High-efficiency 10 J diode pumped cryogenic gas cooled Yb:YAG multislab amplifier

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We report on the first demonstration of a diode-pumped, gas cooled, cryogenic multislab Yb:YAG amplifier. The performance was characterized over a temperature range from 88 to 175 K. A maximum small-signal single-pass longitudinal gain of 11.0 was measured at 88 K. When amplifying nanosecond pulses, recorded output energies were 10.1 J at 1 Hz in a four-pass extraction geometry and 6.4 J at 10 Hz in a three-pass setup, corresponding to optical to optical conversion efficiencies of 21% and 16%, respectively. To our knowledge, this represents the highest pulse energy so far obtained from a cryo-cooled Yb-laser and the highest efficiency from a multijoule diode pumped solid-state laser system.

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Multijoule- to kilojoule-class lasers are pivotal to the advancement of ultrahigh-intensity laser–matter interaction studies such as particle acceleration, intense x-ray generation and inertial confinement fusion. If operated at high repetition rate and high overall efficiency, these lasers offer the potential for development of viable real-world applications. For example, inertial fusion energy production, which is under investigation in the HiPER project, or to generate ultrashort, ultrabright sources of radiation and particles, in projects such as the Extreme Light Infrastructure (ELI). Current kilojoule-class laser facilities such as the National Ignition Facility (NIF) rely on flashlamp pumped Nd:glass technology, which exhibits very poor electrical-to-optical efficiency and can only be operated at very low repetition rates (few shots per day). Therefore, a new approach in the form of diode pumped solid-state laser (DPSSL) systems, using advanced gain media and cooling schemes, is required to overcome these limitations. Current and previous high-energy DPSSL development projects include mercury with average power and efficiency values of 550 W and 7.6% [1], LUCIA with 20 W and 5.7% [2], HALNA with 213 W and 11.7% [3], and Polaris with 1.2 W and 6% [4]. In a previous publication we have presented our conceptual design of a scalable diode pumped, gas cooled, cryogenic multislab Yb:YAG amplifier [5], capable of generating kilojoule-class pulse energies. In order to demonstrate the viability of this concept, a scaled-down prototype, Diode Pumped Optical Laser Experiment (DiPOLE), is currently under development. In this paper, we present first results obtained over a temperature range from 88 to 175 K.

Figure 1 shows a schematic diagram of the DiPOLE system. A Yb: CaF_2 cavity-dumped oscillator, tuneable from 1025 to 1040 nm with a spectral bandwidth of 0.2 nm, was used as the seed source, delivering up to 180 μJ at 1030 nm and 10 Hz in a 10 ns (FWHM) pulse duration. The oscillator output was expanded to a 2 mm diameter beam and further amplified by a thin-disk Yb:YAG multipass preamplifier. This consisted of a 2 mm thick, 2.5 at.% doped Yb:YAG crystal arranged in an active mirror configuration, which was pulse pumped by a 940 nm, 2 kW peak power, diode stack for 1 ms duration. An image-relaying multipass architecture, reported earlier [6] was used to double-pass the gain medium seven times. The preamplifier delivered 107 mJ at 10 Hz with an M^2 value of 1.3.

The DiPOLE main amplifier head contained four ceramic YAG disks (Konoshima), each with a diameter of 55 mm and a thickness of 5 mm. The disks consisted of a 35 mm diameter Yb-doped inner region that is surrounded by a 10 mm wide Cr^{4+}-doped cladding to minimize amplified spontaneous emission (ASE) loss and prevent parasitic oscillations at high gain. The inner two disks had a higher Yb doping of 2.0 at.% than the outer two disks at 1.1 at.%. The thickness and doping levels were chosen to maximize optical efficiency while maintaining an acceptable level of ASE loss at the amplifier's design temperature of 175 K [7]. The disks were held in aerodynamically shaped vanes and arranged in a stack with 1.5 mm gaps in-between disks. Helium gas at cryogenic temperature was forced through the gaps at a typical volume flow rate of 35 m^3/h and pressure of 10 bar. The helium gas was cooled by passing it through a liquid nitrogen heat exchanger and circulated by a cryogenic fan (Cryozone). The amplifier was pumped from both sides by two 940 nm diode laser sources (Ingeneric,

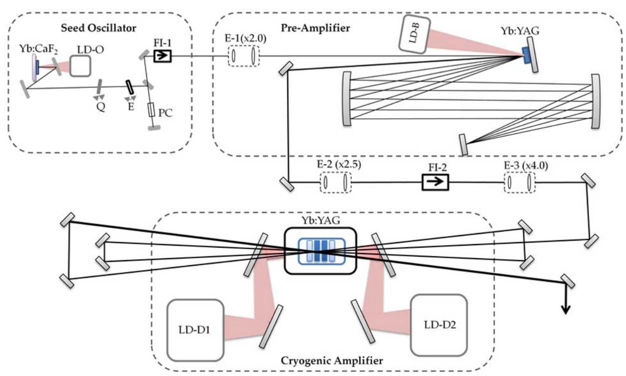

Fig. 1. (Color online) Schematic diagram of the DiPOLE system.

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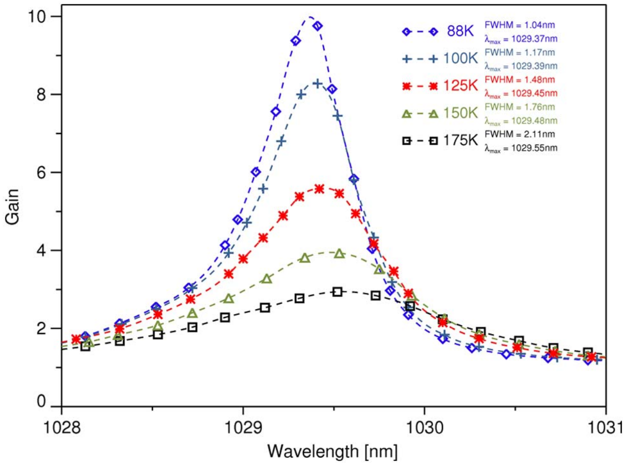

Fig. 2. (Color online) Small-signal single-pass gain for the main amplifier at different temperatures measured at 10 Hz and 1 ms pump duration.

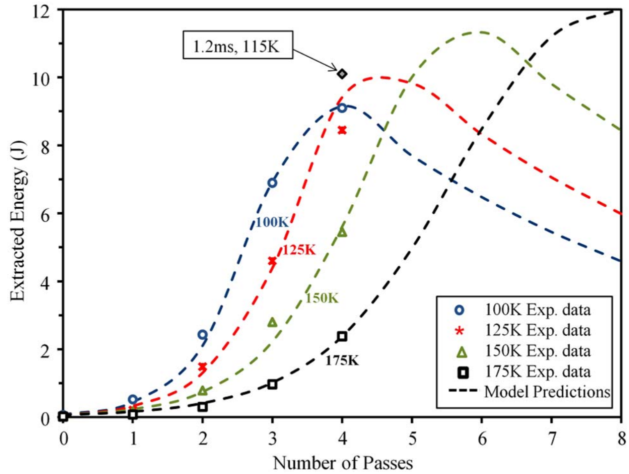

Fig. 4. (Color online) Predicted output energy of the DiPOLE amplifier for eight passes along with the experimental values measured for up to four passes at different temperatures for 1 Hz operation and 1 ms pump pulse duration.

Jenoptik, and Amtron) each delivering 20 kW peak power with variable pulse duration up to 1.2 ms and repetition rate up to 10 Hz. The emission spectrum of the diode sources was less than 6 nm (FWHM) wide. The pump sources produced a $20\ \mathrm{mm} \times 20\ \mathrm{mm}$ square, flat-top beam profile at their image plane, which was arranged to lie at the center of the amplifier head.

A low power cw external cavity tuneable diode laser (ECDL, Sacher TEC520), was employed for small-signal gain measurements of the DiPOLE amplifier. Figure 2 shows the wavelength dependence of the measured single-pass, small-signal gain for different operating temperatures when pumped for 1 ms at 10 Hz and 40 kW peak power. The gain increased with decreasing temperature, owing to the increase in emission cross-section. A maximum small-signal single-pass gain of 9.8 was recorded at 88 K, increasing to 11.0 for 1.2 ms pump duration. However, this was accompanied by a reduction in gain bandwidth to 1.04 nm (FWHM) at 88 K, approximately half the value measured at 175 K, along with a blue shift of the peak gain wavelength by 0.18 nm.

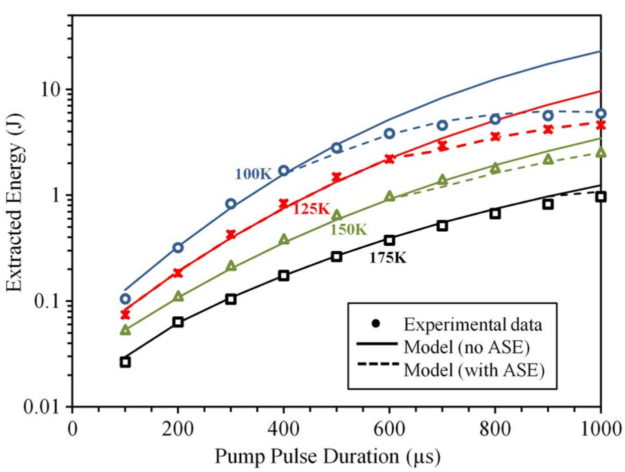

Fig. 3. (Color online) Extracted energy as a function of pump pulse duration measured at different temperatures for 1 Hz operation in a three-pass configuration.

For nanosecond-pulse amplification studies, the main amplifier was seeded by the pulsed output from the preamplifier. The circular beam was expanded to overfill the $20\ \mathrm{mm} \times 20\ \mathrm{mm}$ square pumped region within the amplifier, the energy after beam expansion was approximately 60 mJ. A simple bow-tie arrangement was then installed to pass the seed beam through the amplifier up to four times, as shown in Fig. 1. Figure 3 shows the measured output energy for different operating temperatures as a function of pump pulse duration for a three-pass configuration. Numerical model predictions with and without the inclusion of ASE losses are also shown. The performance of the system was modelled as described in [7] along with empirically derived ASE loss values.

Figure 4 shows the predicted output energy as a function of the number of extraction passes for a pump duration of 1 ms. Experimental values for extracted energy

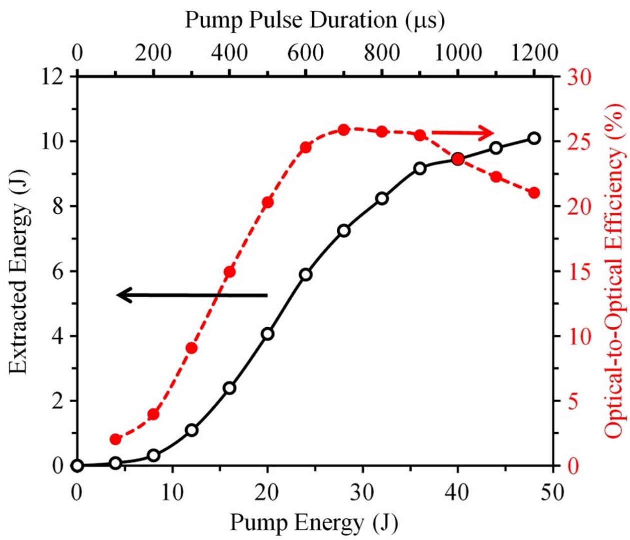

Fig. 5. (Color online) Extracted pulse energy (solid line) and $\eta_{o\text{-}o}$ (dotted line) of the DiPOLE amplifier for up to 1.2 ms pump pulse duration at 1 Hz, four passes and 115 K coolant temperature.

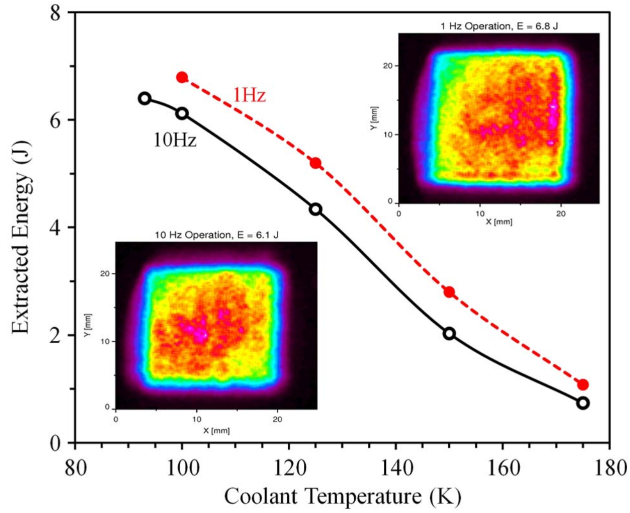

Fig. 6. (Color online) Extracted energy from the main amplifier at 1 and 10 Hz pulse repetition rates for a three-pass extraction setup at different temperatures and for fixed pump pulse duration of 1 ms. Inserted are the typical beam profiles for 1 and 10 Hz after the main amplification stage.

measured for up to four passes, at different temperatures and at 1 Hz repetition rate, are also included in the graph. At 100 K, the maximum energy predicted and observed was clamped at 9.1 J in a four-pass configuration owing to increased ASE losses. However, at the higher design temperature of 175 K, pulse energy as high as 12 J is expected for eight passes.

In a separate experiment with the pump pulse duration increased to 1.2 ms, the amplifier delivered 10.1 J at 115 K with a repetition rate of 1 Hz, which corresponds to an optical-to-optical efficiency ($\eta_{o\text{-}o}$) of 21%. Figure 5 shows extracted pulse energy and $\eta_{o\text{-}o}$ as a function of pump energy. Here the amplifier was operated in a four-pass configuration and the pump energy was varied by changing the pump pulse duration at constant total pump power of 40 kW.

Figure 6 compares the output energy from the amplifier at 1 and 10 Hz pulse repetition rates for a three-pass extraction setup over a range of operating temperatures and for a fixed pump pulse duration of 1 ms. The dependence of extracted energy on coolant temperature is similar for both 10 and 1 Hz operation, with an offset of approximately 8 K. This offset is believed to be caused by an increase in gain medium temperature due to the additional heat load at 10 Hz operation. This can be compensated by reducing the inlet temperature of the coolant, thus restoring performance to a level similar to that at 1 Hz operation. For 10 Hz operation, the highest pulse energy recorded was 6.4 J, in three-pass configuration, at a coolant temperature of 93 K. This corresponds to an average power of 64 W and an $\eta_{o\text{-}o}$ of 16%. At this operating temperature, approximately 80 K below the design temperature, output energy and efficiency were limited by ASE loss. A relay-imaging multipass extraction architecture, capable of supporting up to nine passes, is currently being installed. This will increase $\eta_{o\text{-}o}$ by maintaining a better overlap between pump and extraction beams and, more importantly, by enabling operation at higher coolant temperatures with reduced gain and ASE loss.

In summary, we have demonstrated 10.1 J at 1 Hz (four pass) and 6.4 J at 10 Hz (three pass) from a diode pumped, gas cooled, cryogenic multislab Yb:YAG amplifier with an $\eta_{o\text{-}o}$ of 21% and 16%, respectively. This confirms the viability of multislab cryogenic amplifier concept, which is scalability to the kilojoule level. Further increases in average power to greater than 100 W and optical-to-optical efficiency greater than 25% are expected at the design temperature of 175 K.

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