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MASTER THESIS WORK

Ultrashort Pulse Characterisation Using an Acousto-Optic Bulk Pulse Shaper

Seth Lucien Cousin

Supervised by Prof. Dr. Jens Biegert, ICFO

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Ultrashort Pulse Characterisation Using an Acousto-Optic Bulk Pulse Shaper

Seth Lucien Cousin
ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

E-mail: Seth.Cousin@icfo.es

Abstract. A basic optical setup including an acousto-optic programmable dispersive filter (Dazzler) has been used to fully characterise an ultrashort pulse. A baseband FROG technique has been used to measure the pulse, with pulse replica creation and inter pulse delay controlled by the Dazzler. The system has been calibrated with Fourier transform spectral interferometry to ensure that dispersion calculated for the Dazzler crystal was accurate. A 12.2 fs pulse was measured with the Phazzler, which as far as we are aware is the shortest pulse measured in such a device.

Keywords. Ultrashort pulse measurement, Acousto-optic pulse shaper, FROG

1 Introduction

Ultrashort physics encompasses the realm of physical processes occurring at very small time scales: femtosecond 10^{-15} s , attosecond 10^{-18} s and beyond. Primarily, these processes involve electron dynamics, in which attosecond resolution is required. Many applications in ultrashort physics are currently being investigated, such as attosecond time-resolved spectroscopy and attosecond metrology [1, 2, 3]. The ultimate goal of this field of physics is nothing short of coherent control of atoms, molecules and chemical reactions on an electron level, the most fundamental and elemental control that we can possibly have. High harmonic generation (HHG) is used to generate attosecond pulse trains and attosecond pulses, however to generate single attosecond pulses, sub 5 fs input pulses are essential [4].

From the invention of the first continuous wave (CW) laser in 1960 [5], the field of laser physics has progressed at a blistering pace. The first pulsed lasers appeared in 1962 employing Kerr-cell Q-switching in a ruby laser [6]. Lasers have since been created in many media, such as gases, liquids (dyes), semiconductors and solid-state media. Thus far, the most important of these in ultrafast physics has been the solid-state laser, in the form of the titanium doped sapphire (Ti:Sa) laser characterised in the mid 1980s [7]. Ti:Sa offers the spectral bandwidth to directly support ultrashort laser pulses, however a new problem arose from the fact that the high intensity of these pulses, posed problems when trying to amplify them. Around the same time the chirped pulse amplification (CPA) scheme was invented [8], in which pulses could be safely amplified. The current state of the art amplified pulsed Ti:Sa lasers are capable of producing ~ 20 fs laser pulses, however shorter pulses are needed to interrogate the world of attoscience.

To support even shorter pulse creation, greater spectral bandwidths are required. Spectral broadening can be achieved in various ways, but I will focus on supercontinuum generation achieved in a hollow-core fiber (HCF) [9].

With pulses compressible down to the single cycle regime desired for ultrashort physics experiments, it is important to know and control pulse durations. Reliable pulse characterisation techniques are required, however the fastest photodiodes and the fastest electronics are not capable of directly measuring such short timescales. An entire branch of ultrashort physics has stemmed from this problem, resulting in three prominent pulse characterisation techniques, namely: autocorrelation [10], Frequency Resolved Optical Gating (FROG) [11] and Spectral Interferometry for Direct Electric field Reconstruction (SPIDER) [12].

Both the FROG and SPIDER techniques provide spectral phase information about the pulses being measured. The key to obtaining perfectly compressed pulses is controlling the dispersion that has been imparted to the pulse during generation, amplification and spectral broadening. Various dispersion compensation mechanisms exist, including: prisms, gratings, chirped dielectric mirrors [13] as well as active components, such as spatial light modulators (SLM). A novel approach to dispersion control using an acousto-optic modulator has also been invented. The commercially available Dazzler is an example of such an acousto-optic programmable dispersion filter (AOPDF)[14]. Dazzlers have been used, both in the amplification chain of short pulse lasers, as well as post supercontinuum generation, to control dispersion. AOPDFs offer great flexibility and range of control and these characteristics are used in the Phazzler ultrashort pulse measurement system.

The Phazzler is an ultrashort pulse measurement system, employing a Dazzler AOPDF to generate the pulse replicas, shears and delays required in its implementations of FROG and SPIDER. Commercially available Phazzlers can only measure pulses down to around 30 fs, due mainly to the bandwidth over which the integrated Dazzler can act upon. The Phazzler in this Masters thesis is modified to enable pulse characterisation of sub 5 fs pulses. As with most pulse measurement techniques, a small fraction of the pulse energy is required so as not to damage components such as the non-linear crystal. Beyond pulse characterisation the Phazzler is also able to compensate for dispersion on the pulse being measured and can thus act as a programmable compressor system, offering tuneable ultrashort pulses to low-energy experiments. For experiments requiring higher energies, the phase information deduced from the Phazzler characterisation can be used to design suitable ultra-broadband chirped mirrors to provide the specifically tailored dispersion compensation required to compress the unattenuated pulses.

2 Phazzler Pulse Characterisation

2.1 The Phazzler System

2.1.1 System Layout

A beam of ultrashort pulses is aligned through a Dazzler AOPDF, which is responsible for creating delayed pulse replicas and shears. A half waveplate is used to return the diffracted beam to its original polarisation (needed for the second harmonic generation (SHG) in the type I βBaB_2O_4 (BBO) crystal). The beam is focused into a type I BBO crystal. The thickness of the crystal is selected to support the high bandwidth pulses that will be measured. A BG39 filter is used to filter out the fundamental frequency whereafter the beam is refocused onto a spectrometer (Avantes, 250-550 nm, 2048 pixels). 5% of the incident beam is mixed with a fraction of the diffracted beam and then sent to a second spectrometer (Avantes, 650-1110 nm, 2048 pixels). Fourier transform spectral interferometry (FTSI) [15] is performed on the resulting interferogram to calibrate the Phazzler. Not shown in Fig. 2.1 is the RF signal generator module and the computer software that controls the system. The RF signal generator has a memory bank that is used to store multiple

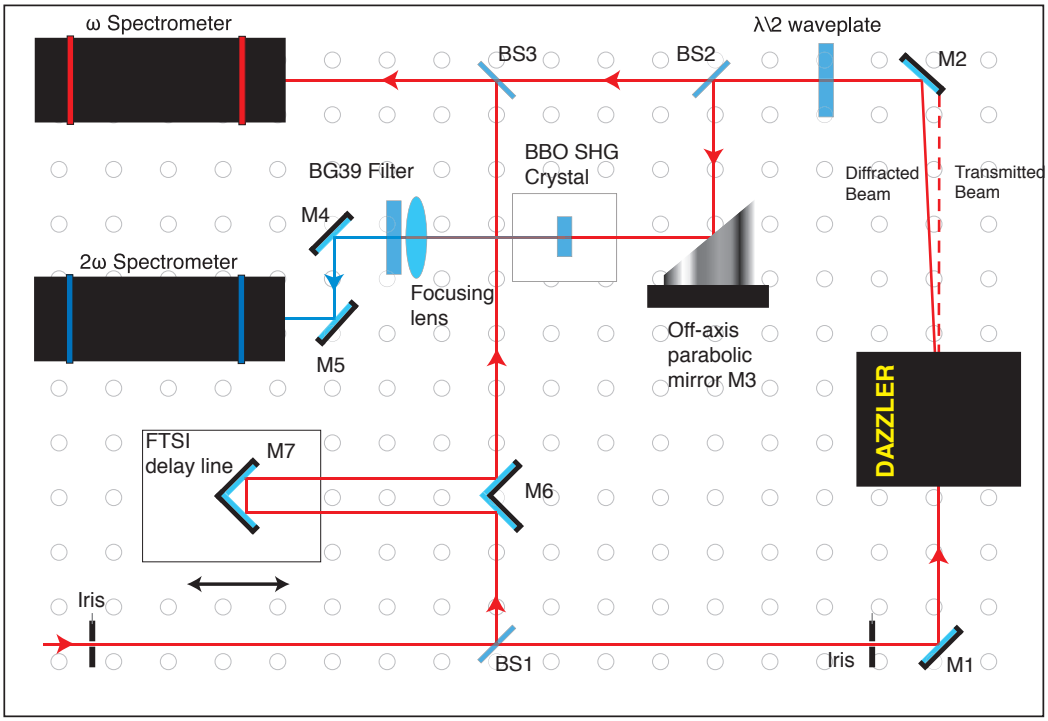


Figure 2.1: Phazzler system layout

RF signals. The signals are programmed by the computer software and transmitted to the memory bank via USB. The Phazzler computer software includes a spectrometer simulator which can be used to simulate various shaped pulses, with control of both the amplitude and phase. This feature has been incredibly useful in learning how to read the various traces and data from the Phazzler.

2.1.2 Working Principles

The heart of the Phazzler is a Dazzler AOPDF. The electric field incident on the Dazzler is polarised in the fast ordinary axis as is the acoustic wave. When a frequency component of the electric field is in phase with a frequency component of the acoustic wave, it is diffracted on the slow extraordinary axis. The total output electric field is composed of all the diffracted components that have been phase matched at various points in the paratellurite (TeO_2) crystal and thus by shaping the acoustic wave, the spectral phase of the output electric field can be controlled. The amplitude of the output electric field scales with the amplitude of the acoustic wave thus offering amplitude control too.

The real electric field of a laser pulse is given by:

$$\varepsilon(t) = \mathrm{Re}\left\{A(t)e^{i\omega_0 t}\right\} \tag{2.1}$$

where $A(t)$ is a complex envelope function (the amplitude), also described by a Fourier transform in the frequency domain as $A(\omega)$ (the spectral amplitude) and ω_0 is the laser pulse central frequency.

Any linear and stationary operation performed on a pulse can be described by a complex spectral filter $H(\omega)$ [17], such that:

$$A_{out}(\omega) = H(\omega)A_{in}(\omega) \tag{2.2}$$

where $A_{out}(\omega)$ is the output spectral amplitude and $A_{in}(\omega)$ is the input spectral amplitude.

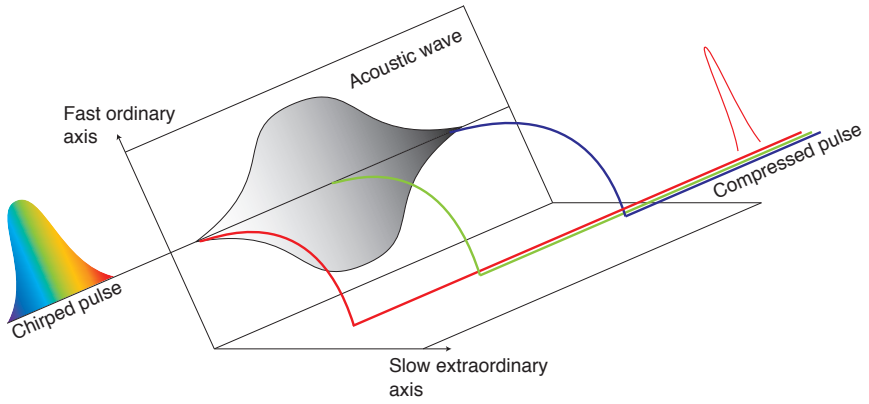


Figure 2.2: A schematic representation of the Dazzler [16]. The shading in the acoustic wave represents a chirped acoustic wave

Some relevant spectral filters are shown below (extracted from the Phazzler documentation)

Description	Time-domain definition	Spectral filter($H(\omega)$)
Attenuation	$A_{out}(t) = kA_{in}(t)$	k
Phase offset	$A_{out}(t) = e^{i\omega_0}A_{in}(t)$	$e^{i\theta}$
Optical Delay	$A_{out}(t) = A_{in}(t-\tau)$	$e^{i(\omega-\omega_0)\tau}$
Chirp	-	$e^{i\phi_2(\omega-\omega_0)^2}$

Table 2.1: Spectral filters common in pulse characterisation optics

A linear and stationary combination of some of the spectral filters in Tab. 2.1 can be used to create two pulse replicas, with a phase offset of $\pi/2$ and delaying them by τ. The spectral filter is described by:

$$H(\omega) = 1 + e^{i\frac{\pi}{2}}e^{i(\omega-\omega_0)\tau} \tag{2.3}$$

Spectral filters can be programmed to mimic the optic setups used in the FROG and SPIDER techniques, as well as being able to create some aspects unobtainable in an optical setup, such as a true delay, offering new pulse characterisation techniques, such as bFROG [17].

2.2 Phazzler's Restrictions

The Dazzler contains a TeO_2 crystal, which is a dispersive medium itself and along with any pulse shaping and external dispersion compensation, it has to compensate for its own intrinsic dispersion $\sim 13000\,\text{fs}^2$ at 800 nm. The maximum group delay that this Dazzler can correct for is $\tau_{max} = 7$ ps. This sets an upper limit for the maximum bandwidth over which the Dazzler can compensate for its own dispersion. From a Taylor expansion:

$$\tau(\omega) = \tau(\omega_0) + \phi^{(2)}(\omega_0)(\omega - \omega_0) \tag{2.4}$$

since

$$|\tau(\omega) - \tau(\omega_0)| < \tau_{max}, \text{then } |\omega - \omega_0| \text{ is limited to} \sim \frac{\tau_{max}}{\phi^{(2)}} \tag{2.5}$$

The pulse shape also plays a role in this bandwidth limit, but for a Gaussian spectrum, it is ~ 80 nm full width half maximum (FWHM) and for a square spectrum it is ~ 200 nm.

The dispersion for the TeO_2 crystal ($\sim 13000\ fs^2$) is based on an exact length of crystal (25 mm) as supplied by a crystal manufacturer. Any deviation of this length, due to manufacturing tolerances for example, will make a difference to the dispersion calculation and hence the accuracy of the Phazzler's measurement. As the spectral bandwidth increases this inaccuracy increases, therefore a method is required to ensure that the dispersion compensation within the Dazzler is calibrated. A method of doing this involves comparing the phase of the input beam, to the phase of the beam once diffracted by the Dazzler. In the condition that the Dazzler is accurately only self compensating, the phase of the pre and post Dazzler beams should be the same. Spectral interferometry can be used to compare the two beams. The Phazzler in this thesis has been modified to make this measurement, with the addition of beam splitting optics, an optical delay line and an additional spectrometer sensitive to the fundamental wavelength. A fraction of the input beam is split off and later recombined with a fraction of the diffracted fundamental wavelength. The two components are overlapped temporally with the optical delay line and their interference pattern is recorded on the spectrometer. FTSI is then used to extract the phase difference, which can then be used to calibrate the Phazzler software to take into account the actual TeO_2 crystal dispersion.

3 Experiment

3.1 Aims

The experiment's aim is to examine the viability of the Phazzler to measure ultrashort pulses. To accomplish this, short pulses will first need to be generated in a HCF. At the high bandwidths generated, essential calibration of the Phazzler will be performed to ensure no error in TeO_2 crystal length has been included in the dispersion calculation. Finally an ultrashort pulse will be characterised.

3.2 Experimental Setup

Femtosecond laser pulse production is handled by a Kapteyn-Murnayne Laboratories (KMLabs) Red Dragon Ti:Sa laser system. The system is configured to deliver 40 nm, $\sim 310\ \mu J$ pulses at 5 kHz. $\sim 260\ \mu J$ is apertured to the focusing mirror whereafter it enters the argon filled gas cell held at 1.2 bar. The output beam is collimated with a concave mirror ($f = 2$ m) and sent to the Phazzler. The centre of the beam with an energy of $\sim 4.4\ \mu J$ is selected to proliferate through the Phazzler. The data and results are shown in Sec. 3.4.1. A 50 μm BBO crystal is used for SHG, ensuring a long interaction length and hence strong, easy to align second harmonic signal generation.

A 250 μm core, 0.93 m HCF housed in a gas cell is used to produce the broad bandwidth needed to support ultrashort pulses. An iris is used before the gas cell. A pair of Layertec chirped mirrors provide dispersion compensation for the dispersion generated in the HCF (The mirrors offer $\sim -40\ fs^2$ of group velocity dispersion (GVD) per bounce). Finally the Phazzler pulse measurement device is used to characterise the pulse.

3.3 Procedure

The beam is focused from the output of the laser, into the 250 μm HCF, with a $f = 2$ m silver mirror. The air is evacuated from the HCF with a Pfeiffer scroll pump. Argon is then pumped into the HCF. The central part of the broadband beam is selected with an iris, whereafter it is collimated and sent to 2 pairs of Layertec chirped mirrors, where 5 bounces are made on each mirror. Phazzler alignment is first done by eye, optimising the second harmonic signal and then by optimising the signal with the use of the spectrometer ensuring a strong, but not saturated signal.

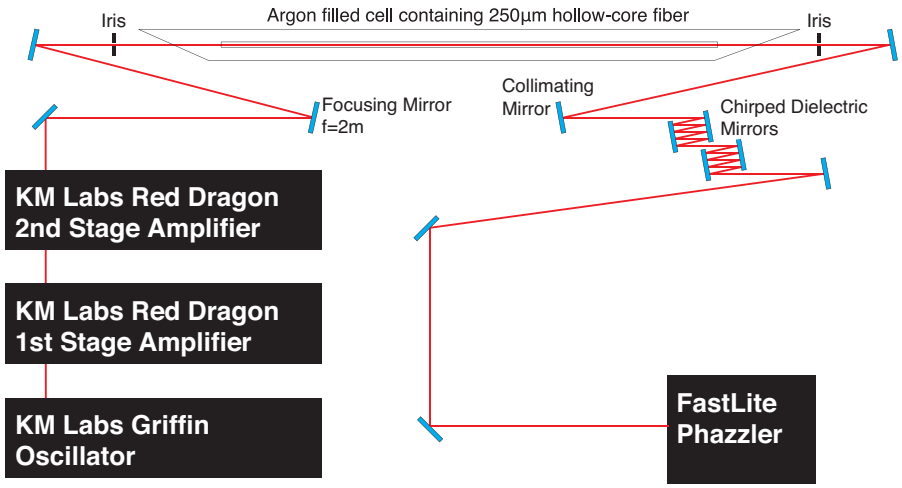


Figure 3.1: Experimental setup

The Phazzler software is configured to act upon a 200 nm window of the bandwidth, to adhere to the limits discussed in Sec. 2.2. Pulse measurement can now be done.

3.4 Data and Results

3.4.1 Pulse Measurement and Phazzler Calibration

To obtain sufficient and compressible spectral broadening in the HCF, the correct combination of input power and gas pressure must be used. The relationship between the two parameters in Fig. 3.2a and 3.2b show that the amount of spectral broadening is proportional to both the input pulse energy and the argon pressure. A balance needs to be found between the two, to find sufficient bandwidth, but avoid unwanted ionisation effects in the argon.

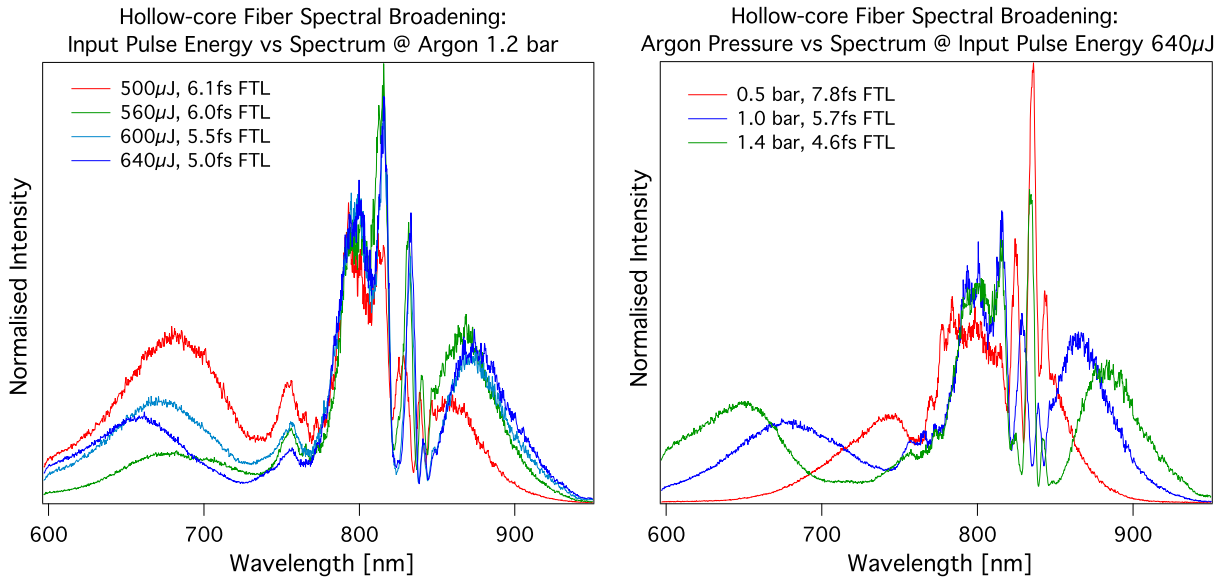


Figure 3.2: The spectrometer used is an Avantes, 650 - 1110 nm, 2048 pixels. (a) Broadened Spectra as a function of input energy for 1.2 bar of argon (b) Broadened Spectra as a function of argon pressure with input pulse energy at 640 µJ

To calibrate the Phazzler and measure calculated dispersion versus actual dispersion of the TeO_2 crystal, the 5% of the input beam was aligned through an optical delay line and recombined with a fraction of the Dazzler diffracted beam and aligned into the second spectrometer. The delay line was used to temporally overlap the input and diffracted pulses to create an interferogram recorded on the spectrometer. The alignment process is arduous and very sensitive, with a strict requirement of both spatial collinearity and good temporal overlap.

The interference pattern seen in Fig. 3.3a manifests when the two beams are collinear and well aligned into the spectrometer and a beating can be seen in the fringes when temporal overlap is achieved. FTSI was performed on the interferogram to reveal a phase difference between the two arms of $-590\,\mathrm{fs}^2$ and $+765\,\mathrm{fs}^3$ shown in 3.3b. The Phazzler software was then configured to take the residual dispersion into consideration. The FTSI calculation revealed that the TeO_2 crystal was slightly shorter than estimated. Only a few tens of fs^2 of residual phase remained after this calibration, which was not a concern with the bandwidth being used.

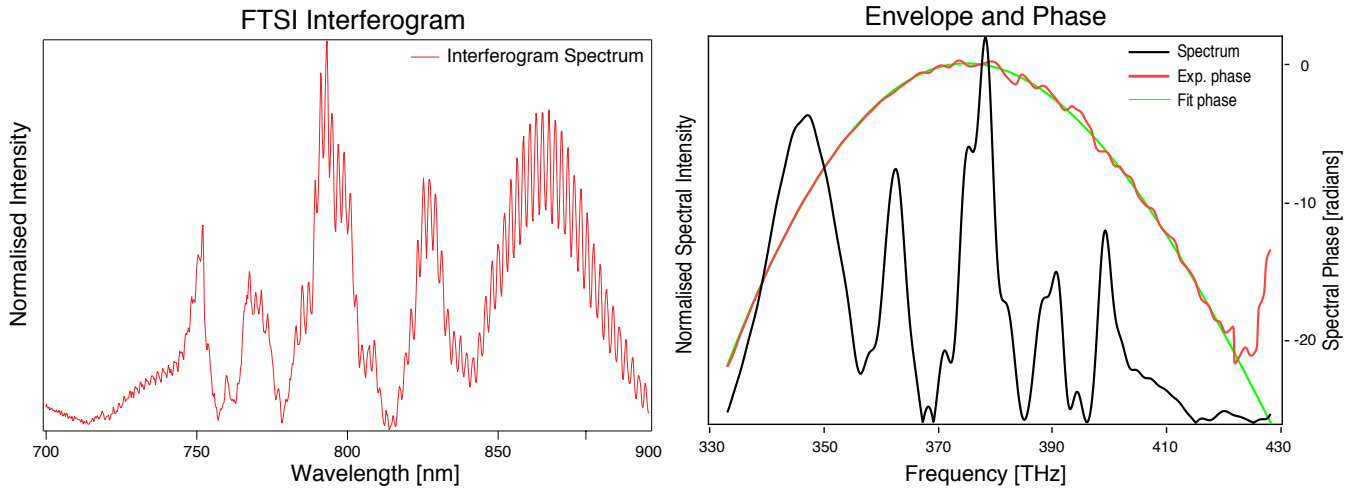
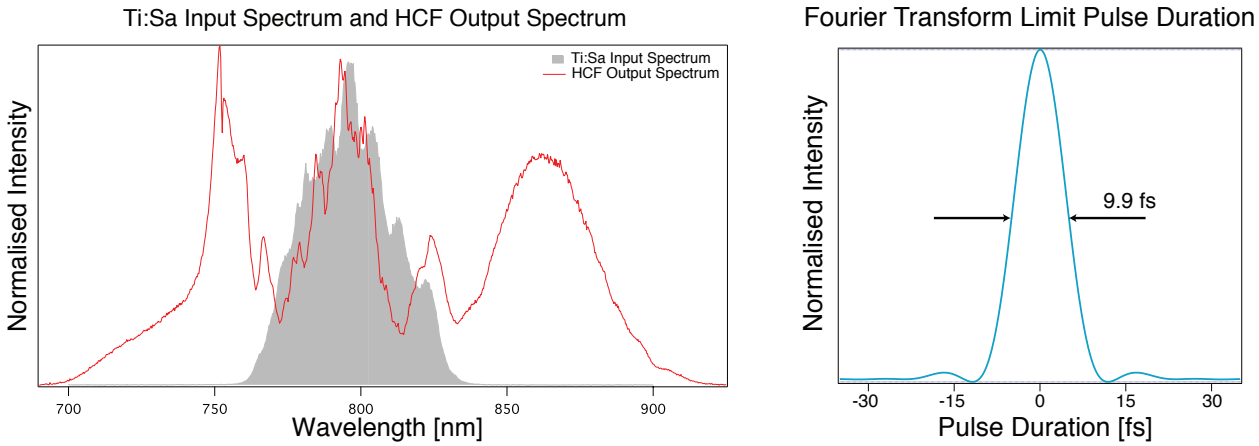


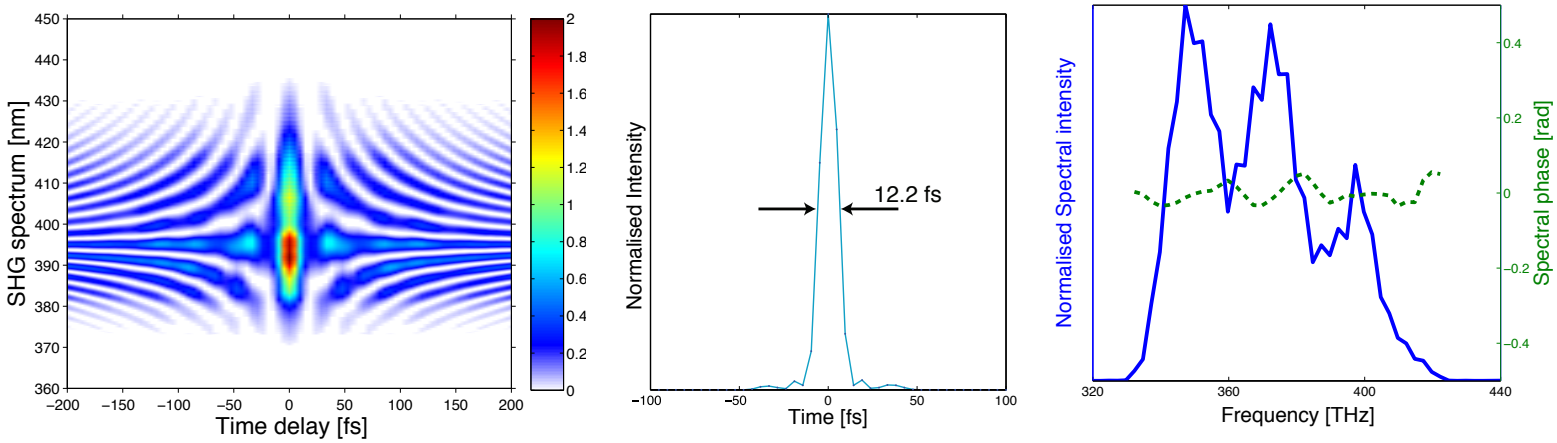
Figure 3.3: (a) Interferogram recorded on the spectrometer (b) FTSI calculated residual phase

Upon successful generation of sufficient bandwidth and calibration of the Phazzler, a 12.2 fs pulse was measured in the Phazzler. The spectrum obtained through the HCF is shown in Fig. 3.4a. (Note the 200 nm window of bandwidth used), with the corresponding 9.9 fs Fourier transform limit in Fig. 3.4b. The retrieved bFROG trace is shown in Fig. 3.5a. The pulse duration and spectral phase are shown in Fig. 3.5b and 3.5c respectively.



(a) (b)

Figure 3.4: (a) Ti:Sa input spectrum (grey) and the HCF output spectrum (red) (b) Calculated Fourier transform limit of the output spectrum



(a) (b) (c)

Figure 3.5: (a) Retrieved bFROG trace of 12.2fs pulse (b) Temporal profile of the measured pulse, showing a 12.2fs pulse duration (c) Spectral intensity and spectral phase of 12.2fs pulse

4 Conclusion

HCF spectral broadening has been successfully employed to create enough bandwidth to support a transform limited pulse of 4.6 fs see Fig. 3.2b.

Calibration of the Phazzler appeared vital, as it was apparent that there was some residual phase in the pre and post Dazzler, diffracted beams. To rely on the Phazzler as an ultrashort pulse measurement device, the calibration is essential.

By limiting the bandwidth over which the Phazzler acts upon, we were able to characterise a 12.2 fs pulse from a spectral bandwidth capable of supporting 9.9 fs see Fig. 3.4b. Fine tuning of the higher order dispersion compensation in the Phazzler may yield a pulse duration closer to the Fourier transform limit. As the pulse duration decreases (the spectral bandwidth increases), both

the dispersion of the Dazzler crystal and the finite SHG acceptance bandwidth of the BBO crystal need to be taken into account.

Once the issues of the Dazzler crystal dispersion and the finite SHG acceptance bandwidth of the BBO crystal are resolved, the Phazzler appears to be a viable ultrashort pulse measurement device.

5 Outlook

To measure sub 10 fs pulses, the Phazzler's limitations can no longer be ignored. Two adaptations will be made to overcome these limitations. Firstly, a thin non-linear crystal (10 μm) will be used, to increase the SHG acceptance bandwidth and secondly, some pre-compensation of the TeO_2 Dazzler crystal will be performed in the form of a compressor system based on a grism pair [18].

Once the phase of the spectrally broadened pulses is reliably characterised, ultra-broadband chirped mirrors can be designed to compress the pulses and use all of their available energy for further ultrafast physics experiments.

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