A cryogenic gas cooled multi-slab Yb:YAG amplifier producing 6.4 J at 10 Hz

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Abstract: We present preliminary results for DiPOLE, a cryogenic Yb:YAG DPSSL amplifier using a temporary extraction architecture. Measured average powers and optical-to-optical efficiencies already compare favourably to existing systems.

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1. Introduction

The next generation of ultra-intense laser facilities, currently being developed in European projects such as HiPER [1], and ELI [2], require laser amplifier technology capable of producing kJ-level pulses, with nanosecond duration, at multi-Hz repetition rate, and with high wall-plug efficiency. This will only be possible using diode-pumped solid-state laser (DPSSL) technology.

In previous papers [3,4] we have presented a scalable concept for a DPSSL amplifier based on cryogenic gas cooled multi-slab Yb:YAG technology with designs capable of generating kJ pulse energies. In order to demonstrate the viability of this concept, a scaled-down prototype amplifier, DiPOLE, is under development at the Central Laser Facility. The DiPOLE amplifier system is designed to deliver 10 J pulses at 10 Hz and consists of an amplifier head, with cryogenic helium gas cooling system, a pair of pump diode sources, and a front-end seed laser system. A relay imaging multi-pass extraction architecture, capable of supporting up to 9-passes, is currently under construction.

In this paper, we present preliminary pulse amplification results from DiPOLE using a temporary bow-tie extraction geometry, measured over a range of temperatures. Extraction energy measurements are used to quantify amplified spontaneous emission (ASE) losses and to refine performance predictions for the full DiPOLE system.

2. Setup

The DiPOLE amplifier head consists of four ceramic YAG discs consisting of an inner 35 mm diameter, Yb^{3+}-doped region, and an outer 10 mm thick cladding, doped with Cr^{4+} to absorb unwanted transverse fluorescence. Each disc is 5 mm thick, the doping concentration in the outer two discs is 1.1 %, and 2.0 % in the two central discs. The discs are arranged in a stack with small gaps in-between through which a turbulent flow of helium coolant is passed at a typical volume flow rate of 35 m^3/h and pressure of 10 bar. The helium gas is cooled by circulation through a liquid nitrogen heat exchanger. The amplifier is pumped from both sides by two diode laser sources each delivering 20 kW peak power pulses near 940 nm, with variable duration up to 1.2 ms, and repetition rate up to 10 Hz. The emission linewidth is less than 6 nm full-width-half-maximum (FWHM) and the central wavelength can be tuned to maximise pump absorption for specific operating conditions. The pump beams are coupled into the amplifier by reflection from a pair of dichroic mirrors that are transparent at the amplification wavelength near 1030 nm. The pump beam profile inside the amplifier is a $2 \times 2\,cm^2$ square shape, with a very uniform intensity distribution and very steep edges. The amplifier is seeded by a front-end laser system, delivering pulses of ~ 7 ns duration and > 100 mJ energy. After expanding the round beam, ~ 50 mJ are incident on the square pumped region. In the current preliminary setup the seed beam is passed through the amplifier three times in a simple bow-tie configuration.

3. Results

Fig. 1 shows the output energies obtained for different helium inlet temperatures, pump pulse durations, and repetition rates. The highest energies measured for 1 ms pump duration were 6.8 J at 1 Hz and 100 K, and 6.4 J at 10 Hz and 93 K. A comparison to modelling predictions, shown in Fig. 1(a), reveals that at low temperatures and long pump durations, ASE significantly reduces the amount of stored energy and hence the output energy. We also found that output energies were generally lower at higher repetition rate. Output energies measured for different coolant temperatures at 1 Hz and 10 Hz are compared in Fig. 1(b). This graph indicates that the observed reduction is probably a pure heating effect, caused by the increased temperature of the gain medium at higher repetition rate. This can easily be compensated for by reducing the inlet temperature of the coolant.

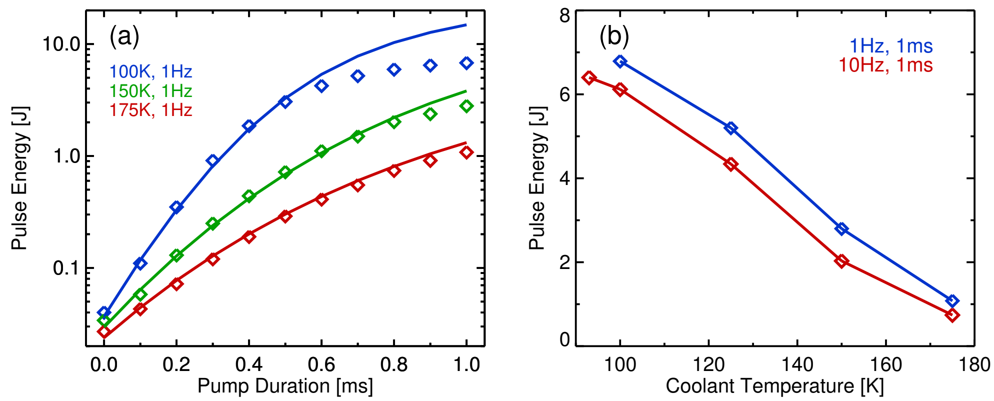

Fig. 1. Output energy as a function of pump pulse duration for different temperatures (a), and as a function of temperature for different repetition rates (b). Diamonds in (a) are measurements, and solid lines represent model predictions assuming no ASE loss.

In order to predict pulse energy levels that are obtainable with the planned refined extraction scheme which incorporates image relaying and spatial filtering, and allows up to nine extraction passes, we adapted our numerical model to take ASE losses into account. The stored energy in the model was reduced to a point where the calculated output energy at 1 ms pump duration agreed with the measured values. The model was then re-run for different numbers of extraction passes. The results shown in Fig. 2 indicate that the target output of 10 J should be comfortably within reach, with an optimum output of almost 15 J predicted for a gain medium temperature of 150 K and six extraction passes.

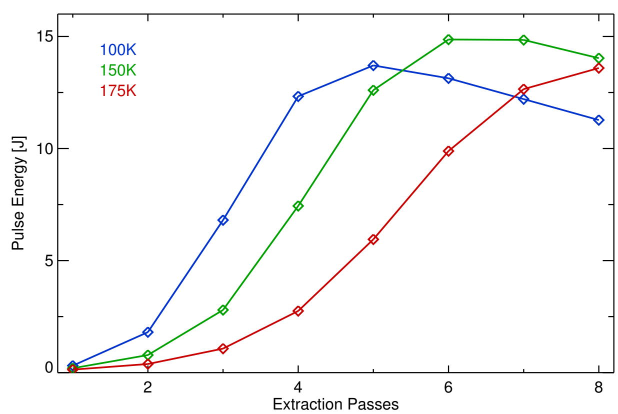

Fig. 2. Predicted output energy for different numbers of extraction passes for different temperatures.

The measured output near-field intensity profiles for the highest output energies measured are shown in Fig. 3. Despite the lack of image relaying and spatial filtering, a fairly uniform top-hat shape can be observed both at 1 Hz and 10 Hz repetition rate. The observed asymmetry is probably due to non-optimal alignment of the seed beam, which was difficult to establish due to large beam pointing fluctuations.

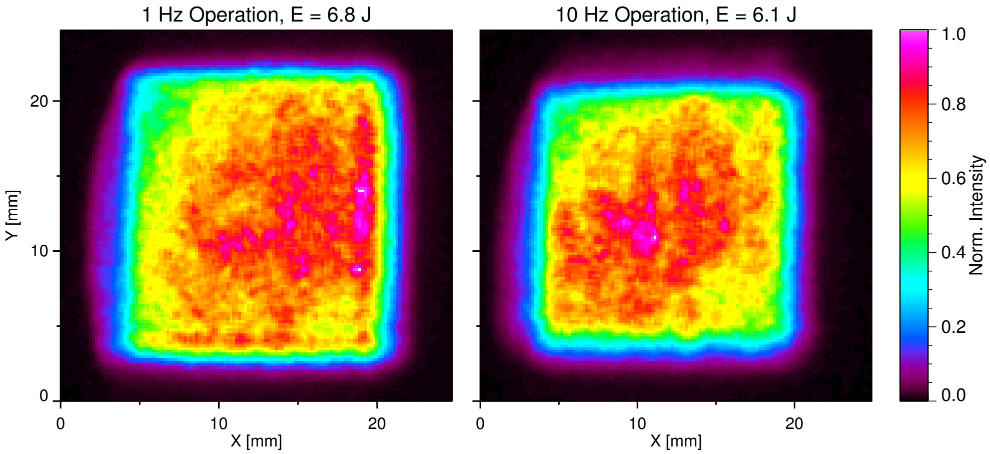

Fig. 3. Near-field intensity distribution of output beam measured at 100 K.

4. Conclusion

We have demonstrated that the DiPOLE laser system has already come very close to its target performance of 10 J output energy at 10 Hz repetition rate, which would equate to an average power of 100 W and an optical-to-optical efficiency of 25 %. Even in its current state, the measured maximum average power of 64 W and the corresponding efficiency of 16 % compare very favourably to other ongoing high-energy DPSSL projects. The respective values for average power and efficiency are 213 W and 11.7 % for HALNA [5], 1.2 W and 6 % for Polaris [6], and 20 W with unspecified efficiency for LUCIA [7]. Once the new extraction scheme is in place, $>$ 25 % efficiency should be achievable at much higher coolant temperature, which will further improve the overall efficiency of the system.

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