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Report on characterization of amplifier optical parameters

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Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	R
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PU

A. Abstract / Executive Summary

The objective of this deliverable is to characterize two prototype test bed amplifiers operating at 10 J at 10 Hz with a diode pumped solid state laser amplifier that can be scaled to 1kJ systems.
There are two concepts being developed to achieve this goal. The first prototype is being built with a multi disk concept based on transmission of the seed beam. This also incorporates active cooling of the amplifier medium by Helium flow over the large surface of the slabs. The second concept is based on the active mirror concept where the cooling is achieved by cooling the back surface of the disk while pumping and extraction occur through the front surface in reflection mode. These are being developed respectively within the DiPOLE and LUCIA programs of STFC CLF and CNRS-LULI partners. The main differences are the gas pressure, the number of gain medium elements, as well as the cooled surfaces: One ceramics cooled on a single face with 0.1 Atm in LUCIA, and up to 5 slabs cooled on both faces with high pressure (>1 Atm) in DiPOLE.

B. Dipole Deliverable Report

1 Introduction
This section describes the 10 J DiPOLE amplifier and the current state of the setup. This is written by Jonathan Phillips from Central Laser Facility STFC.

2 Objectives
The objectives were to assembly the components that were delivered and to produce 10 J output at 1 Hz, to test the viability of all the components.

3 Work performed / results / description
We provide performance details of the 10J amplifier when used with an extraction source consisting of a Yb:CaF_2 cavity dumped, tuneable oscillator, tuneable from 1025-1040 nm with a spectral bandwidth of 0.2 nm. This source delivered up to 280 uJ at 1030 nm and 10 Hz in a ns (FWHM) pulse duration.
The oscillator output was expanded to a 2 mm diameter beam and further amplified by a thin-disk Yb:YAG multi-pass pre-amplifier. 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. The pre-amplifier delivered 107 mJ at 10 Hz with an M2 value of 1.3. This is shown in Figure 1, which also shows the bow-tie arrangement of the main amplifier.
The DiPOLE main amplifier head contained four ceramic YAG disks (Konoshima) each with a diameter of 55 mm and a thickness of 5 mm, as previously described in the last report. 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. 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, 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 mm × 20 mm square, flat-top beam profile at their image plane, which was arranged to lie at the centre of the amplifier head.
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 x 20 mm square pumped region within the amplifier, the energy after the beam expansion was approximately 60 mJ. A simple "bow-tie" arrangement was then installed to pass seed beam through the amplifier up to 4 times as shown in Figure B 3-1.

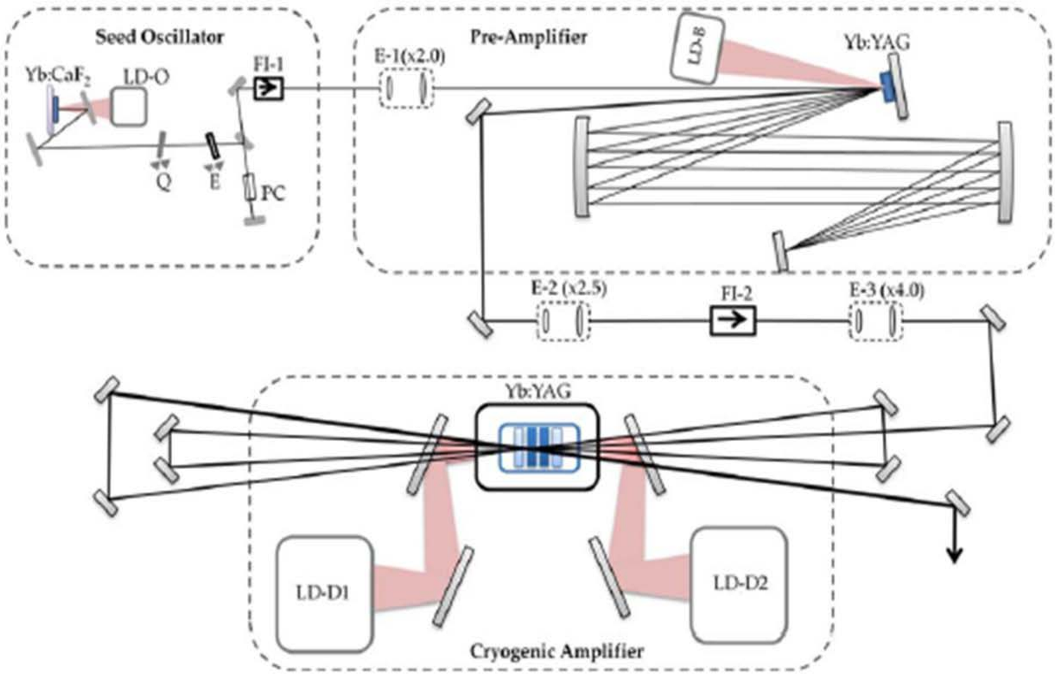

Figure B 3-1 Schematic diagram of DiPOLE system

Figure B 3-2 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 measured for up to 4 passes, at different temperatures and at 1 Hz repetition rate, are also included in the graph. To obtain enough gain for this low number of passes, the amplifier was operated at temperatures as low as 100 K, at which point significant ASE losses are expected. At 100 Kelvin, the maximum energy predicted and observed was clamped at 9.1 J in a 4-pass configuration owing to increased ASE losses.

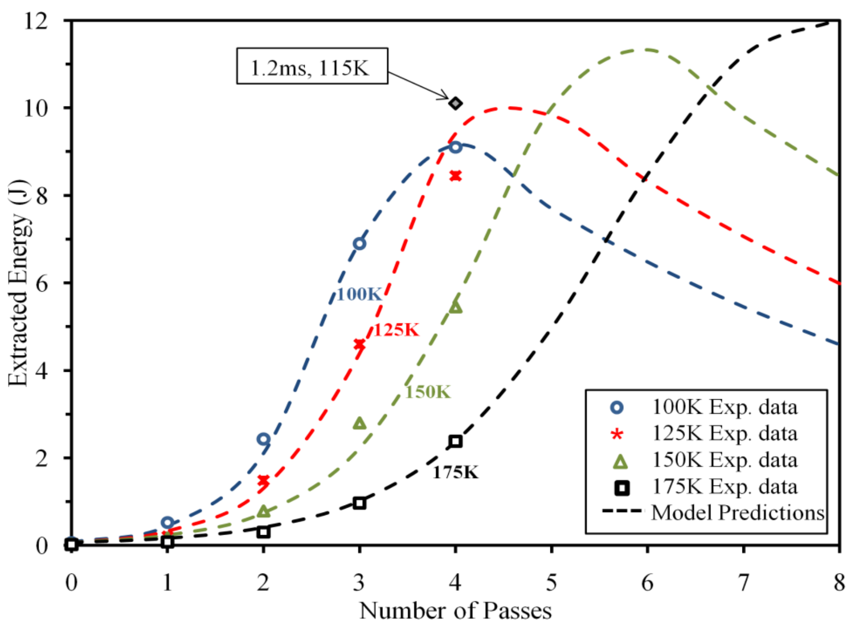

Figure B 3-2 Predicted output energy of the DiPOLE amplifier for eight passes along the experimental values measured for up to four passes at different temperatures for 1 Hz operation and 1 ms pump pulse duration.

In a separate experiment with the pump pulse duration increased to 1.2 ms, the amplifier delivered 10.1 J at 115K with a repetition rate of 1 Hz, which corresponds to an optical –optical efficiency (η_{0-0}) of 21%. Figure B 3-3 shows extracted energy and n0-0 as a function of pump. Here the amplifier was operated in a four pass configuration and pump energy was varied by changing the pump pulse duration at constant total pump power of 40 KW.

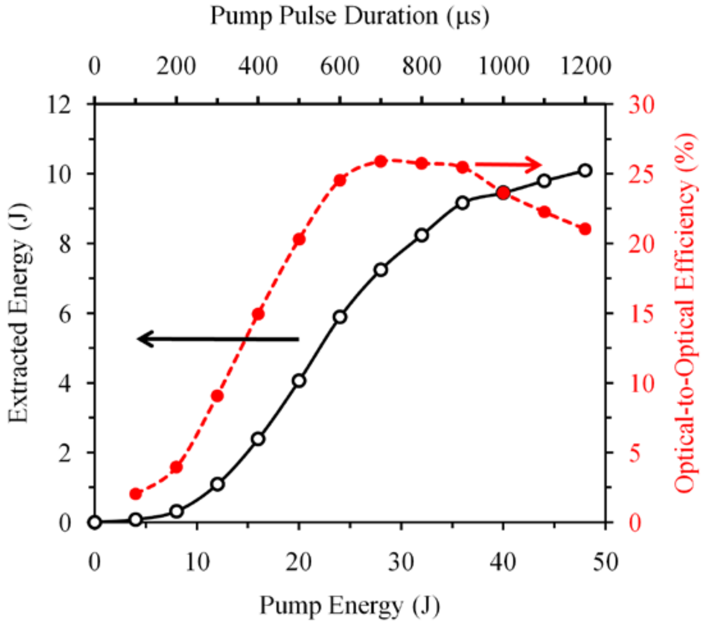

Figure B 3-3 Extracted pulse energy (solid line) and $\eta_{0\text{-}0}$ ~(dotted line) of the DiPOLE amplifier for up to 1.2 ms pump pulse duration at 1 Hz, four passes and 115 K coolant temperature.

Figure B 3-4 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. 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 a 6.4 J, in the three pass configuration, at a coolant temperature of 93 K. This corresponds to an average power of 64 W and an $\eta_{0\text{-}0}$ of 16%. At this operating temperature approximately 80 K below the design temperature, output energy and efficiency are limited by ASE loss. A relay imaging multi-pass extraction architecture, capable of supporting of up to nine passes, is currently being installed. This will increase $\eta_{0\text{-}0}$ by maintaining a better overlap between pump and extraction beams, more importantly by enabling operation at higher coolant temperatures and reduced gain and ASE loss.

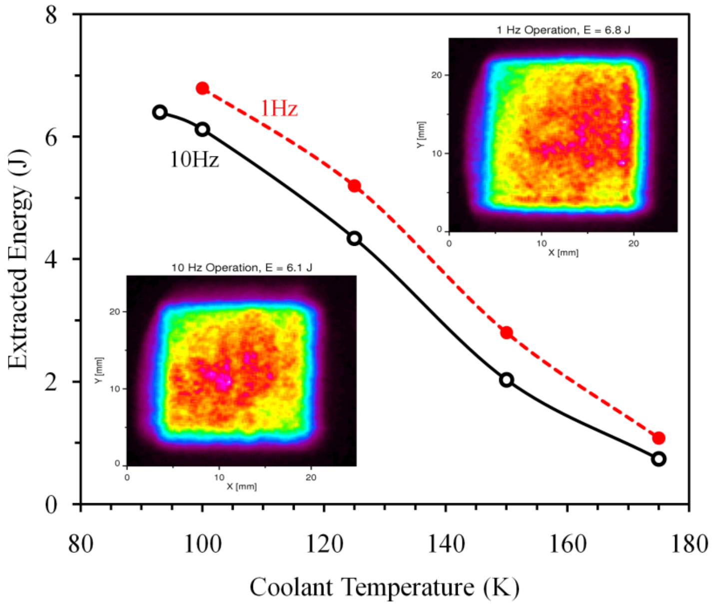

Figure B 3-4 Extracted energy from the main amplifier at 1 and 10 Hz pulse repetition rates for a three-pass extraction setup at different temperatures and for the fixed pump pulse duration of 1 ms. Inserted are the typical beam profiles for 1 and 10 Hz after the main amplifier.

4 Conclusions

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 multi-slab Yb:YAG amplifier with an $\eta_{0\text{-}0}$ of 21% and 16% respectively. This confirms the viability of multi-slab cryogenic amplifier concept, which is scalability to the kilojoule level. Further increases in average power to greater than 100 W and optical and optical efficiency greater than 25% are expected at the design temperature of 175 K.

5 References/Publications

Saumyabrata Banerjee, Klaus Ertel, Paul D. Mason, P. Jonathan Phillips, Mathias Siebold, Markus Loeser, Cristina Hernandez-Gomez, and John L. Collier, "High-efficiency 10 J diode pumped cryogenic gas cooled Yb:YAG multislab amplifier," Opt. Lett. **37**, 2175-2177 (2012)
http://dx.doi.org/10.1364/OL.37.002175
Open access

C. LUCIA Deliverable Report

1 Introduction

This section is dedicated to LULI-CNRS Lucia DPSSL laser chain low temperature power amplifier study. This is written by Jean-Christophe Chanteloup from the CNRS LULI laboratory. The Lucia laser chain relies on two main amplifier, the first one operating at room temperature (~300K) while the second one is a prototype able to operate at a temperature down to 80K.

2 Objectives

The objective of this deliverable is to explore Lucia low temperature amplifier gain performances when operated at temperature below 300K. After a first comparison between Yb^{3+}:YAG crystal gain medium and Cr^{4+}/Yb^{3+}:YAG ceramic, the impact of the operating wavelength is evaluated.

3 Work performed / results / description

3.1 Absorption properties

Ensuring ASE generated parasitic oscillation is performed through the use of a co-sintered Cr^{4+}/Yb^{3+}:YAG ceramic as pictured on figure C 3-1 of Deliverable 20 report. Absorption spectrum is given on figure C 3-1 below.

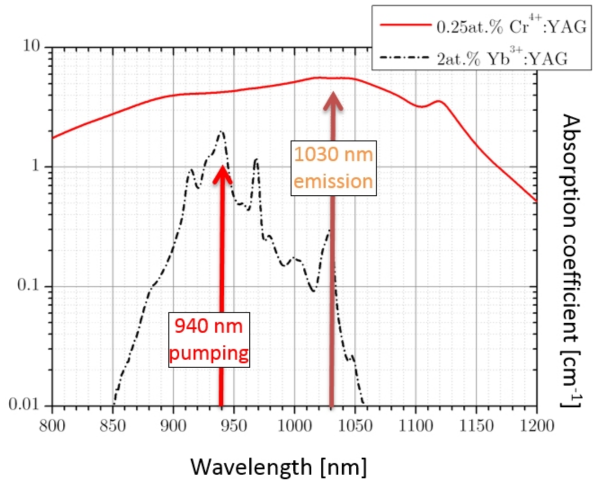

Figure C 3-1. Cr^{4+}:YAG and Yb^{3+}:YAG absorption spectrum

3.2 Single pass gain curve at 1030.3 nm

Comparative ability to mitigate parasitic oscillations was first evaluated for both a single crystal Yb^{3+}:YAG disk and the above mentioned co-sintered ceramic. In both cases, the doping level in Yb^{3+} was 2 at%. While a clear gain saturation can be observed in the crystal case (figure C 3-2), the situation appears much more satisfying in the ceramic case (figure C 3-3). For both experiments, the pump duration is limited to 1 ms (blue area on the graphs).

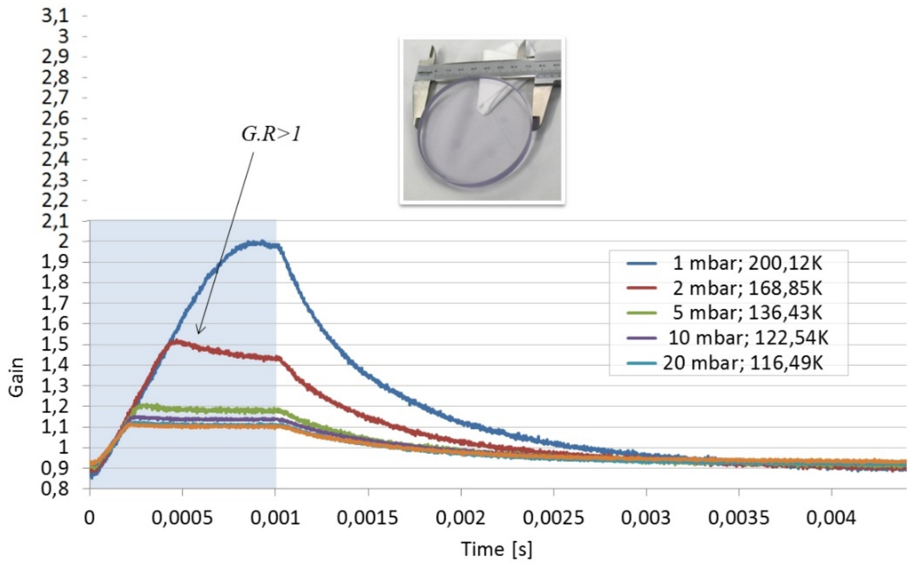

Figure C 3-2. Crystal Case. Single pass gain curves recorded when using a 1030.3 nm seed source; the Helium gap is 147 µm; the pump brightness is 5.5 kW/cm²; the repetition rate 2 is Hz.

A 50% increase in gain available after 1 ms pumping is observed when using the ceramic.

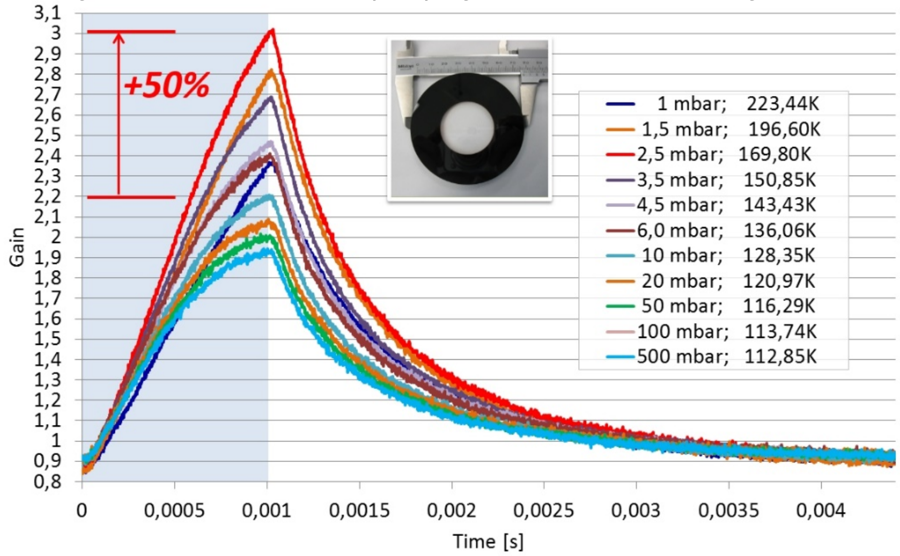

Figure C 3-3. Ceramic case. Single pass gain curves recorded when using a 1030.3 nm seed source; the Helium gap is 157 µm; the pump brightness is 5.5 kW/cm²; the repetition rate 2 is Hz.

Figure C 3-4 give the distribution of maximum gain values obtained with the ceramic. While reducing the temperature a clear increase in gain takes place down to 160K. Below a rapid decrease occurs, which can be related to the seed wavelength mismatch as illustrated Ion figure C 3-5.

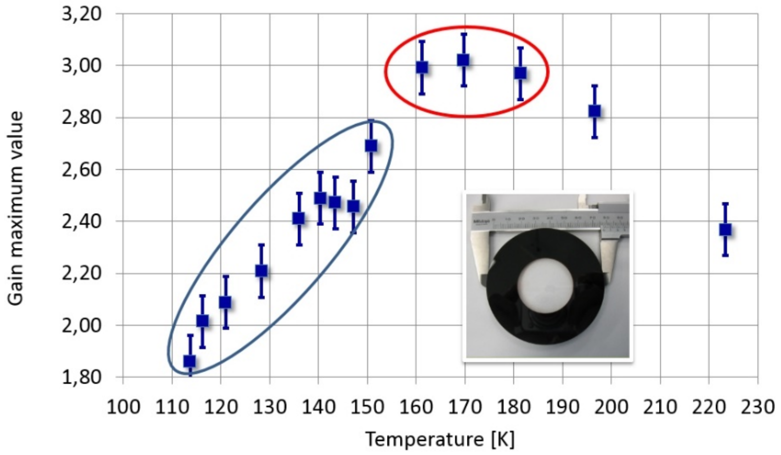

Figure C 3-4. Maximum single pass gain value versus temperature for the ceramic. Optimum value occurs in the 160-180K range (red circled)

When decreasing the temperature, Yb^{3+}:YAG peak emission wavelength shift toward the low blue side of the spectrum. This phenomenon is illustrated on figure C 3-5. The source used for these experiment so far could not be tuned at a lower value than 1030.28 as illustrated on figure C 3-6. This wavelength mismatch at temperature below 160 K explain the low values for the data points circled in blue on figure C 3-4.

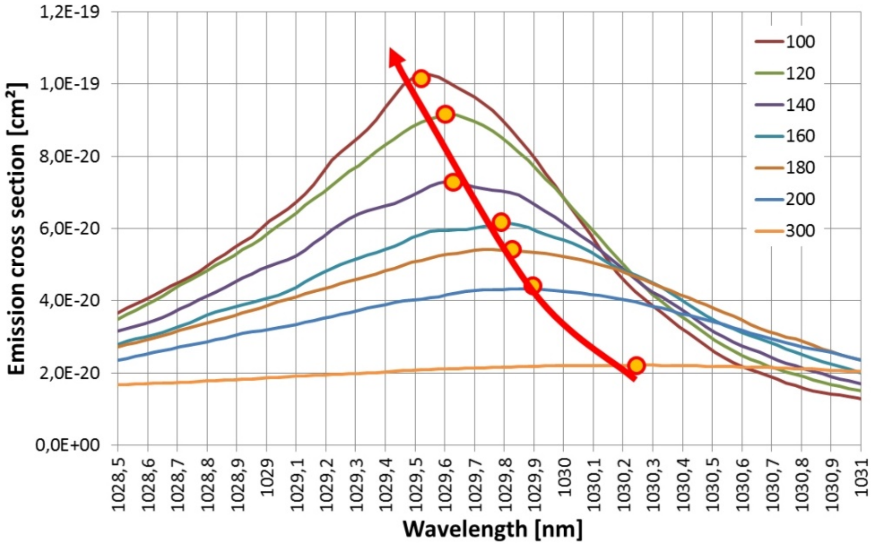

Figure C 3-5. Yb:YAG emission spectrum versus temperature. Data fom F.Schiller Universität, Jena, Germany.

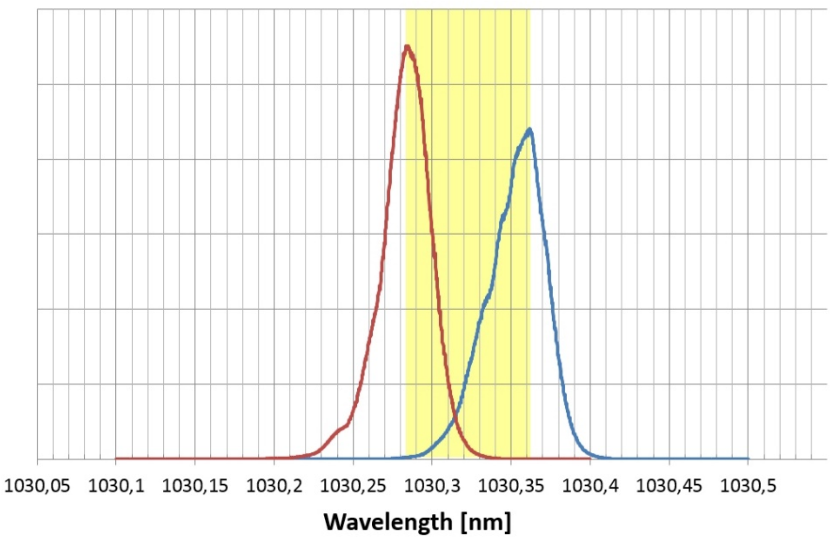

Figure C 3-6. NP Photonics 80 mW CW source spectrum. The source is tuneable between 1030.28 nm and 1030.36 nm

3.3 Single pass gain curve at 1029.6 nm

In order to explore the gain performances of our low temperature operated amplifier we then turned to a second seed source allowing us to explore bluer wavelength down to 1029.6 nm as illustrated on figure C 3-7.

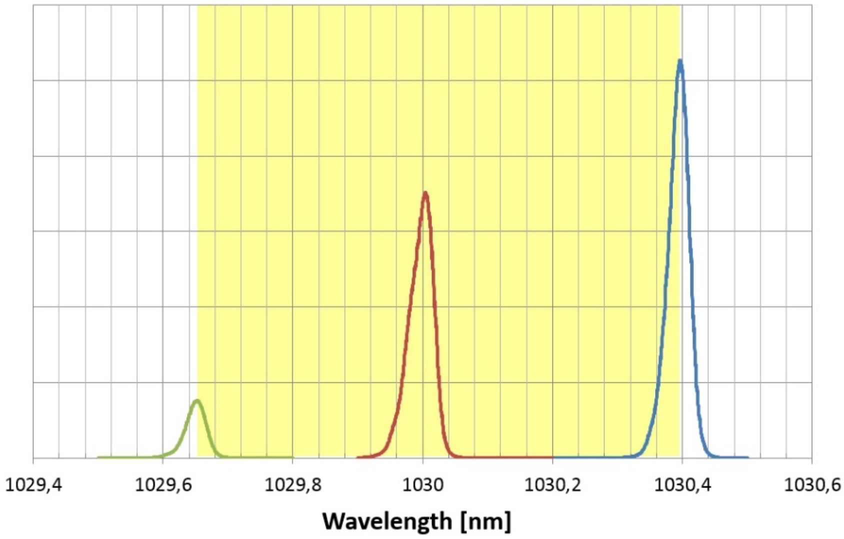

Figure C 3-7. NKT 30 mW CW source spectrum. The source is tuneable between 1029.6 nm and 1030.4 nm

Much higher gains reaching values close to 20 were then reachable.

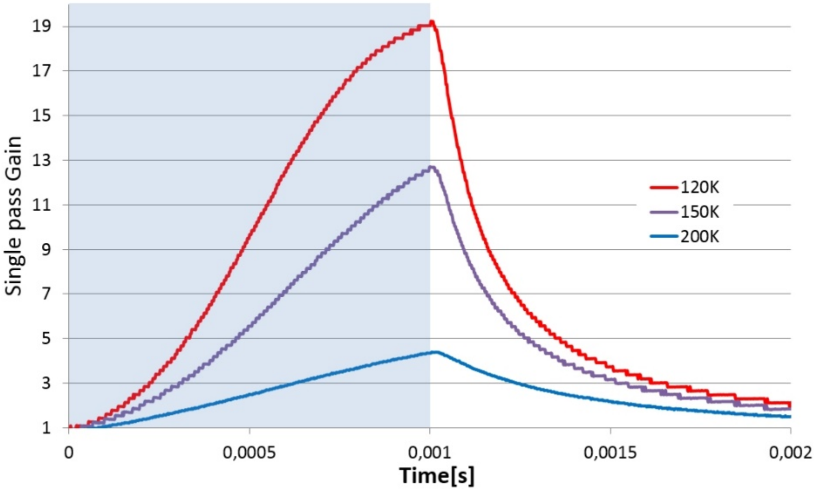

Figure C 3-8. Single pass gain recorded with the ceramic with a 1029.65 nm seed.

4 Conclusions

The clear advantage offered by co-sintered Cr^{4+}:Yb^{3+}:YAG ceramic over Yb^{3+}:YAG crystal in terms of ASE management was demonstrated. Reaching high gains with the low temperature amplifier required to work with a seed source tuneable to low wavelengths in order to take into account Yb^{3+}:YAG peak emission wavelengths shift at low temperatures. Gain values close to 20 in a single pass were achieved.

5 References/Publications

T. Gonçalvès-Novo, S. Marrazzo, B. Vincent and J.-C. Chanteloup, “Low temperature active mirror crystal vs ceramic Yb:YAG laser amplifier gain comparison”, International Conference on Ultrahigh Intensity Lasers 2014, Goa, India, October 12-17 2014.