses in the two-cycle regime, and pulses with extremely broad spectra [5,6] and with complex space-time coupling, a temporal version of SPIDER has been developed [7] for the mid IR spectral region (down to 10 µm wavelength), that circumvents the lack of efficient spectrometers in this region.
Furthermore, weak single pulses (some few nJ) can be fully characterized using homodyne detection [4] or the modified SPIDER technique [8] by means of an intense, uncharacterized ancillary pulse that enables very high sensitivity.
Also, for pulses longer than 200 fs, linear active filters can be used to implement the spectral shearing [9]. This linear technique, compatible with telecom wavelengths and technologies, achieves extremely high sensitivity (down to 5 µW). Finally, the idea has also been used to measure some of the shortest pulses ever produced, with durations of a few hundred attoseconds, in the XUV spectral region.

7 Conclusions and outlook

The marriage of engineered phase matching and low-distortion pulse replication enabled us to build a miniature device for ultrashort pulse measurements; the micro-SPIDER shown in figure 1. Its size is about that of a compact USB spectrometer and allows retrieval of the spectral phase in real time on any computer (it is the data acquisition rate rather than processing speed that limits the refresh rate). The device covers the 760-900 nm range using a KDP crystal. Other nonlinear materials, such as KTP and BBO allow extensions to different wavelengths such as the telecom band at 1500 nm and the important new ultrafast laser region near 1050 nm.
Spectral shearing interferometry has proven a fruitful concept in the measurement of ultrashort optical pulses. Variants of the idea have been used to completely characterize the space-time fields of few cycle optical pulses, as well as distorted pulses arising from propagation in nonlinear media or in pulse shaping devices. There are a number of important features that make SPIDER particularly suitable for these applications, including the rapidity of the data acquisition and inversion, the robustness with respect to noise and detector-induced spectral distortion, and the ability to measure space-time coupling. We anticipate the range of applications will continue to grow.

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