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A cryogenic gas cooled multi-slab Yb:YAG amplifier producing 5.9 J at 1 Hz

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Abstract: We present preliminary amplification results for the DiPOLE cryogenic gas cooled multi-slab ceramic Yb:YAG amplifier over a range of temperatures from 88 to 175K using a temporary bow-tie multi-pass extraction architecture.
OCIS codes: (140.3280) Laser amplifiers; (140.3480) Lasers, diode-pumped, (140.3615) Lasers, ytterbium

1. Introduction

The next generation of ultra-intense laser facilities, currently being developed in European projects such as HiPER [1] and ELI [2], require the development of a laser amplifier technology capable of producing kJ-level pulses with nanosecond duration at multi-Hz repetition rate and with high wall-plug efficiency, which is only 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 lasers, a front-end seed laser system and a relay imaging multi-pass extraction architecture, capable of supporting up to 9-passes, which is currently under construction.

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

2. Experimental setup and results

Fig.1 shows a schematic of the experimental setup used to test the current performance of the DiPOLE system. The amplifier head consists of four ceramic YAG discs each 55 mm in diameter and 5 mm thick. The inner 35 mm diameter region is doped with Yb^{3+} and the outer 10 mm thick cladding is doped with Cr^{4+} to absorb unwanted transverse fluorescence. To equalise the heat load in the amplifier, when pumped from both sides, the two outer discs have a lower Yb doping concentration compared to the central discs of 1.1 at.% and 2.0 at.%, respectively. These doping levels have been carefully chosen to maximise pump absorption and storage efficiency whilst minimising the level of ASE loss in the amplifier at its design temperature of 175K. The discs are held in aerodynamic vanes each separated by a small gap to ensure a uniform turbulent flow of helium coolant is maintained between the faces of the discs. The helium gas is cooled by circulation through a liquid nitrogen heat exchanger inside a cryostat and is then flown through the amplifier head at a typical volume flow rate of 35 m^3/hr and pressure of 10 bar.

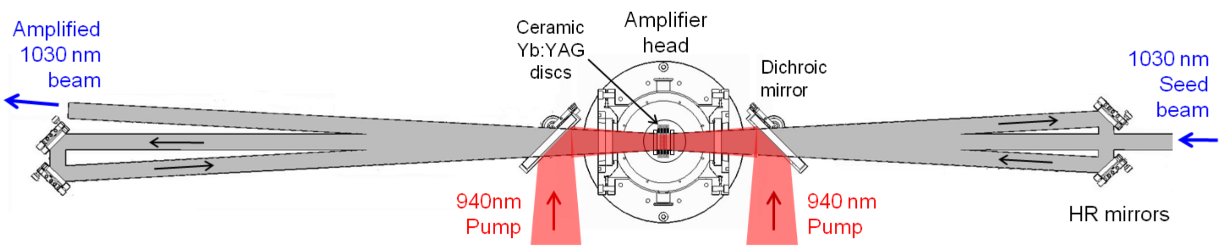

Fig. 3. Schematic of experimental setup showing the temporary 3-pass bow-tie extraction scheme.

The amplifier head is pumped from both sides by two pump diode lasers 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 the chosen amplifier operating temperature. The pump beams are coupled into the amplifier head by reflection from a pair of dichroic mirrors that are transparent at the amplification wavelength near 1030 nm. The pump lasers provide uniform illumination of a 2 x 2 cm^2 square region within the amplifier corresponding to a total peak pump intensity of 10 kW/cm^2.

Before pulse amplification experiments were undertaken an assessment of small signal gain and its dependence on temperature and wavelength was made to identify optimum seed wavelength characteristics. For this the collimated beam from a wavelength-tuneable cw external cavity diode laser (Sacher TEC-520-1060-080) was passed once through the amplifier. The amplified signal was then measured on a photodiode after appropriate spectral and spatial filtering was applied to remove residual pump radiation and reduce background fluorescence. Fig. 2 shows the spectral dependence of small signal gain measured over a range of temperatures between 88K and 175K.

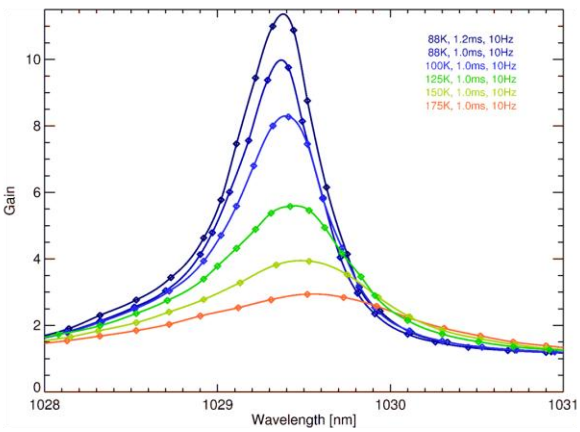

Fig. 2. Spectral dependence of small signal gain measured over a range of temperatures for operation at 10 Hz.

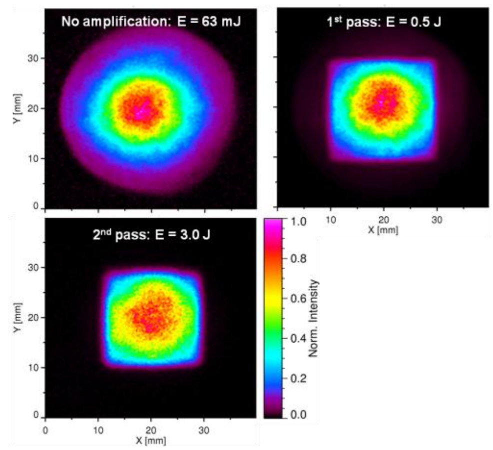

Fig. 3. Spatial profiles after 2-passes through the amplifier measured at 100K and 1 Hz.

It is clear from Fig. 2 that as the amplifier temperature is reduced the optimum seed wavelength shifts to shorter wavelengths and the width of the gain spectrum narrows. A maximum small signal gain of 12.5 was measured at a temperature of 88K using a pump pulse duration of 1.2 ms. The measured small signal gain at the design temperature of 175K was 3.2.

For the pulse amplification experiments the amplifier was seeded by a front-end laser system [4], supplied by onemicron laser [5], consisting of a cavity-dumped Yb:glass oscillator and a multi-pass Yb:YAG thin-disc booster amplifier. This system delivers 100 mJ output pulses of between 5 and 10 ns duration at up to 10 Hz repetition rate in a near diffraction limited beam. The output is tuneable between 1028 nm and 1032 nm, with a linewidth of 0.2 nm, and the seed wavelength was selected to maximise gain at the chosen operating temperature of the amplifier. Prior to injection the seed beam passes through a Faraday isolator and is then expanded to overfill the pumped region in the amplifier. The energy of the amplified beam after each pass is measured directly by positioning a diverging lens followed by a pyroelectric detector (Gentec QE50-LP) with ceramic attenuator in the relevant beam path. Single-side anti-reflection (AR) coated fused silica discs are inserted into the beam path at various points to sample the amplified beam and enable spatial profile monitoring.

Fig. 3 shows spatial profiles measured after the first pass through the amplifier, with and without amplification, and after the second pass at an operating temperature of 100K and 1 Hz repetition rate. The Gaussian nature of the seed beam is clearly evident in the spatial profile shown with no amplification, i.e. with the pump beams switched off. This profile is gradually transformed into a squarer shaped beam with each pass through the pumped amplifier, reflecting the well defined square shape of the gain region produced by the pump. A maximum pulse energy of 3 J was measured after two passes, which reduced to 2.7 J when operated at 10 Hz, although this energy difference could be recovered by reducing the amplifier temperature slightly.

The measured extraction energy for the 3-pass geometry over a range of temperatures and pump pulse durations is shown in Fig. 4. At the time 3-pass extraction was restricted to operation at 1 Hz as the energy detector used could not handle more than 30 W average power and a suitable beam dump capable of handling higher powers at 10 Hz was not available. The maximum pulse energy obtained at 1 Hz was 5.9 J at 100K compared to 1 J at 175K, both achieved at a pump pulse duration of 1 ms. From the plots it is clear that at 100K (75K below the design temperature) the gain is sufficiently high that ASE losses become significant for pump pulse durations longer than approximately 0.5 ms. Despite the increase in pump energy with pulse duration, the corresponding rise in ASE loss limits the level of stored energy resulting in the saturation effect observed. A minimal level of ASE loss is observed at the design temperature of 175K.

Also shown in Fig. 4 are predicted performance curves obtained from our numerical model, details of which have been reported previously [3,6]. The solid curves show model predictions with no ASE and the dashed curves represent predictions from a revised model that includes an ASE loss term, which increases the loss in each disc as a non-linear function of the single-pass gain. The precise dependence has been determined from a fit to the measured data at 100K and corresponding performance predictions are in reasonable agreement with measured data at 150K and 175K. The revised model was then used to refine performance predictions for the full DiPOLE system employing the relay-imaging multi-pass extraction architecture and these simulation results are shown in Fig. 5, along with experimental data obtained to date at 1 Hz for a pump pulse duration of 1 ms. These curves indicate that the target energy of 10 J is achievable at operating temperatures above 125K once more amplifier passes are available.

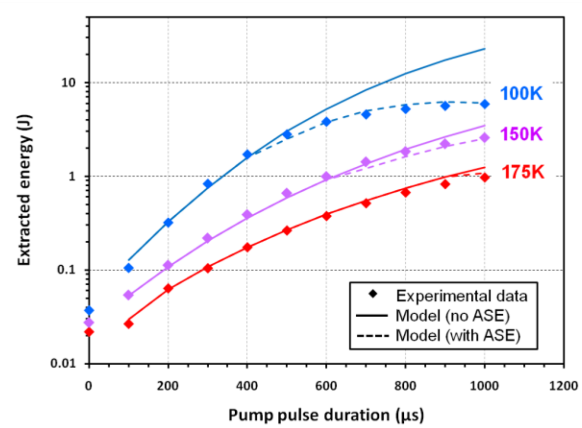

Fig. 4. Measured and predicted extraction energy for 3-pass configuration measured a 1 Hz.

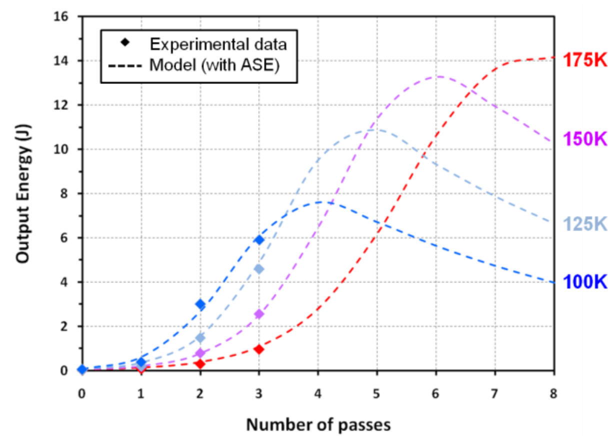

Fig. 5. Predicted performance of full DiPOLE system employing multi-pass relay-imaging extraction architecture.

4. Conclusion

Preliminary performance results from the DiPOLE amplifier are very encouraging and give confidence that the target specification of 10 J at 10 Hz will be achievable at the design temperature of 175K once the relay-imaging multi-pass is installed. Installation of the relay-imaging multi-pass is scheduled to be completed before the end of 2011. The refined model of our cryogenic gas cooled multi-slab Yb:YAG amplifier is now being used to optimise designs for a 100 J and 1 kJ amplifier system.

5. References

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