High energy and high stability optical parametric chirped pulse amplifier for seeding the petawatt beamlines of the Orion laser facility

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ABSTRACT

A high-conversion-efficiency optical parametric chirped-pulse amplifier (OPCPA) with high-energy-stability is demonstrated using lithium triborate (LBO) crystals. Total conversion efficiency of 25% is realised with a net gain of greater than $10^8$. An output energy of ~180mJ at a 2-Hz repetition rate, with a stability of better than 1.5% rms is achieved. The output beam takes the spatial profile of the 20th-power super-Gaussian pump beam, whose intensity deviates by less than 7.5% rms over the central 90%. The far-field, whose diameter is near diffraction limited, has a pointing stability of less than one-twelfth of an airy-radius. To the authors’ knowledge this is the first demonstration of an all LBO OPCPA to simultaneously achieve this level of performance.

Keywords: Optical Parametric Chirped Pulse Amplification, Optical Parametric Amplification, LBO, High energy.

1. INTRODUCTION

The Orion laser facility, currently under construction, will be used for high energy density plasma physics experiments. Of the twelve beamlines, ten are 'long pulse', delivering 500J at 351nm in a variable pulse length from 100ps to 5ns. The two remaining ‘short pulse’ beamlines will each be capable of achieving a petawatt using chirped-pulse amplification, delivering 500J at 1054nm in a variable pulse length from 500fs to 20ps.

Optical parametric chirped-pulse amplification (OPCPA) has been widely used for the purpose of seeding short pulse beamlines since its invention in the early 1990’s [1]. The higher the proportion of the overall gain that is realised in the OPCPA front-end the more the bandwidth is maintained.

OPCPA systems have been demonstrated using a variety of nonlinear crystals, pumping regimes and stretched signal techniques. $\beta$-Barium-Borate (BBO) [2-5] and Lithium triborate (LBO) [6-11] crystals have both been widely demonstrated. LBO crystals have similar nonlinear properties to BBO, most significantly its extremely broad nonlinear gain bandwidth (~150nm centred at 1.05µm), using near-degenerate Type I phase matching. With LBO, pulse energies from 100µJ [6] to 95mJ [10] have been demonstrated, some of which have been boosted to higher energy with the use of a power amplifier consisting of LBO or KDP crystal [10-12]. Energy stability of 1.6% rms and 29% nonlinear conversion efficiency [7, 8] has been demonstrated, with amplified bandwidths typically in the region of 6-8nm [7-10] and up to 16nm [6].

In this paper a three-stage all LBO OPCPA system is presented, which demonstrates its suitability for injection into the short-pulse beamlines of the Orion facility. An all LBO system was chosen because although the nonlinear gain coefficient is lower than BBO, the double-refractive walk-off angle is also lower. A longer nonlinear interaction length is therefore achievable, and the system is less sensitive to pump or signal beam pointing drift.

Our OPCPA system possesses many important attributes, including high gain and high gain bandwidth, a uniform output spatial profile, low far-field pointing variability, high energy and high energy stability.

2. OPG2 OVERVIEW

The room layout of OPG2 is shown in Figure 1. A single, commercially-available short-pulse oscillator, (Newport Spectra-Physics Tsunami), is split and used to seed the two separate stretcher systems. The stretchers induce a strong...
spectral phase distortion on the pulse, giving a much longer temporal pulse length at their output. Two stretchers are employed to allow different pulse lengths to be generated for the two short-pulse beamlines by varying their effective grating separations.

![Diagram of OPG2 room layout in Orion](image)

Each stretcher output is image-relayed onto a table where optical parametric amplification (OPA) of the chirped pulses takes place. This non-linear optical process is employed here as it generates several orders of magnitude of gain without reduction in the spectral width of the pulse. Each OPA system consists of three stages of amplification, which is achieved using three pairs of non-linear optical crystals of lithium triborate (LBO). These crystals require a pump source, which supplies the energy for the amplification process. This is delivered from a single, custom-designed, commercially-available, frequency-doubled Nd:YAG pulsed laser from Continuum Lasers Inc.. Figure 2 shows the four main components of OPG2.

![Image of short pulse oscillator (Newport Spectra-Physics Tsunami)](image)
3. OPA OPTIMISATION

During 2007 the short pulse oscillator and the OPA pump laser were installed, and a single stretcher and OPA were constructed. This allowed initial characterisation of the OPA and enabled the necessary design changes to take place.
3.1 Stage 1 initial performance, and theoretical modeling parameters

During the design phase an OPA interaction theoretical model was run in which the desired performance of each OPA stage was calculated based on input parameters such as the crystal length, nonlinear gain coefficient, input seed pulse energy, spectral bandwidth and pump beam intensity. OPG2 must achieve a pulse energy of ~20mJ with 15nm of spectral bandwidth in a 6mm diameter beam with a spatial profile whose central third intensity does not vary by more than 10% rms. Stages 2 and 3 were designed to operate at gain saturation whereby a significant energy transfer from the pump to the signal beam occurs, to the point where energy begins to be converted back from the signal to the pump beam. Gain saturation ensures a greater shot-to-shot energy stability and uniform beam spatial profile. Table 1 shows the parameters from the OPA theoretical model.

<table>
<thead>
<tr>
<th>OPA theoretical model parameters</th>
<th>Pump beam diameter</th>
<th>Pump energy</th>
<th>Crystal length</th>
<th>Output energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>3mm</td>
<td>149 mJ</td>
<td>50 mm</td>
<td>126 μJ</td>
</tr>
<tr>
<td>Stage 2</td>
<td>3mm</td>
<td>123 mJ</td>
<td>50 mm</td>
<td>21 mJ</td>
</tr>
<tr>
<td>Stage 3</td>
<td>6mm</td>
<td>594 mJ</td>
<td>20 mm</td>
<td>175 mJ</td>
</tr>
</tbody>
</table>

3.2 Stage 2 initial performance

Initially, stage 1 was set up as per the parameters in the model which gave an output energy of 264μJ, twice what was expected. With no appreciable gain saturation, however, the output energy is a strong function of the pump energy, so this difference is not unexpected. Stage 1 output was imaged relayed to stage 2, and it was found that gain saturation occurred with a pump energy of ~150mJ, giving ~30mJ output energy as can be seen in Figure 3. In other words, saturation occurred at higher energies than expected. This is probably a result of non-idealised, imperfect beams seen in practice.

![Figure 3. Stage 2 output energy as a function of pump energy](image)

It would be expected to observe a local maximum in output energy at the peak of gain saturation, followed by a drop as the pump energy is further increased, (back conversion). What is seen instead is a plateau in output energy at gain saturation, followed by a further increase in output energy, this being the result of amplified parametric fluorescence through the OPA system. It is necessary to remove this plateau to be certain that gain saturation is established and a significant amount of fluorescence is not present. The amount of amplified fluorescence through the system can be reduced by reducing the gain in stage 1 and increasing the gain in stage 2. This can be achieved by either altering the relative pump energy or the relative crystal length between stages 1 and 2. Altering the relative crystal length is preferable as this keeps the pump intensity evenly distributed between the stages which reduces the risk of laser induced damage and parametric fluorescence and ensures that stage 2 will gain saturate with lower pump intensity.
3.3 Stage 1 and 2 optimisation

The crystal lengths in stages 1 and 2 were changed to 40 mm and 60 mm respectively. We investigated the change in performance of stage 2 as a function of input signal energy. See Figure 4 where the legend illustrates the stage 1 pump energy which is proportional to the stage 2 input signal energy.

![Figure 4. Stage 2 output energy versus input pump energy as a function of input signal energy](image)

Figure 4 shows that the pump energy required to reach saturation in stage 2 decreases as the input signal energy increases. Interestingly, the output energy from stage 2 at the point of saturation also decreases as the input signal energy increases. In addition, as the input signal energy increases it is harder to distinguish the saturation point from the onset of parametric fluorescence. It would appear that, with higher stage 1 pump energy, parametric fluorescence may be preventing the useful signal energy from reaching its full potential value.

The ideal scenario would be to operate stages 1 and 2 such that stage 2 had the most pronounced peak of gain saturation (129 mJ of pump energy to stage 1) and also giving the highest stage 2 output signal energy. However, this requires a significant imbalance of pump intensity between stages 1 and 2 which, as discussed above is desirable to avoid, and so a compromise between the most pronounced peak of gain saturation and pump intensity balance between stages 1 and 2 was sought. Therefore it was decided to operate stage 1 with a pump energy of 149 mJ as dictated by the model, which results in a similar pump intensity to each stage whilst still saturating stage 2, and an output energy of ~40 mJ.

It should be noted that, at the optimum operating points, the parametric fluorescence is heavily suppressed by the growth of the signal. It is difficult to be precise on the degree of pre-pulse that the parametric fluorescence will produce, without the facility to recompress the pulses post-amplification, as is the case here. However, the parametric fluorescence has a different spectral character than the signal beam and so can be discriminated to a certain extent using a spectrometer. Measurements of the output spectra with and without the seed beam demonstrate that the parametric fluorescence is immeasurably small on the spectrometer (which admittedly has only a linear response) in the presence of the signal beam. Gain narrowing in the glass amplifiers of the laser chain, plus the geometry of the compressor, further inhibit the growth and transmission of the parametric fluorescence. All these factors give us confidence that the pre-pulse requirements, a contrast of at least $10^6$, of the short pulse beamlines will be met.

3.4 Stage 3 optimisation and comparison with theoretical modelling

With stages 1 and 2 optimised it was possible to measure the performance of stage 3. Figure 5 shows the theoretical modelling of stage 3. This shows that with an input signal energy of greater than ~25 mJ and for a constant pump energy the stage 3 output is gain saturated (Figure 5a). Due to the low gain of stage 3 the graph of output energy as a function of pump energy (Figure 5b) does not show the same maxima relating to gain saturation as can be seen for stage 2; the
output energy is approximately linear with pump energy in the region of operation. The experimental data obtained matches the theoretical model as can be seen in Figure 6.

![Figure 5a. OPA numerical modelling results showing the output energy of stage 3 as a function of input signal energy with a constant pump energy](image)

![Figure 5b. OPA numerical modelling results showing stage 3 output energy as a function of input pump energy with a constant input signal energy](image)

![Figure 6. Stage 3 output energy as a function of pump energy, (pre-optimisation, and with additional pump energy from the other beamline, to validate the modelling over an extended pump range.](image)

In confirming that gain saturation was taking place in stage 3 it was desirable to maintain the operating parameters of stages 1 and 2 so that stage 2 maintained gain saturation to ensure that the input signal beam properties to stage 3 were consistent. It was not feasible therefore to alter the input signal energy to stage 3. An alternative method to confirm gain
saturation is to measure the output energy as a function of crystal length. Figure 7 shows the results of this investigation; it can be seen that for 30mm of crystal (or more) stage 3 was gain saturated.

![Figure 7. Stage 3 output energy as a function of crystal length. All other parameters (seed input energy and pump energy to all stages) were constant.](image)

Further optimisation of the spatiotemporal overlap of signal and pump beams in all stages resulted in an OPA output energy of ~250mJ (with ~600mJ stage 3 pump), and it was therefore possible to reduce the pump energy to stage 3 whilst still maintaining gain saturated output. The optimised final operating parameters are shown in Table 2.

<table>
<thead>
<tr>
<th>Experimental (optimised) OPA parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump beam diameter</td>
</tr>
<tr>
<td>Stage 1</td>
</tr>
<tr>
<td>Stage 2</td>
</tr>
<tr>
<td>Stage 3</td>
</tr>
</tbody>
</table>

### 4. FINAL OPA PERFORMANCE

Having optimised the OPA performance, the output of the OPA was fully characterised. The spatial output from stages 2 and 3 are shown in Figure 8, together with line-outs of stage 3 and the output far-field focal spot. The input signal beam to the OPA has a Gaussian spatial profile while the OPA pump laser has a top-hat spatial profile. As the input beam passes through stages 2 and 3 it increasingly resembles the spatial profile of the pump beam. This is due to gain saturation in Stages 2 and 3 where the edges of the signal beam experience more gain than at the centre. This produces a ~5.8mm diameter output beam whose intensity varies by ~7.3% rms over the central 90% of the beam diameter. The final output of the OPA is image relayed onto a serrated aperture, which only allows the central 1/3 of the beam to propagate and be amplified by the rest of the short pulse beamline. The far field pointing stability of the OPA was also measured and was found to be near diffraction-limited and moves by less than 1/12 of an airy radius during normal operation.
Figure 8a. Stage 2 output near-field spatial profile

Figure 8b. Stage 3 output near-field spatial profile

Figure 8c. Line-outs through the centre of the stage 3 output beam
The OPA output spectrum is shown in Figure 9. This was produced using a 6ns temporally square pump pulse (as measured with a photodiode). The measured spectra have a negative gradient towards longer wavelengths. This could be a real effect or may be due to measurement techniques (spectral or temporal). Due to the predominantly linear chirp induced by the stretcher the spectral profile and temporal profile of the beam are broadly interchangeable. Like the spatial profile the gain saturation in stages 2 and 3 results in the output beam increasingly resembling the temporal profile of the pump beam. Therefore it is possible to alter the pump laser temporal profile to tailor the spectral output of the OPA. The bandwidth of the OPA output spectrum is ~17.5nm, (equivalent to a pulse duration of ~6ns), whose intensity varies by less than 11% rms.
The OPA output energy was measured to be 180mJ with an energy stability of 1.2% rms (Figure 10) over 1000 shots and this was simultaneously compared with the pump laser whose energy stability was 0.7% rms. It was possible to increase the OPA output energy further (to ~250mJ), by increasing the stage 3 pump energy, whilst still maintaining performance. There is some correlation between the OPA output energy and the pump laser output energy. However, the more significant cause of energy fluctuations was due to jitter between the arrival time of the pump and signal pulses at the OPA. This was a result of a surrogate timing system used for the offline design proving tests. It is expected that the stability will improve further when the final timing system is implemented.
5. FUTURE WORK

Work has commenced to transfer the equipment from the design proving laboratory to OPG2 in Orion. The short pulse oscillator and the two stretchers have been successfully installed and commissioned in their final location (comprising a major project milestone). The OPA pump laser and the two OPA systems are now being installed.

6. CONCLUSIONS

The design proving activities form part of the installation and commissioning strategy for OPG2. The results demonstrate that the OPG2 subsystem meets, and in most cases exceeds, all the requirements placed upon it for injection into the petawatt beamlines of the Orion facility. Much has also been learnt about the performance and behaviour of the OPA system as a function of the parameters of the OPA, and where best to set these parameters to obtain the most stable and highest quality OPA output.

REFERENCES