High performance Ti:Sa amplifier for 10PW front-end system

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Introduction

A new front-end system has been developed in phase I of the Vulcan 10 PW OPCPA project [1-5]. This new front-end system has been tested and characterized. It is demonstrated that an amplified spectral band width of >100 nm FWHM was obtained at the output energy of ~0.4 J. This amplified pulse was compressed down to <30 fs. However, the preliminary measurement using a commercial third-order auto-correlator (SEQUOIA) shows that the pulse contrast is only 10^7 [6]. This value is much lower than the required specification. This is the critical and key issue to be addressed in phase I of the Vulcan 10 PW OPCPA project.

In order to improve the pulse contrast of the 10 PW front-end system on the ns time scale to meet the required specification, the amplification gain of the current 1st J-stage optical parametric amplifier (OPA) needs to be reduced to an optimum value. This will reduce the ratio of injected seed pulse energy to the amplified OPA pulse energy while retaining a similar output energy. This requires increasing the output pulse energy of the mJ-stage OPA pre-amplifiers on the ps time scale significantly from its current value of ~40 µJ to ~1 mJ. However this is currently limited by the output power of the existing pump laser, a commercial Ti:Sa amplifier (Compact Pro), giving a pulse energy of only ~1.8 mJ at 800 nm. To achieve the required seed pulse energy for subsequent J-level OPAs, a boost Ti:Sa amplifier has been designed and developed to increase the pump pulse energy to ~30 mJ at 800 nm. This boosted IR pulse will be then frequency doubled using a thin BBO crystal to generate the required pump pulse of ~4.5 mJ at 400 nm that will be used to upgrade 3rd and possible 4th mJ-stage OPA pre-amplifiers to produce a 1mJ ps pulse while retaining the full spectral bandwidth.

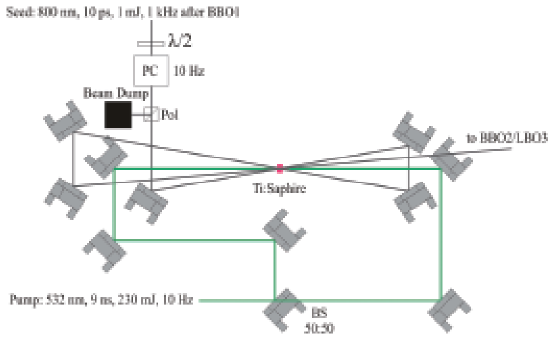

Figure 1. Schematic of the boost Ti:Sa amplifier.

Boost Ti:Sa amplifier design and development

The schematic of the boost Ti:Sa amplifier is shown in Fig. 1. This compact additional boost Ti:Sa amplifier is designed and developed based on a 3-pass bow-tie geometry, pumped from both ends of the Ti:Sa crystal for a uniform pumping distribution throughout the gain medium.

A relatively high doping Ti:Sa crystal with an absorption coefficient of ~5.5 cm^{-1} at 532 nm and a single pass absorption of ~89% was chosen to be used as the gain medium of the amplifier. The optical pass length of the Ti:Sa crystal is 4 mm and the diameter of the crystal is 7 mm. The crystal has uncoated Brewster-end cut at the both ends, so that it could withhold a high pulse energy up to ~30 mJ of short infrared (IR) pulses of ~10 ps at the maximum fluence of ~1 J/cm^2.

A simplified zero-dimensional code was developed to simulate the performance of this Ti:Sa amplifier under an assumption of flat top beam profiles for both the pump and seed pulses. A typical simulation result is shown in Fig. 2 for a nominal pump beam size of 3.25 mm and seed beam size equivalent to 80% of the pump beam. As can be seen, this amplifier is capable of delivering the required output energy in IR for various seed pulse energies. It is not operated in the saturation regime and the output energy is largely dependent on the seed pulse energy. For example, for seed pulse energy of ~1 mJ, the amplifier is able to deliver output energy of ~30 mJ at 800 nm at the pumping energy of ~205 mJ after 3-pass amplification with an average single pass gain of ~3.1. Under those conditions, the maximum accumulated B-integral of this amplifier is calculated to be around ~0.8 for ~10 ps pulses, which is believed to be acceptable. The simulation results have provided a useful basic guideline for design, development and optimization of this boost Ti:Sa amplifier.

A very compact commercial pulsed Nd:YAG laser (CFR400) with an internal second harmonic conversion (SHG) was selected to be used as the pump laser for this amplifier. CFR400 is capable of delivering laser pulse energy up to ~230 mJ at 532 nm at a repetition rate of 10 Hz, which meet the pump energy requirement for this amplifier as predicted in the simulation above. The full specifications of this pump laser are summarized in the Table 1. In addition, due to its ultra compactness, the CFR400 together

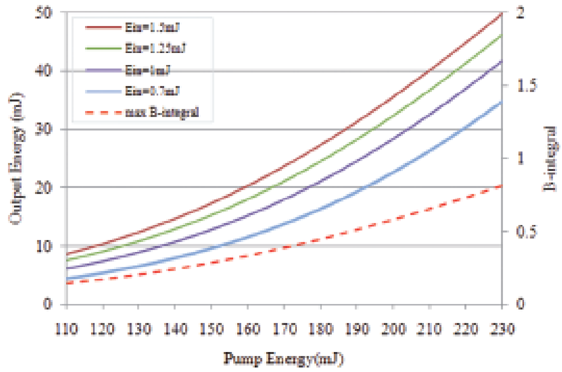

Figure 2. Simulation results of the Ti:Sa amplifier performance.

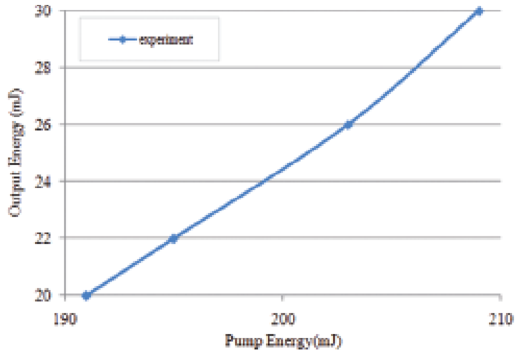

Figure 3. Amplifier performance.

with the boost Ti:Sa amplifier could be integrated into the existing front-end system with a minimal impact on the established mJ OPA-stage set-up.

Table 1 Pump laser CFR400 specification

Pulse energy (mJ)	Pulse duration (ns)	Beam diameter (mm)	Beam Divergence (mrad)	Energy Stability (%)
230	9	7	<3.5	<2.5

Experimental results and discussion

The original pump laser beam size of CFR400 was reduced to ~2.5 mm in diameter via an optical image relay while retaining its top-hat beam aspect. The pump laser beam was split into two identical beams by a 50:50 beam splitter and then injected on to the Ti:Sa crystal to pump it from the both ends for a relatively uniform longitudinal pump distribution throughout the gain medium. The correspondingly nominal pump beam size inside the Ti:Sa crystal is about ~3.25 mm as predicted in the simulation results, giving a pump fluence of ~1.3 J/cm^2. Both pump beams are carefully optimized by inspection of the pump beam profile and symmetry of generated fluorescence inside the Ti:Sa crystal using a CCD camera.

The IR pulse centered at ~800 nm with a negative chirp of ~2 nm/ps is used to seed a commercial 10-pass Ti:Sa amplifier (Compact Pro) as the pump laser for the current mJ-level OPAs [4]. The Compact Pro is capable of delivering only ~1.8 mJ pulse energy with the pulse duration of ~14 ps. This pulse was frequency doubled in a thin second harmonic generation (SHG) crystal BBO1. The generated blue pulse at 400 nm is used to pump the 1st and 2nd mJ-stage OPA pre-amplifiers. The residual IR pulse of ~1.2 mJ after the SHG crystal BBO1 and separator is directly injected into the 3-pass boost Ti:Sa amplifier for further amplification without any beam re-shaping or re-formatting. The seed beam is carefully centered at the pump beam at each pass for effectively spatial overlapping between the pump and seed. However, the seed beam slightly overfills the laser crystal at the 3rd pass due to beam divergence, resulting in ~80% throughput for the seed beam.

The initial test of the boost Ti:Sa amplifier shows that the performance of this amplifier was severely hampered by a considerable ASE loss. The measurement of fluorescence pulses indicates that the ASE loss is dominated by the pulsed transversely parasitic lasing on a few ns time scale due to the internal reflection on the barrel surface of the crystal. There is an evident demonstration that the ASE back-scattering on the fine-ground crystal surface is sufficient to cause severe gain depletion [7]. This has resulted in a limited output energy at only ~15 mJ for various pumping energies up to ~215 mJ. This is only half of the designed value of the output energy of the amplifier. In addition, the optimum amplification could only be obtained within a very tight timing widow of accuracy of ~1 ns before the parasitic lasing occurred. To overcome this problem, a thin film of index-matching paint was carefully coated on the barrel surface of the Ti:Sa crystal to minimize the internal reflection. This is the same material as that is used to suppress the ASE in Astra-Gemini high energy Ti:Sa amplifier [7]. The index-matching coating has greatly reduced the pulsed transverse parasitic lasing inside the gain medium and significantly enhanced the performance of the boost Ti:Sa amplifier in terms of the output energy. The amplifier is now capable of delivering the required pulse energy.

The performance of this amplifier is shown in Fig.3 as a function of pumping energies. As seen, an output pulse energy of ~30 mJ in the IR was obtained at the pumping level of ~209 mJ at a repetition rate of 10 HZ with an overall gain factor of ~35. Fig. 4 shows the near-field beam profiles of a) the generated fluorescence in the Ti:Sa crystal and b) amplified IR pulse on the Ti:Sa crystal at the 3rd pass. It was observed that both the fluorescence and amplified IR beam profile were quite uniform across the gain medium that is critical and important feature as the pump beam for efficient OPA amplification. The measurement shows that the spectral aspects of the IR seed pulse were almost maintained after amplification due to the negligible gain narrowing effect of this amplifier.

This boosted IR pulse is frequency doubled in a thin SHG crystal BBO2 to produce an energetic blue pulse at 400 nm, which is to be used to upgrade the 3rd and possible 4th mJ-stage OPA pre-amplifiers. However, the initial test shows that the pulse energy of ~5 mJ at 400 nm could be obtained with a very poor beam profile. The non-uniform beam profile of the blue pulses is believed to be caused by the excessively accumulated B-integral in the system. Therefore, further investigation and optimization of the system is required to overcome this problem in due course.

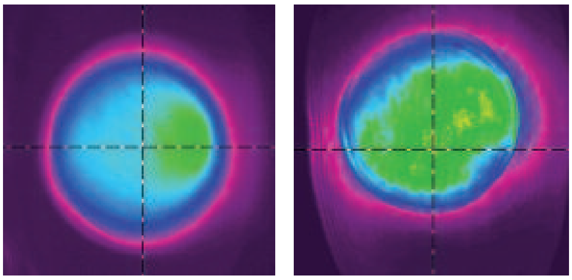

Figure 4. Beam profile of a) fluorescence and b) amplified IR pulse.

Conclusions

A boost Ti:Sa amplifier has been designed and developed, delivering an IR pulse energy of ~30 mJ at 800 nm with a good beam profile in the near field while retaining the spectral band width of the seed pulse. An energetic blue pulse of ~5 mJ at 400 nm could be obtained with a very poor beam profile. Further investigation and optimization is under the way to overcome this problem.

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