DESY Summer Student 2008

-Work Report-

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During my time as a summer student at HASYLAB, part of DESY, I designed and built an ultrafast optical pulse characterization setup based on Spectral Phase Interferometry for Direct Electric-field reconstruction (SPIDER). This is described in the following review. I would like to thank Prof. Meyer and Andrea Schrader for organizing and running the Summer Student Program and especially my Supervisors Sven Toleikis and Franz Tavella for all their help, advice and guidance and for lending me a desk in their office.

Spectral Phase interferometry for direct electric-field reconstruction (SPIDER)

I. Introduction

Ever since the invention of the Laser by T.H. Maiman[1] in 1960 much effort was spent on producing ever shorter pulse durations, a quest that is still an active field of research today. By 1974 impulses with sub-picosecond resolution were produced, however it took until 1981 to reach the femtosecond regime (<0.1ps), realised by Fork, Greene and Shank at Bell labs, using a colliding pulse modelocked dye laser.[2] Current laser physics research is extending into the attosecond domain, producing pulses of less than 100as using high harmonics of femtosecond lasers produced in Neon filled capillaries.[3] These ultrashort pulses require new techniques to characterise their spectral, temporal and phase profile. Over the past two decade numerous techniques have evolved, most importantly autocorrelation measurements[4], frequency-resolved optical gating (FROG)[5,6,7] and most recently spectral phase interferometry for direct electric-field reconstruction (SPIDER)[8].

The SPIDER technique is based on spectral interferometry and offers unique advantages over other pulse characterisation techniques. As will be shown in the course of this report it is a self-referencing technique offering single-shot capabilities to measure the spectral phase of single cycle ultrafast pulses. Its non-iterative algorithm allows for fast data acquisition and pulse reconstruction, opening possibilities for real time beam characterisation.[9]

The following sections will focus on the SPIDER setup and process (section II), the theory behind the SPIDER technique and the mathematical formalism required (section III) and lastly the setup of our SPIDER will be discussed and results shown (section IV). A conclusion and future outlook is provided in section V.

II. The SPIDER process

With lasers providing the shortest EM pulses available, the usual characterisation process of applying an even shorter reference pulse to probe the temporal evolution of a process, the fundamental idea behind any pump-probe-experiment, cannot be applied. Thus the temporal characterisation and full reconstruction of the electric field require a self-referencing technique such as autocorrelation or interferometry. Whereas autocorrelation measurements such as FROG[5,6,7] and temporal decorrelation[4] rely on iterative algorithms, SPIDER is a type of spectral shearing interferometry and allows the reconstruction of the electric field using a purely algebraic algorithm with signal to noise ratio limited results.[8]

The SPIDER process is based on the non-linear process of sum frequency generation (SFG) of two temporally separated replicas of the incoming laser pulse with a spectrally sheared (chirped) pulse. This creates two copies of the initial pulse that are separated temporally by a delay τ and sheared in frequency with respect to one another by a shear Ω. The interference of those pulse replicas is

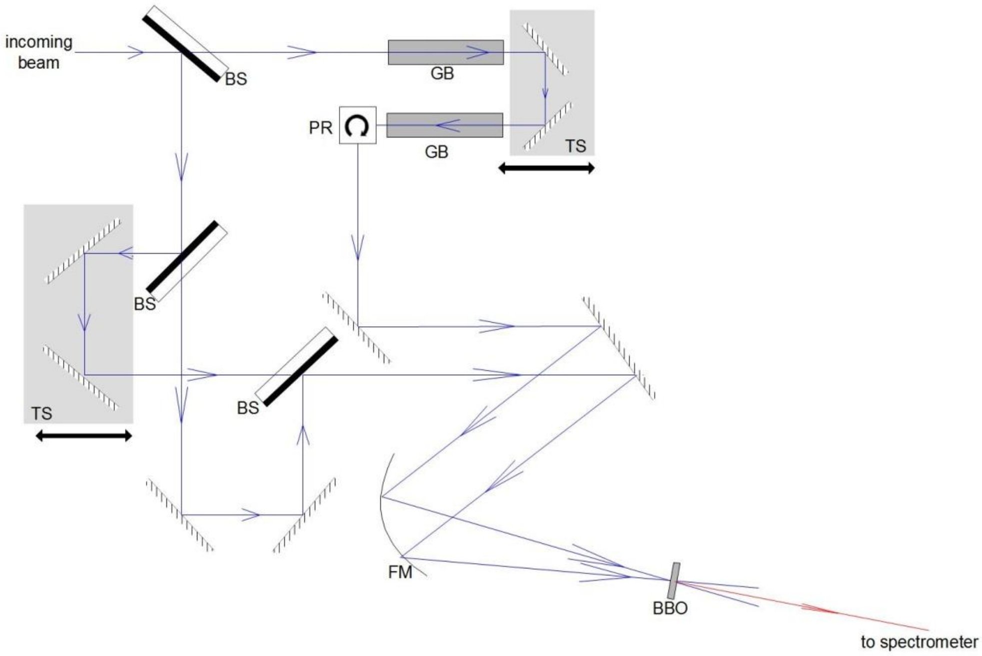

Figure 1: Schematic of the SPIDER apparatus. The incoming pulse is split by a beam splitter. One half now travels through a pair of glass blocks to generate a chirp and a phase rotator, the other half generates two pulse replicas by using a Michelson interferometer. Both pulses are then focussed onto the crystal using a focussing mirror. The produced SFG signal is send to a spectrometer. BS= beam splitter, GB= glass block, PR= phase rotator, TS= transition stage, FM= focussing mirror

recorded and allows the reconstruction of the electric field of the initial pulse using a purely algebraic algorithm (section III).[10]

A schematic of a typical SPIDER layout is shown in Figure 1. The incoming laser pulse is split by a first beam splitter (BS). One half of the pulse now travels through some dispersive elements such as glass blocks (GB), stretching the initial ultrashort laser pulse to picosecond duration. This pulse now passes a phase rotator (such as a periscope), depending on the type of non-linear crystal used, to maximise the sum frequency generation process. It is then focussed into the non-linear crystal by means of a focussing mirror (FM). The other half of the initial pulse is used to generate two pulse replicas, separated by a temporal delay τ. This can be done using an Etalon[9] or, as shown in the schematic, using a simple Michelson interferometer[8]. The transition stage (TS) allows accurate calibration of the temporal delay between the pulse replicas. These pulses are then focussed into the crystal using the same focussing mirror that is used for the chirped pulse, and carefully calibrated for maximum overlap between the two pulses. Inside this non-linear crystal the frequency upconversion and sum frequency generation takes place. Care needs to be taken that the spectral bandwidth of the employed crystal is sufficiently large for the spectral range of the incoming pulse. A type II crystal is used to produce a background free signal even in a collinear setup. As in a type II crystal the ordinary axis is of a broader spectral bandwidth, the test pulses should be polarised along it, and the chirped pulse is rotated into the extraordinary axis.[10] The SFG signal produced in the crystal is then send to a spectrometer for data analysis.[11]

Furthermore three calibration measurements need to be performed. As the SPIDER apparatus is free of any moving components the calibration procedure needs to be performed once only.[10] In order to determine the temporal delay τ an ordinary interferogram of the two replicas is taken by simply covering up the chirped pulse. To determine the spectral shear Ω of the two replicas a spectrum of

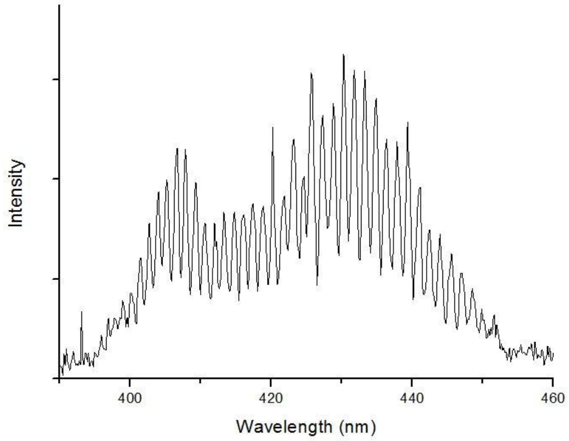

Figure 2: Experimentally recorded SPIDER trace for an ultrashort laser pulse.

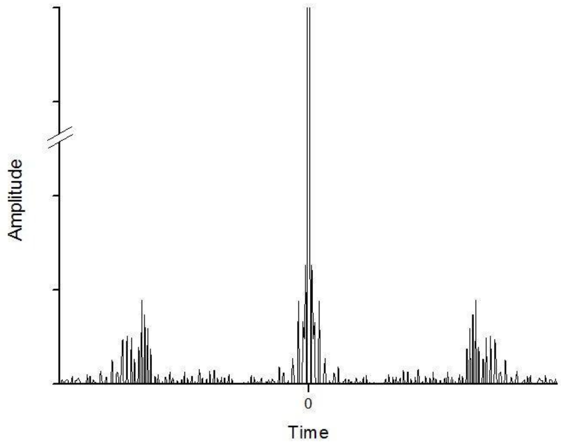

Figure 3: Fourier Transform of the SPIDER trace shown in Figure 2. The sidebands at ±τ can clearly be identified and filter out using a super-Gaussian filter.

each is taken in turn (by covering up one arm of the interferometer), yielding two full spectra from which Ω can be extracted by observation. For the electric field reconstruction using a Fourier transform, as showing in the next section, a fundamental spectrum of the pulse to be characterised is required. Recently it has been shown by Dorrer that all necessary measurements can be performed simultaneously by recording a SPIDER trace and a reference interferrogram and calculating the fundamental spectrum, this method however sacrifices some experimental accuracy.[12]

III. SPIDER theory

The signal received by the spectrometer is shown in Figure 2 and consists of the two pulses after SFG as well as the interference between them and mathematically is given by[11]:

$$S(\omega) = |E(\omega)|^2 + |E(\omega+\Omega)|^2 + 2|E(\omega)E(\omega+\Omega)|\cos[\varphi(\omega) - \varphi(\omega+\Omega) + \omega\tau]$$

Where ω is the central frequency, Ω the spectral shear between the pulse replicas, φ the phase and τ the temporal delay between the two pulse replicas. The first two terms on the right hand side of this equation are the two pulses that are spectrally sheared by an amount Ω with respect to each other whereas the last term describes the interference. All phase information is contained in the cosine term and needs to be filtered out. This is done by means of a Fourier transform of the measured Spectrum which separates the DC terms (non temporally varying) which appear in the centre of the transform, from the AC terms (temporally varying) that contain the phase information which form satellites at a separation of ±τ as shown in Figure 3. One of these sidebands is now selected by means of a super-Gaussian filter and back transformed into the frequency domain. The signal now consists of $\varphi(\omega) - \varphi(\omega+\Omega) + \omega\tau$. The term ωτ is known from the calibration measurement without the chirped pulse and is subtracted from the signal. We are now left with $\varphi(\omega) - \varphi(\omega+\Omega)$. The spectral shear Ω was determined in the second calibration measurement and we can thus reconstruct the initial phase $\varphi(\omega)$ by concatenation in steps of Ω (see [10] for full details). This allows a full reconstruction of the initial phase as long as the Whittaker-Shannon[13] sampling theorem is fulfilled, stating that the sampling frequency interval needs to be equal to or smaller than

$$\Omega = \frac{2\pi}{\tau_N}$$

where the pulse to be measured has non-zero energy over the duration τ_N. Once the phase $\varphi(\omega)$ is obtained this is combined with an intensity spectrum and the electric field reconstructed via a Fourier transform.

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}[\sqrt{I(\omega)}e^{i\varphi(\omega)}]e^{i\omega t}\,d\omega$$

Therefore the reconstruction procedure eventually yielding the temporal evolution of the electric field of the incoming laser pulse is purely algebraic in nature and can be performed within milliseconds on modern computers. This makes the SPIDER technique ideally suited for real-time characterisation of ultrashort laser pulses at video refresh rates as has been shown by Shuman *et al*.[14]

IV. Experimental realisation of SPIDER

Our SPIDER setup is shown in figure 4 and was designed to be small and portable (mounting board ca. 50 x 25cm) and is optimised for ultrashort pulse characterisation (< 100fs FWHM). The incoming pulse is split by a first beam splitter; the transmitted pulse passes through a glass block (SF50, refractive index ≈ 1.71) and is reflected back by two mirrors on a translation stage, allowing accurate adjustment of the path length. A second glass block is passed followed by a periscope for phase rotation of the chirped pulse. A system of mirrors then transports this pulse to the focussing mirror and onto the crystal. The reflected pulse from the first beam splitter is sent into a Michelson interferometer to create two pulse replicas. The delay τ can be adjusted using a micrometer translation stage holding one arm of the Michelson. Both replicas now traverse a system of mirrors and are focussed into the crystal by the same focussing mirror as the chirped pulse. A CCD camera with a magnifying lens is used to observe the crystal and ensure a full pulse overlap. The crystal is followed by a filter to minimise the fundamental signal as well as a lens focussing the beam into the spectrometer that is connected using fibre optics.

All data processing and analysis is done using a LabView virtual instrument, the front panel of this is shown in figure 5. The software is provided with calibration measurements as outlined in II (fundamental spectrum, separate spectra of the SFG from the two arms of the Michelson interferometer and a non-sheared interferrogram) and calculates the phase and duration of the measured pulse from the SPIDER trace. It also allows accounting for the group delay introduced by the beam splitters and for higher order dispersion effects from the glass block. The Fourier transform limit of the measured pulse is calculated and displayed together with the retrieved temporal pulse profile. The retrieved phase and temporal information can be exported for further data analysis.

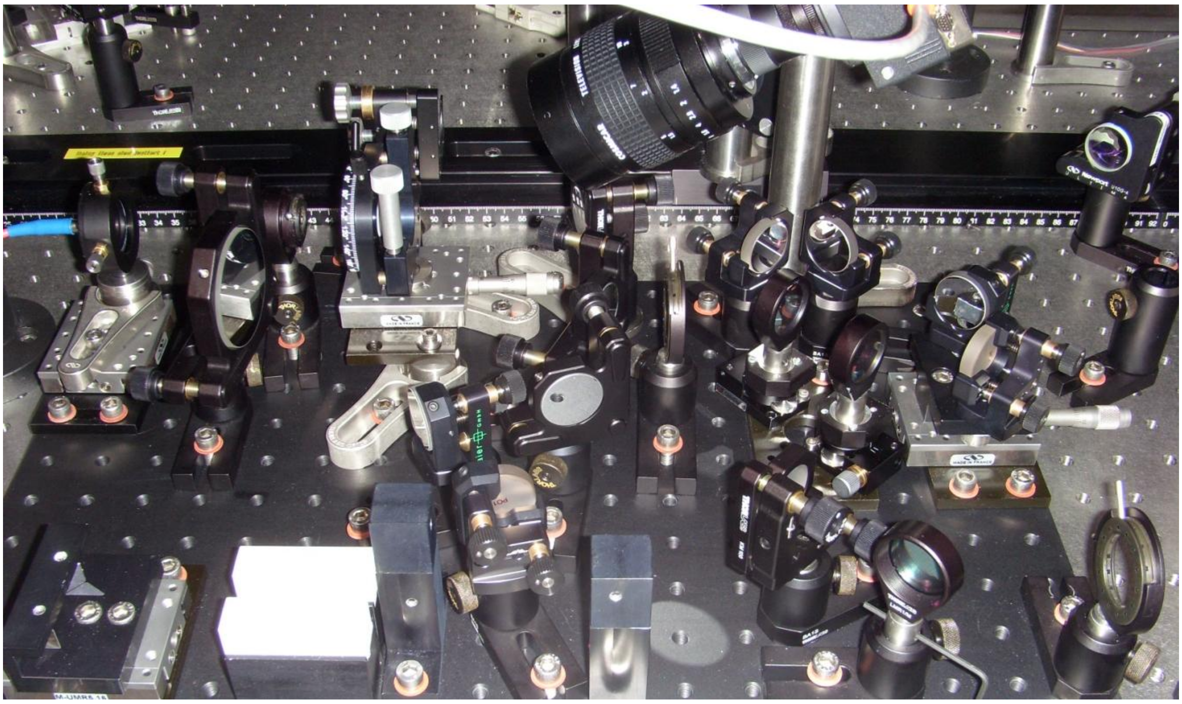

Figure 4: Our SPIDER setup. The pulse to be characterised enters from the bottom right and hits the first beam splitter. The transmitted part is send through two SF50 glass blocks to create the chirp and then focussed into the type II BBO crystal. The reflected part enters a Michelson interferometer and is, using a system of silver mirrors, focussed onto the crystal as well. A CCD camera ensures full overlap on the crystal. The obtained SFG signal is then analysed with a spectrometer connected using fibre optics (top left).

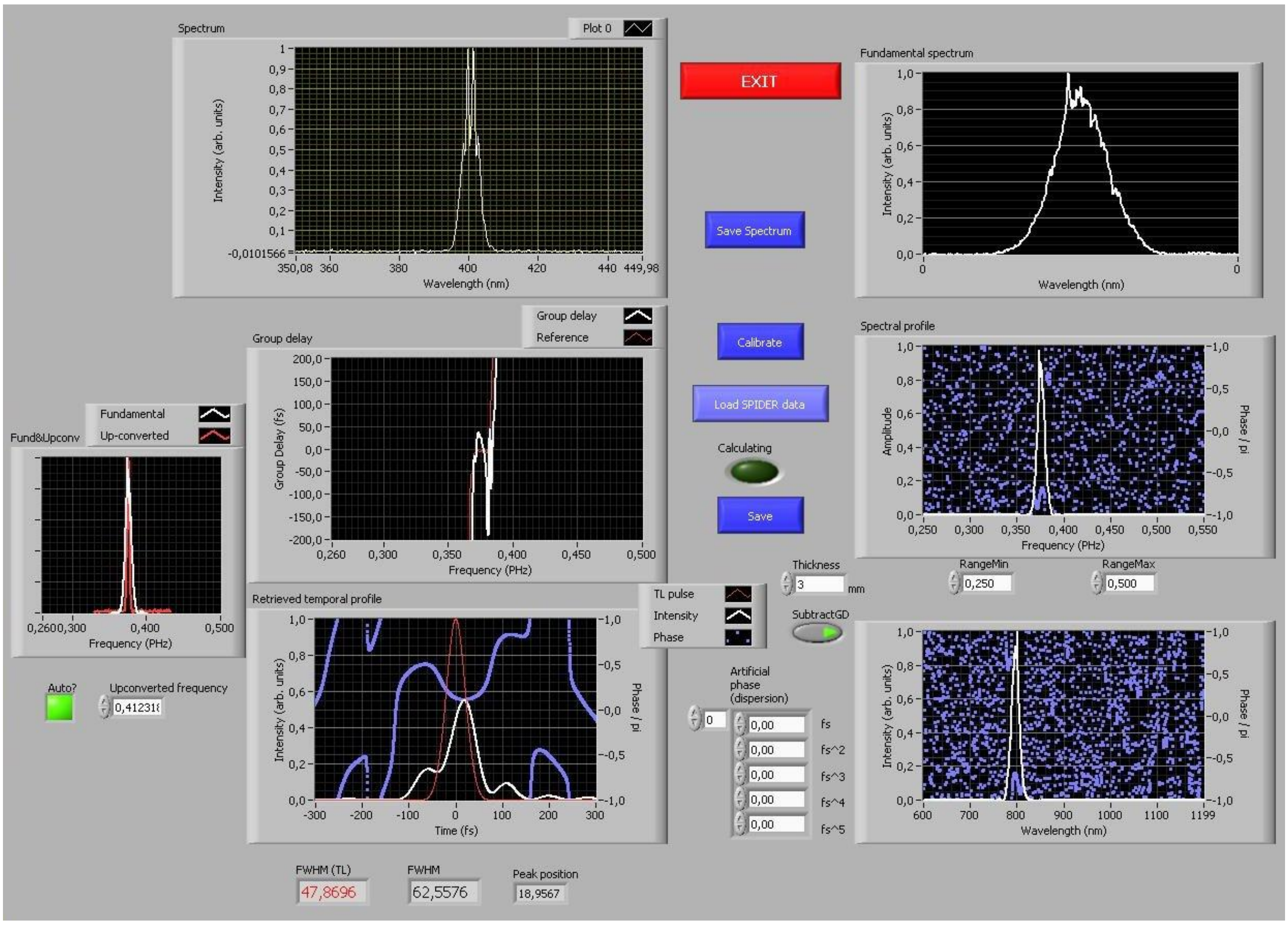

Figure 5: Front panel of the virtual instrument used for calibration and data analysis. The software also allows accounting for higher order dispersion effects.

The results presented hereafter were obtained with a compressed Ti:Sapphire oscillator with a Fourier transform limit of 50fs. This is at the upper limit for pulse length that can be accurately characterised with our setup. The results are furthermore limited by the spectrometer resolution. We only had a spectrometer with a 3 Å resolution available and as such the results presented provide a proof of principle and show without a doubt the working of our build, but do not provide an accurate pulse characterisation for which a better spectrometer is needed.

Figure 6 shows a fundamental spectrum of the pulse to be characterised. Shown in grey is a Gaussian pulse for comparison. After passing through the SPIDER apparatus two temporally separated and spectrally sheared pulse are recorded as shown in figure 6. Here the two pulses were recorded independently so no interference effects are shown on the graph. The spectral shear Ω between the two pulses can be clearly identified and is around 2nm. The SPIDER trace was recorded and sent through the virtual instrument using the algorithm described above. The reconstructed pulse shape is shown in figure 7, together with the Fourier limit of the fundamental spectrum (shaded in grey). The obtained pulse duration is 64fs FWHM. This value was confirmed by a commercial autocorrelator measurement. Ahead of the pulse a ringing feature is observed due to 3^{rd} order dispersion effects in the glass blocks used to create the chirped pulse. This feature can be minimised by accounting for higher order dispersion terms in the virtual instrument panel, and with the correct dispersion coefficients only the reconstructed pulse is obtained.

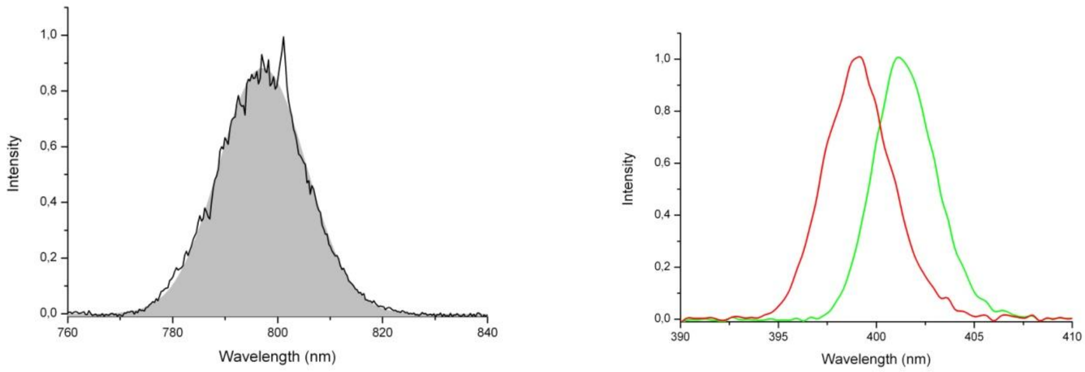

Figure6:Fundamental spectrum of the ultrashort pulse characterised in our SPIDER setup (left) and the two replica pulses with a spectral shear introduced by SFG with a chirped pulse inside the BBO crystal (right).

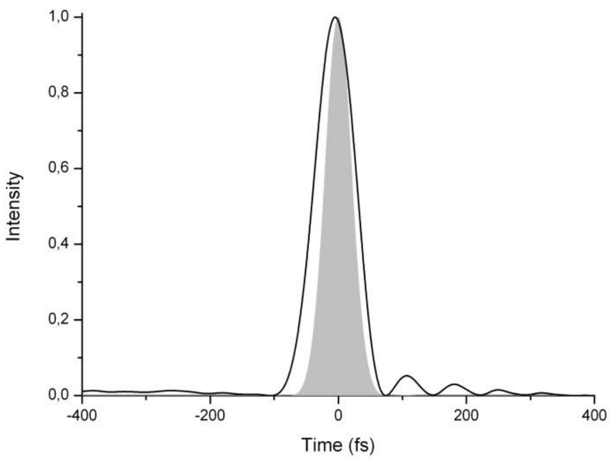

Figure7: Reconstructed pulse shape. The Fourier limit of the pulse is shown in grey. FWHM of the reconstructed pulse is 64fs.

V. Conclusion

Spectral phase interferomety for direct electric-field reconstruction was presented as a method for characetrising ultrashort laser pulses down to the few-cycle regime. The principle and theory were introduced and our setup presented. SPIDER is a type of spectral shearing interferometry in which the laser to be characterised is split into two temporally seperated and spectrally sheared replicas whos interference is recorded and used to reconstruct the spectral phase which allows full reconstruction of the electric field. Our setup was presented and results shown as a proof of principle for the operation of our build. SPIDER is one of many techniques to characterise ultashort pulses, however it is unique in its ability to operate at video refresh rates (due to a simply algebraic algorithm) and has been shown to work in single shot operation.[15] With the increasing use of ultrafast lasers in applications in Chemistry, Physics, Biology and Material Science live and online pulse monitoring is vital to the success of experiments and SPIDER can provide this.

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