A scalable high-energy diode-pumped solid state laser for laser-plasma interaction science and applications

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Abstract Laser systems efficiently generating nanosecond pules at kJ energy levels and at multi-Hz repetition rates are required in order to translate laser-plasma interactions into practical applications. We have developed a scalable, actively-cooled diode-pumped solid state laser amplifier design based on a multi-slab ceramic Yb:YAG architecture called DiPOLE (Diode-Pumped Optical Laser for Experiments) capable of meeting such requirements. We demonstrated 10.8 J, 10 Hz operation at 1030 nm using a scaled-down prototype, reaching an optical-to-optical efficiency of 22.5%. Preliminary results from a larger scale version, delivering 100 J pulse energy at 10 Hz, are also presented.

1. Introduction

The ongoing strong effort to improve the understanding of laser-plasma interactions and to convert this knowledge into viable real-world applications has given a great impetus to the development of high-energy laser sources. These lasers have so far relied on flashlamp-pumped amplifier technology, which severely limits the repetition rate and the electrical-to-optical efficiency. This results in a limitation on the amount of science which can be carried out and prevents the translation of laser-plasma interactions into practical applications. An innovative approach, based on diode-pumped solid-state laser (DPSSL) technology, allows overcoming these limitations and is currently under development within the framework of the DiPOLE project at STFC's Central Laser Facility. DPSSL systems can be either used directly to compress matter to extreme densities or to drive high-energy femtosecond laser chains for the generation of laser-driven secondary sources of particles (electrons, protons) or photons (from THz to gamma), making them suitable for a wide range of laser-plasma applications such as inertial confinement fusion, intense X-rays generation and particle acceleration research. In this paper, results from a cryogenically-cooled, multi-slab DPSSL amplifier, delivering 10J pulses at 10 Hz repetition rate, will be presented along with initial results from a 100 J, 10 Hz system under development.

2. DiPOLE: 10 J, 10 Hz prototype amplifier

The DiPOLE amplifier concept, already extensively described in previous publications [1, 2], is based on a diode-pumped, cryogenically cooled, multi-slab ceramic Yb:YAG scalable architecture designed for amplifying 1030 nm pulses with a time duration between 2 ns and 10 ns to kJ-level energies at multi-Hz repetition rates. A scaled-down prototype, designed to produce 10 J pulses at 10 Hz

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repetition rate with a target optical-to-optical efficiency of 25%, has been built to test the viability of DiPOLE concept and is used as a test-bed for further developments [3].

2.1. Energy and beam quality

As shown in figure 1, at 10 Hz repetition rate and at a temperature of 140 K, the system amplified 10ns pulses to an energy of 10.8 J for a pump pulse energy of 48 J, corresponding to an optical-to-optical conversion efficiency of 22.5% and an electrical-to-optical efficiency of 12.8%. To the best of our knowledge, this is the highest energy level achieved by a cryogenically-cooled Yb-doped laser and the highest efficiency achieved by a multi-J DPSSL system. However, while the specification on output energy was fulfilled, the design target of 25% optical-to-optical efficiency has not been met yet. Design modifications have been put in place to reach higher efficiency values on future systems.

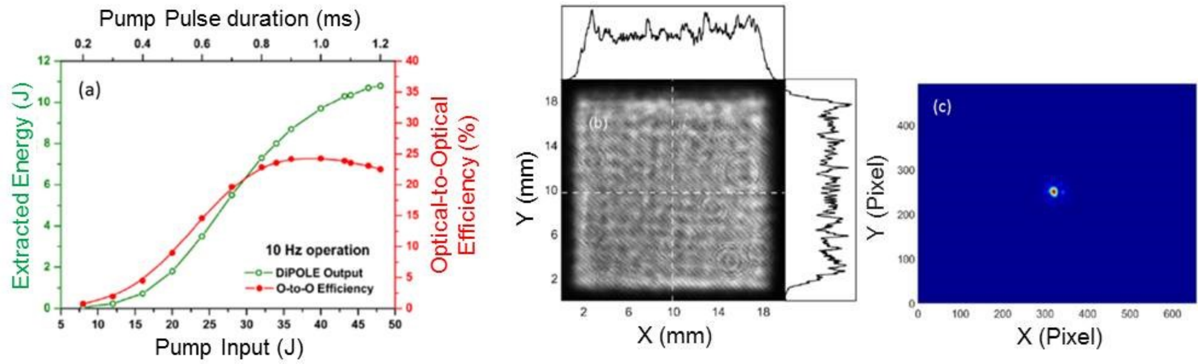

Figure 1. (a) DiPOLE performance at 10 Hz, 140 K: output energy, optical-to-optical efficiency of the system. Near-field (b) and far-field (c) profiles measured at 10 Hz and 10.8 J.

Figure 1 also shows the near-field (b) and the far-field (c) beam profiles. Comparison with a predicted diffraction limited spot-size showed that the far-field spot is 2 and 1.9 times diffraction limited in the x and y-axes respectively. Inhomogeneity on the near-field profile is partly due to diffraction effects caused by optical filters used in the beam diagnostic system.

2.2. Long-term stability tests

In order to validate the long-term operation of the DiPOLE amplifier at the design baseline fluence of 2 J/cm^2 chosen for a 100 J upgrade, the system was operated at 10 Hz repetition rate and at a pulse energy of 7 J for more than 50 hours (figure 2). Data was collected in runs lasting from 4 to 6 hours. Shot-to-shot energy stability over this period was 0.85% rms.

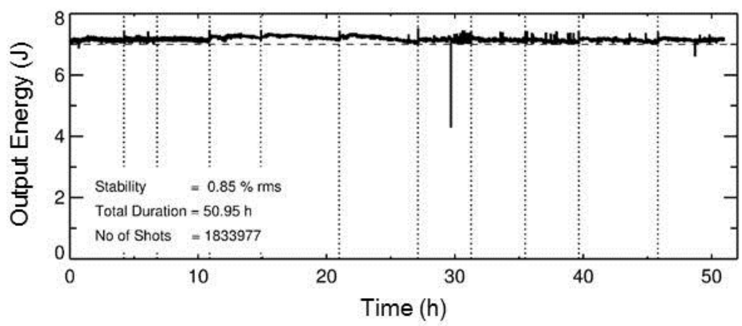

Figure 2. Output energy during long-term operation of the DiPOLE amplifier at 7 J, 10 Hz. Vertical lines denote start and finish of individual runs.

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Long-term and short-term beam pointing stability plots are shown in figure 3(a) and 3(b), respectively. While short-term beam pointing stability was affected by random fluctuations characterised by an amplitude smaller that the diffraction limit of the system, a drift in the beam pointing was observed during long-term operation. This drift could be easily compensated by active beam stabilisation systems, a measure which will be implemented both in DiPOLE and in new systems.

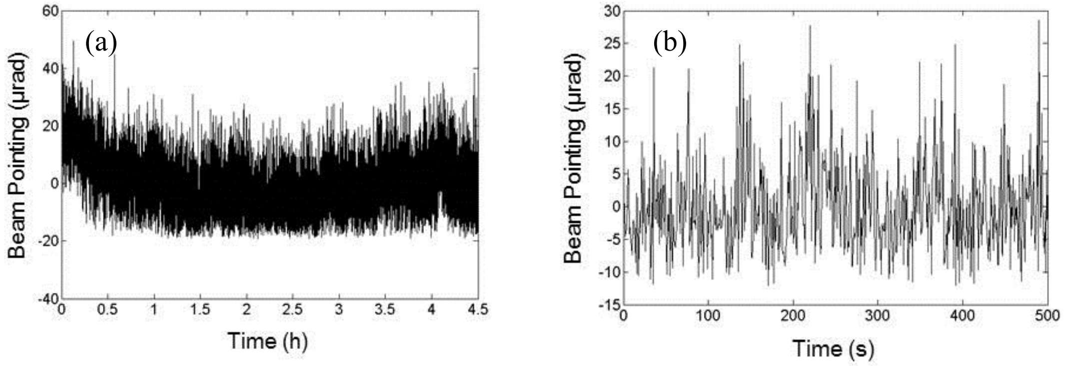

Figure 3. Long-term (a) and short-term (b) beam pointing stability at 10 Hz, 7 J operation.

2.3. *Second harmonic generation results*

Second harmonic generation (SHG) tests were carried out to assess the suitability of the system for pumping femtosecond laser chains. An LBO crystal in Type-I configuration was employed. As shown in figure 4(a), 82% conversion efficiency was achieved at 10 Hz, 6.25 J operation.

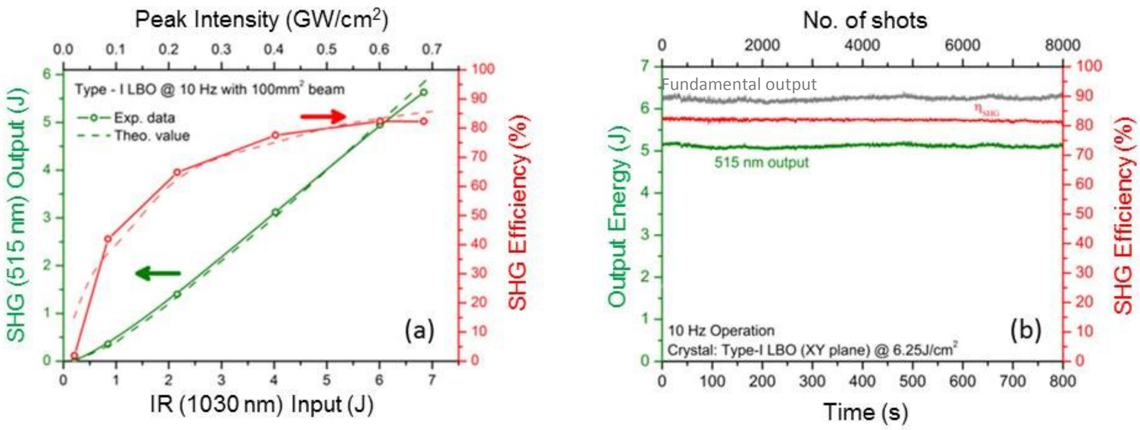

Figure 4. (a) Energy of second harmonic beam and conversion efficiency. (b) Long-term operation.

The system was operated for 8000 shots without any damage to the LBO crystal (Figure 4(b)). The energy stability for the second harmonic was 1.4% rms.

3. DiPOLE100: 100 J, 10 Hz upgrade

Results shown above have confirmed the validity of the DiPOLE concept, giving confidence for energy up-scaling. A new system, under construction at the CLF for the HiLASE project in the Czech Republic [4] and described in previous publications [5], is designed to amplify 1030 nm pulses, with super-Gaussian (order ≥ 8) square spatial profile and arbitrarily shaped temporal profile between 2 and 10 ns, to an energy of 100 J with a repetition rate up to 10 Hz. The architecture is similar to DiPOLE with front-end, 10 J stage and additional 100 J stage.

3.1. Initial results

First amplification tests with the 10 J stage were carried out at a repetition rate of 1 Hz and a seed energy of 33 mJ from the front-end. Figure 5(a) shows output energy as a function of pump pulse duration. The maximum energy obtained was 9.1 J with a pump energy of 33 J. This equates to an optical-to-optical efficiency of 27.5%, a significant improvement over DiPOLE, achieved through a higher peak pump power and reduced passive losses.

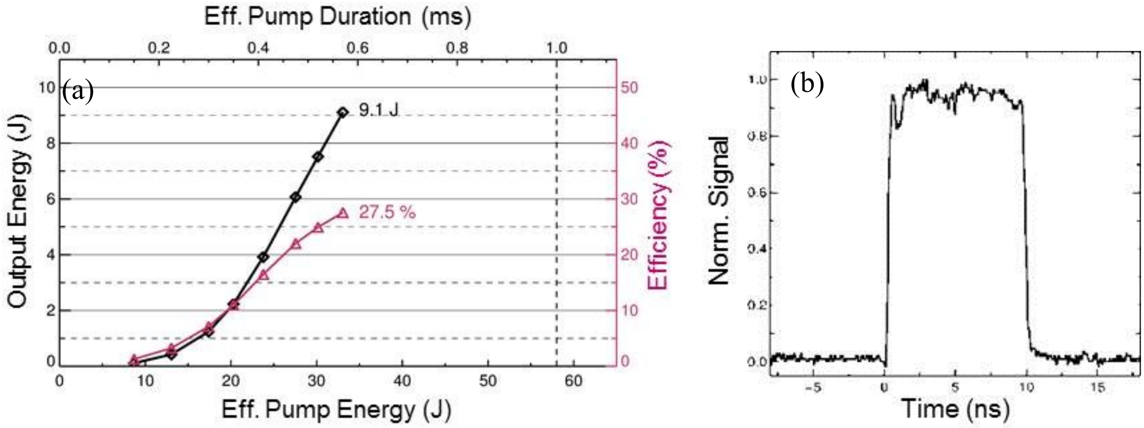

Figure 5. (a) Output energy and optical-to-optical efficiency of the 10 J amplifier operated at 1 Hz repetition rate at different pump pulse energies. (b) Temporal pulse profile at 9.1 J.

4. Conclusions

The validity of DiPOLE concept has been demonstrated using a scaled-down 10 J, 10 Hz prototype. A 100 J, 10 Hz system is under construction at STFC's Central Laser Facility. While the architecture of the new system is similar to the scaled-down prototype, great effort has been devoted to improve the performance and the reliability of the system. Initial results from the 10 J stage confirmed a relevant increase in optical-to-optical efficiency compared to the prototype. Moreover, while the output energy was limited to 9 J to minimise risk of laser-induced damage to the gain medium, the system has the potential to produce higher energies since more than 58 J pump energy is available. Advanced processing techniques for ceramic Yb:YAG are currently being investigated to increase gain media resilience to intense laser irradiation for reliable operation at higher fluence levels [6]. Initial results described in this paper confirm the effectiveness of amplifier architecture design improvements and indicate that demonstration of the 100 J target specification will be achieved in the near future.

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