High energy broadband ultrashort pulse OPCPA system

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Introduction

There is great interest in the generation of a high energy and high intensity ultrashort laser pulse using the concept of Optical Parametric Chirped Pulse Amplification (OPCPA). Although the first demonstration of OPCPA[1)] had been done for a low energy laser system the applicability of OPCPA to existing large scale lasers was realised later by Ross *et al.* [2)] and the potential to scale to unprecedented powers and intensities was explored. Since the proposal of high intensity OPCPA[2)], the Central Laser Facility (CLF) has conducted a number of trials, initially on a tabletop scale[3)] and peak powers in excess of 1 TW were demonstrated later using a sub aperture of one of the Vulcan beam lines[4)]. The purpose of the current work was to build on this and to demonstrate the full potential of the technique by scaling up to the PW level. There were three experimental periods in Vulcan Target Area East (TAE) within the programme. The first experimental period demonstrated[5)] an uncompressed 15 J, ~30 nm bandwidth output pulse in a high quality beam close to the diffraction limit and with extraction efficiency of 25%. In this paper we present experimental results of the latest PW level OPCPA experiment which demonstrated an increase in the uncompressed output pulse energy to 35 J. It also demonstrated an increase in the output bandwidth to 70 nm and compression to 85 fs indicating a potential power level between 0.3 and 0.4 PW.

Experimental set-up, improvements and results

The second and third experimental periods contained several important improvements resulting from previous experience[5)]. There were subtle changes to the amplification scheme, a shorter pulse oscillator and a grating compressor. Figure 1 shows a schematic diagram of the layout of the OPCPA system and Figure 2 a photo of the actual experimental arrangement in TAE. The signal beam was generated by first enhancing the bandwidth of a 100 fs pulse from a Spectra Physics Tsunami Ti:sapphire oscillator (KLM oscillator Figure 1) in an optical fibre using self-phase modulation. The KLM oscillator produced ~120 mW output power at a centre wavelength ~1040 nm and up to 60 % of the input power was transmitted through the single-mode fibre. Improvements to the fibre coupling meant that for the second experimental period more than 70 nm of bandwidth was available and the use of just a few tens of centimetres of fibre material ensured that this bandwidth enhanced pulse remained compressible. The self-phase modulated pulse had a resultant bandwidth sufficient to support a sub-30 fs pulse then was stretched in a grating stretcher prior to injection into a 3-stage Optical Parametric Amplifier (OPA) system. The single mirror achromatic stretcher, designed at RAL, had a calculated group velocity dispersion ~5* 10^{-24} sec^2 for a 50 cm separation between the gratings providing stretching of a 30 fs pulse to 500 ps. The whole seed system with the stretcher was located on one optical table in the target area adjacent to the experiment (Figure 2).

The OPA chain was pumped using a 150 mm beam from Vulcan operating in the 2nd harmonic (526 nm). In all three stages the pump beam was correspondingly down sized to generate the appropriate fluence. The pump fluence, and thus intensity, was originally designed to be approximately the same in all three stages. The output of this OPA chain was then sent to a number of diagnostics and a grating compressor. The maintenance of high beam quality was ensured by using image relays in both the pump and signal beams between all amplification stages and between the OPCPA system and Vulcan. The pumping conditions were slightly non-collinear with a 0.5º angle inside the crystals between signal and pump beams. The crystals used for OPA1 and OPA2 stages were 20 mm long LBO and 35 mm KDP crystal for stage 3. The aperture size of the KDP crystal was greater than 110 mm. It was necessary to use KDP for the final stage because this is the only crystal available in a sufficiently large aperture. It does

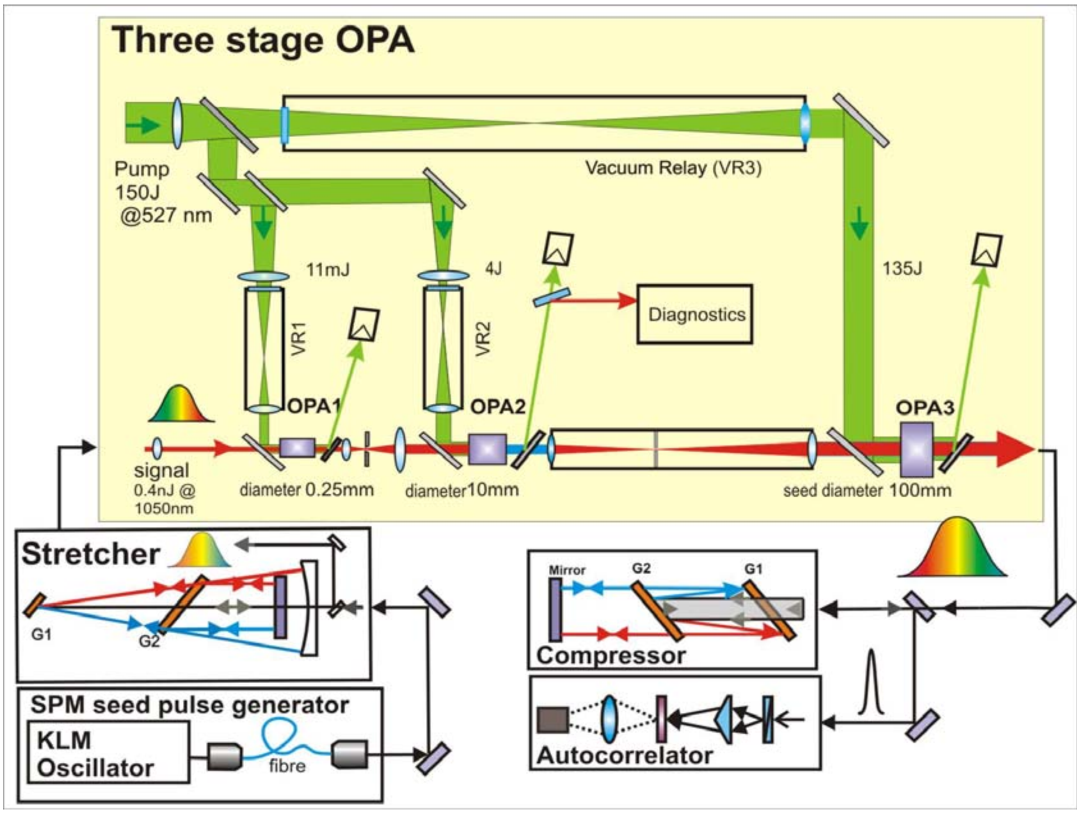

Figure 1. Schematics of the OPCPA experimental set-up in TAE.

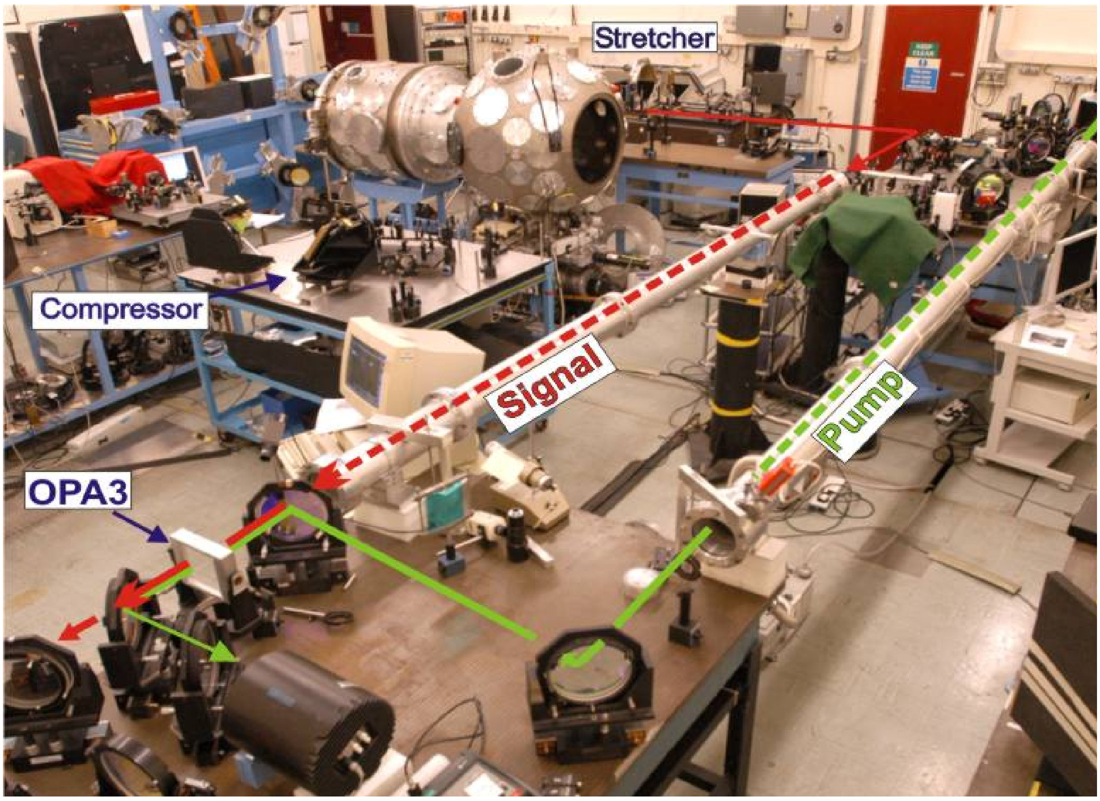

Figure 2. Photo of the experimental set-up in TAE.

unfortunately provide the bandwidth limit for the process but it has broad enough gain bandwidth to support a 100 nm bandwidth[2)] for the almost degenerate regime of OPA in our experiment.

Changes were made to the Vulcan pulse generation system through shaping the pump pulse with a system combining fast and slow Pockels cells[6)]. The fast cell operated as before, slicing a square section from a single mode source for injection into the Vulcan chain. The slow cell served to superimpose a slowly increasing ramp on top of this top hat section. This was intended to circumvent pulse shortening due to the gain saturation that the pulse would experience upon amplification. The improved pulse shaping provided the temporal shape of the pump pulse close to a top hat shape at the highest pump energy with the duration typically ~0.8-0.9 ns.

There was also a change in the gain balance between amplifiers 1 and 2 with gain shifted from amplifier 2 to amplifier 1 by pump beam re-sizing. The seed beam injected into amplifier 1 was also reduced in size to attempt to saturate the gain in amplifier 1. This however brought the intrinsic divergence of the seed beam in amplifier OPA 1 too close to the angular acceptance of the process and it was suspected that this contributed to an actual reduction in gain of the OPA 1 contrary to our expectations. Another problem that arose during the first experiment and was eventually eliminated in the 2nd experiment was parasitic generation in OPA2. We observed a dependence of the level of parametric fluorescence (or ASE) on pump beam diameter. The crystal pumped by a 12 mm diameter beam supported an amplification of the parametric ASE in different directions for a broad wavelength spectrum. The issue of parametric fluorescence was partially attributed to multi-trip parasitic emission due to incorrect direction of the wedge of the OPA2 crystal in the non-critical angle direction which was corrected in the second experiment. Furthermore a substantial reduction of the ASE was observed by reducing pump beam size to 10 mm diameter in OPA2. This caused the reduction of the output beam diameter to 70 mm in the first experiment. A change in the telescope magnification between OPA2 and OPA3 occurred for the second experiment to bring the output beam diameter to a 100 mm.

The changes to the gain staging and the OPA 2 crystal meant that close to the full aperture could be used for the 2nd and 3rd experiments. Output pulse energies of up to 35J were recorded with a maximum 25% conversion efficiency. This is illustrated in Figure 3 where conversion efficiency dependence of the idler beam on the pump beam fluence is presented. Direct measurements of the amplified energy were performed on the idler beam giving us a freedom to analyse pulsewidth and the spectrum of the amplified signal pulse. The 25% conversion efficiency was less than expected and was due to a number of reasons. Firstly the gain was lower than expected in OPA1 and therefore it was difficult to strongly saturate the second and third amplifiers. Secondly there were issues concerned with the spatial quality of the Vulcan pump beam that had degraded from the previous experiment and finally it was necessary to use a longer duration pump to allow for timing jitter. These three factors limited the extraction efficiency to 25%.

The spectral bandwidth output from the oscillator/fibre system was approximately 70 nm (Figure 4,top), some 20 nm more than in experiment 1. This in turn compressed to a duration of

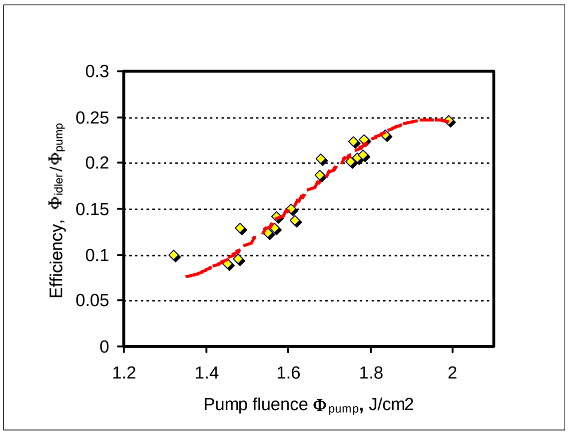

Figure 3. Output conversion efficiency as a function of pump fluence- the peak 25% corresponds to a 35 J output pulse energy.

~30fs when measured immediately after the fibre using a prism pair compressor. This indicated that the spectral phase was essentially free from excessive aberration across this bandwidth. As a result of the changes to the Vulcan pulse generation system, much better pump temporal profiles were produced under saturated conditions which in principle enabled a greater single shot bandwidth to be amplified. This indeed turned out to be the case and Figure 4 shows a comparison between the input and output bandwidth – the gain is more than 10^{11}. There is a slight asymmetry in the output spectrum, which we believe is due to partial back conversion arising from a residual asymmetry in the pump.

A double path grating compressor with separation similar to the stretcher was designed to compress a pulse with a 100 mm beam diameter. The size of the compressor was small enough to be situated in the existing vacuum chamber in TAE (Figure 2) Although it had been the intention of the investigators to attempt full aperture compression under vacuum, the temporal compression of the seed pulses was undertaken in air due to the limited time available. The pulsewidth was measured with a single-shot autocorrelator. Compression in air meant that only a fraction of the energy of the output seed beam could be used. The best recompression of the seed pulse without amplification was measured at 75 fs. This is after stretching and compressing using the systems developed and is approximately a factor of 2 longer than the direct compression after the fibre. This implies that there is an un-resolved spectral phase error that has as its source either a setting or a geometric error within the stretcher-compressor system. However, upon amplification, as shown in Figure 5, the pulse duration only increases to 85 fs with a smooth autocorrelation trace. The autocorrelation traces were smooth and without pedestals. These results, both in terms of temporal duration and energy were stable over many shots.

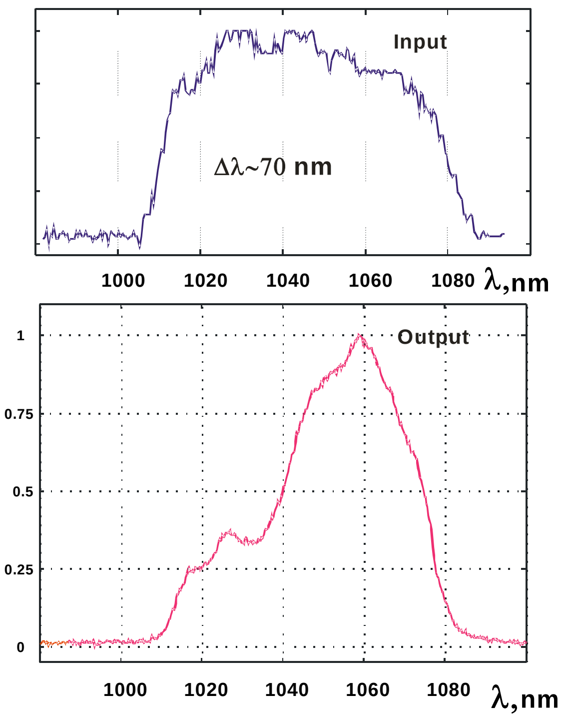

Figure 4. Comparison between the input (top) and output (bottom) bandwidth. The 70 nm bandwidth is preserved over more than 11 orders of magnitude of gain.

Summary

The primary objectives of the experiment were largely achieved. This experiment demonstrated for the first time

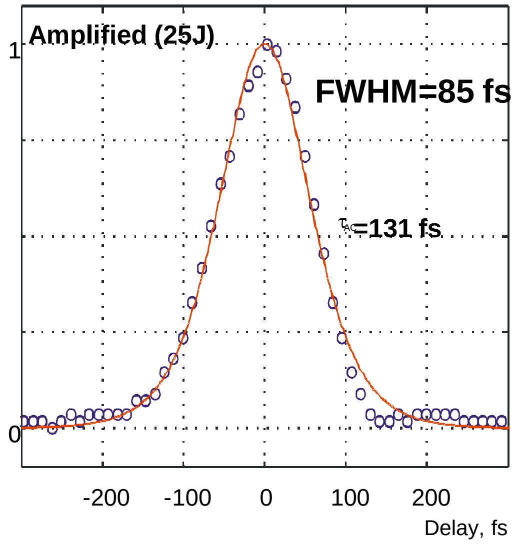

Figure 5. Autocorrelation trace of an amplified pulse in the OPCPA system. The ~80 fs duration of these is however a factor of more than two longer than the output of the oscillator/fibre arrangement implying that there is a residual phase error arising from the stretcher-compressor combination

uncompressed output pulse energy to 35 J using the OPCPA technique. The amplified energy corresponds to a total gain in the system of 10^{11}. It also demonstrated an increase in the output bandwidth to 70 nm. A fraction of this energy (glass plate reflection) was compressed in air to 85 fs indicating a potential power of between 0.3 and 0.4 PW if the full energy were to be compressed in vacuum. This figure depends on what is assumed for grating compression efficiency, and whether for example gold or higher efficiency dielectric gratings would be used. Nonetheless, the production of this level of energy with this bandwidth and compression to this pulse duration is a major step forward for the OPCPA technique. Furthermore it is close to the expected performance indicated by modelling and therefore gives confidence to future plans The full potential of using OPCPA on Vulcan is between 10 and 20 PW and therefore this technique offers the possibility of an affordable upgrade for Vulcan in the medium term. This work was supported by an EPSRC Grant GR/R31768/01. The authors are grateful to CLF staff for their help and interest in this work.

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