Design of a stretcher-compressor system for high energy 5 fs pulses

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Introduction

Recently there has been growing interest in the generation of intense femtosecond pulses with durations below 10 fs. One of the applications for these pulses is the production of attosecond XUV pulses by high harmonic generation[1). For reliable production of single attosecond pulses, the drive laser producing the harmonics must have stable carrier-envelope phase (CEP) and pulse duration of no more than two cycles of the underlying electric field[2). This is necessary to ensure there is only one strong peak of the electric field underneath the pulse envelope, and hence a single strong recollision event between the atom and electron.

Current systems that generate sub-10 fs pulses are generally hybrid systems consisting of relatively long pulse, 30 fs chirped pulse amplification (CPA) systems followed by spectral broadening in a gas filled capillary and final compression using chirped mirrors. These systems avoid the complexity of designing a CPA system for the full 5 fs bandwidth and can produce pulses as short as 3.4 fs[3). However they are limited to low energies by ionisation of the gas inside the capillaries.

Optical Parametric Chirped Pulse Amplification (OPCPA)[4) provides a method for scaling these ultrashort pulses to much higher energies. In OPCPA, a short pulse is chirped before being amplified parametrically in a non-linear crystal. OPAs have extremely large gain bandwidths. For example, a LBO amplifier has a gain bandwidth adequate to support a 2.6 fs pulse. This allows amplification of the full bandwidth of the 5 fs pulses, leading to orders of magnitude higher pulse energies. Minimal thermal deposition in the OPA medium allows for high average power operation and high optical quality due to the absence of thermal lensing.

We are building an OPCPA system to produce 5 fs, 10 mJ pulses with stable carrier-envelope phase. The project is part of the Attosecond Basic Technology program and will be used to produce attosecond XUV pulses for molecular physics and surface science experiments[5).

Stretcher-Compressor Design

An 800nm, 5 fs pulse has a bandwidth of ~ 200 nm FWHM and requires a stretcher-compressor system capable of compensating for spectral phase distortions across ~ 400nm. For this type of system the pulse energy and therefore the amount of stretch required is a crucial factor. At below 1mJ good fidelity can be achieved by amplifying modestly chirped pulses and using relatively simple systems to compensate for spectral phase variations. To achieve higher pulse energies we must stretch more, and compensation for higher order spectral phase errors becomes more difficult as the dispersion of the different elements becomes non-linear.

In systems which require stability of the carrier envelope phase (CEP) it is important to ensure that any design of stretcher/compressor gives a CEP which is stable to positional and angular instabilities of the laser beam. Our proposed design is insensitive to first order in this respect.

A number of devices are available which contribute to the chirping and de-chirping of pulses in a CPA system. Positive group velocity dispersion items include grating stretchers, bulk media or a prism stretcher, while negative GVD can be achieved using a prism or grating compressor. Grating based devices can in principle exactly compensate for each other for spectral phase over all orders. However there are necessarily bulk media in the system and when these are included the grating devices are not able to sufficiently compensate for the higher order phase terms. A CPA system for 5 fs pulses must therefore include a number of these dispersive devices and also some programmable or custom made dispersive control.

The basis of our design is to use gratings as the principal means for stretching and compressing. As mentioned above, this is not enough to compensate for the higher order terms in the system, so it has been necessary to include a prism stretcher which compensates for the higher order terms at short wavelengths. The gratings can then be adjusted to compensate for the higher order terms at longer wavelengths and a programmable phase filter removes any fine residual phase errors. Figure 1 shows a schematic of the proposed system:

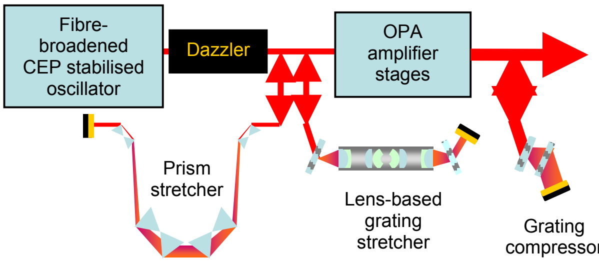

Figure 1. Schematic of the stretcher and compressor for OPCPA of 5 fs pulses.

Transmission Gratings

A novel feature of the design of grating stretcher and compressor is the use of transmission gratings. These can have both high efficiency and damage threshold and commercial software (GSOLVER) indicates a larger bandwidth than reflection gratings. An additional advantage is the ability to use them at the Littrow angle with small separations, which has proved necessary to enable the use of optimised stretched pulse duration and groove densities free of other diffracted orders which reduce the efficiency. Figure 2 shows calculated and measured grating efficiencies for 1000 line/mm transmission gratings with optimised groove depths.

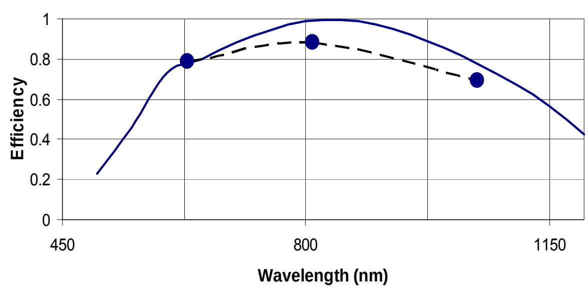

Figure 2. Calculated (solid line) and measured (circles) diffraction efficiency into the first order.

The grating compressor consists of two 1000 lines/mm gratings separated by just 11 mm. It allows adjustment of the beam angle in the non-dispersive plane and so provides additional control over the higher order spectral phase terms. The transmission grating substrates are also included in the calculation as they can strongly affect the GVD depending on whether they are within or outside the dispersion region.

The grating stretcher has been designed as a standard Martinez type grating stretcher using a lens system with -1 magnification. We have chosen to use a lens rather than a reflective stretcher system due to the constraints of generating a small stretch factor of 10^3 over such a large bandwidth. The lens system has been carefully designed to be as achromatic as possible, and it preserves both beam collimation and an angular magnification of -1 for all wavelengths. In addition to this the lens does not introduce excessive variation in group delay between rays traversing different parts of the lens aperture.

Prism stretcher

Our prism stretcher design has two prisms at each beam deviation since we can conveniently arrange for the deviation to be close to 90 degrees with air-glass incidence angles close to the Brewster angle. This 4 prism-pair scheme also allows us to easily adjust the length. Modelling has shown that two passes of the stretcher are necessary to ensure CEP variation with beam pointing is minimised.

Final Phase Correction

The group delay from each dispersive element is shown in Figure 3 over the range 650-1050nm. It can be seen that there is a residual error in the group delay of approximately 3ps. We have chosen to correct this final phase error using a programmable phase filter.

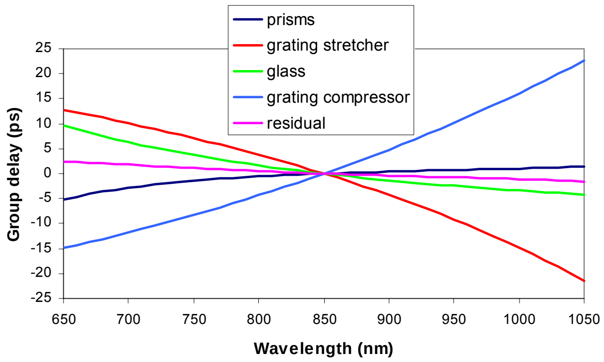

Figure 3. Group delay against wavelength for each of the components of the system.

For this work an AOPDF (the "Dazzler" from Fastlite) has been selected to be the final control of spectral phase. This device is inherently broad bandwidth, can apply smooth spectral phase filters with large magnitudes, has a simple collinear geometry and has the added benefit of being able to modulate the spectral amplitude. Inclusion of one of these devices in the stretcher compressor system gives a quick and simple way to perform day to day optimisation of the compressed pulse duration.

The Dazzler can compensate for a maximum linear group delay of approximately 3 ps. For highest efficiency, the filter applied by the Dazzler should correspond to this full group delay and its slope should not vary by more than a factor of 3-4, which corresponds to the delay shown in Figure 3.

Spider

For full optimisation of the final pulse duration we have built a device based on SPectral Interferometry for Direct Electric field Reconstruction (SPIDER)[6]. This provides a rapid measurement of the spectral phase of the compressed pulse, which can be inverted and programmed into the Dazzler to optimally compress the pulse. It also provides a full reconstruction of the temporal profile of the pulse.

In our SPIDER, front and back reflections off a 30 micron fused silica etalon create two pulse replicas separated in time by ~295 fs. The transmitted part of the pulse is stretched in a 55mm SF10 block (dispersion 7890 fs^2) and each replica pulse upconverts with a quasi-monochromatic slice of the stretched pulse in a 300 micron KDP type II crystal. The two upconverted pulses are then sent into a spectrometer and the phase is extracted from the resultant interferogram via a computer. The use of an etalon in such a short pulse system is normally avoided due to the unbalanced dispersion it introduces between the two pulse replicas, but careful modelling has shown that this effect can be removed in the calibration of the apparatus.

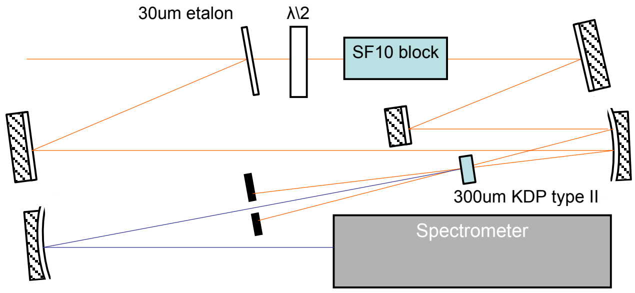

Figure 4. Schematic showing the layout of the SPIDER.

Current tests have shown that we are capable of stretching the ~120nm bandwidth of our oscillator to 3.4 ps using the prisms and can recompress it to within 0.1 fs of the 11.7 fs transform limit using the Dazzler and Spider in a feedback loop. The fact we have managed to recompress the pulse so well is a good indication of the stability and reliability of the SPIDER-Dazzler system as a means of final pulse compression.

Conclusions

OPCPA laser systems offer a route to high power few cycle laser pulses but require a complex stretcher compressor system operating over an extremely wide bandwidth. We have designed such a system to compensate for all phase errors over 400 nm, which will form part of a 5 fs, 10 mJ OPCPA drive laser for attosecond pulse production.

Another major component of this laser system is the high average power high peak power pump laser for the OPA stages, the amplifier of which is described in "High Power Diode Pumped Nd:YLF Amplifier Development".

The complete system will be on the cutting edge of current sub-10 fs laser technology and will provide a valuable experimental tool for use in the Attosecond Basic Technology programme at Imperial College London.

The authors would like to acknowledge EU funding support for this project via the OTTER JRA.

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