

Low temperature diode pumped active mirror Yb³⁺:YAG disk laser amplifier studies

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Abstract: An experimental study of a static helium gas gap heat switch concept for laser amplification is presented. High single pass gains with large co-sintered ceramic Yb:YAG disks are recorded in the 80-200K temperature range on a diode pumped active mirror amplifier.

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1. Introduction

High average power and energy Diode-Pumped Solid-State Lasers (DPSSL) have been driving strong and continuous interest among the laser physicist community over the past decade. Whereas early stage work on DPSSL was confined on room temperature operated programs [1–4] with a still un-surpassed record average power set at 550W (55J/10Hz) with the Mercury project [2], a crucial shift took place in the recent years when almost all teams

moved towards DPSSL chains relying on at least one low temperature (100 to 200K) operated amplifier [5–10].

Tradeoffs between thermal management, extraction efficiency, Laser damage threshold and Amplified Spontaneous Emission (ASE) [11,12] management are at the core of DPSSL amplifier engineering and design [13]. The Laboratoire pour l'Utilisation des Lasers Intenses (LULI) has been engaged in the development of a DPSSL chain named Lucia where amplifying stages rely on Yb³⁺:YAG active mirrors cooled from the High Reflectivity (HR) coated back surface [7,14].

Thermal and ASE issues specific to this architecture are detailed in [15,16]. The mitigation of ASE deleterious effect (like parasitic lasing) can be performed through several well-known approaches [17–19] when operation takes place at room temperature. On the other hand, operating in the 100-200K range makes it almost inevitable to rely on co-sintered Cr⁴⁺/Yb³⁺:YAG ceramics [20,21]. Transparent laser ceramics [22] have been made available in large size only recently [23]. Although it offers interesting perspectives in terms of laser gain media engineering [24], a recent cross evaluation study [25] of crystalline versus ceramic Yb:YAG amplifier disks pointed out how sensitive to stress (mechanical or thermal) ceramics could be. A careful thermal management minimizing thermal stress is indeed requested to make sure a ceramic based Yb:YAG medium will not totally depolarize the beam it aims at amplifying.

Within the Lucia project, a cooling approach based on a static helium gas gap acting as the heat transport medium between the hot YAG disk and a heatsink was proposed [26]. This thermal management concept is known as a “heat switch” or “thermal switch” [27,28] which allows controlling the heat-conduction paths in the enclosed helium thin layer and consequently the Yb:YAG medium temperature. Based on this architecture, we have built a prototype laser head minimizing the radial temperature gradient generating thermal lens or depolarization through birefringence. This paper describes this active mirror amplifier prototype based on this concept and its qualification in terms of thermal management and gain performances.

2. Low temperature active mirror amplifier cooled with a static helium gas gap

2.1 Thermal management principle

While Lucia DPSSL chain first active mirror amplifier is cooled with high pressure water jets directed towards the reflecting surface [7], a fundamentally different solution has been devised [26] for this low-temperature amplifier. The idea is to rely on static helium gas enclosed into a thin (<100 μm) cell while the pressure is adjusted at a level below atmospheric pressure. This is very different from the cooling technique originally developed for Mercury [2] and later implemented in DiPOLE [9] DPSSLs for instance. In these cases, the amplifier heads are indeed cooled with a high velocity helium flow circulating in between several Yb doped slabs; and special care is requested in the design to minimize vibrations and helium pollution. Lucia low temperature amplifier head does not face such considerations and the gain medium is preserved from being altered by impurities and vibrations potentially carried by the helium forced flow.

The principle is based on the dependence of helium thermal conductivity k with the temperature T , the pressure p and the gas gap thickness e as illustrated in the formula:

$$k(T) = k_{bulk}(T) \cdot \left(1 + \frac{8}{3} \cdot \frac{k_{bulk}(T) \cdot T}{e \cdot p \cdot \sqrt{3} \cdot R \cdot T} \cdot \left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1 \right) \right)^{-1}$$

where $k_{bulk}(T)$ is the helium bulk conductivity, R is the specific gas constant for Helium and α_1 and α_2 are the thermal accommodation factors [26].

Within the helium layer located between the cold source (copper at the temperature of liquid nitrogen (LN₂), 77 K) and the hot source (the Yb:YAG subjected to the pump laser flux), the thermal exchanges occur through two processes: He molecule-wall and molecule-molecule interactions (Fig. 1).

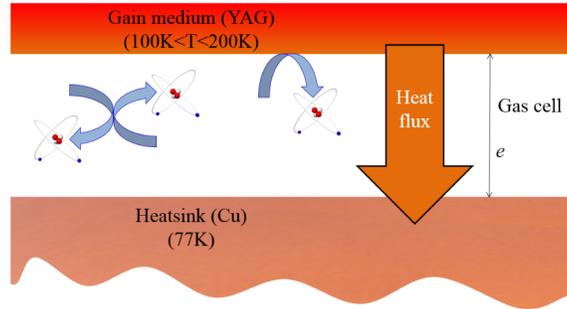


Fig. 1. Schematic illustration of heat transfer processes at work between faces of a helium filled cavity.

The prevalence of one of these two processes (or its simultaneous occurrence) is related to p and T for a given gas gap thickness e . Calculating the molecules mean free path λ as a function of these variables allows to define three different heat conduction regimes: Viscous ($\lambda \ll e$), transition ($e/10 < \lambda < 10e$) and free molecular ($\lambda \gg e$) regimes as illustrated in Fig. 2.

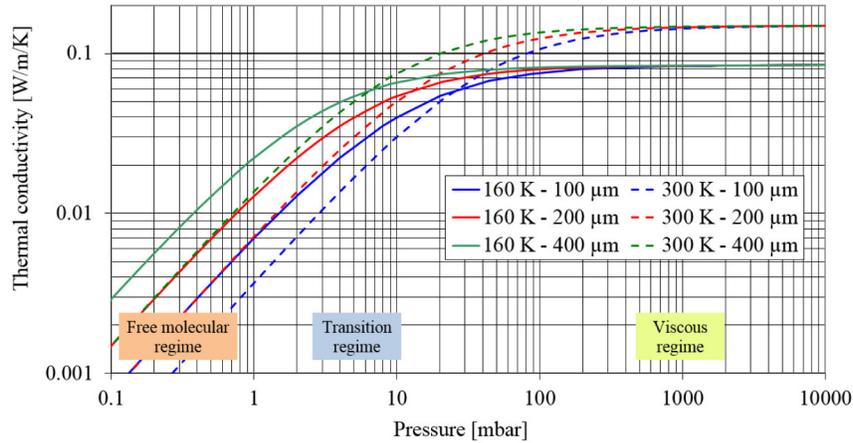


Fig. 2. Thermal conductivity of Helium as a function of pressure for temperature of 160 K (plain lines) and 300 K (dashed lines) and various Helium gap thicknesses.

2.2 Co-sintered ceramics as gain medium disk

Taking advantage of Yb reabsorption at 1030 nm was proven to be quite efficient to mitigate ASE-triggered effect like parasitic oscillations when operating a Yb:YAG amplifier in the vicinity of room temperature [29, 30]. However, when operation below 150K is requested, 1030 nm reabsorption almost vanishes (cross section $< 5 \cdot 10^{-22} \text{ cm}^2$) as illustrated in [31]. Absorbing spontaneously emitted radiations at this temperature level therefore requires a YAG disk with a Cr⁴⁺ doped periphery. In order to investigate that approach, a first generation of Cr⁴⁺/Yb³⁺:YAG cosintered ceramic was manufactured by Konoshima, Japan (Fig. 3, left) where the Cr⁴⁺ doped radial thickness is 5 mm whereas doping concentration is estimated to be 0.25at%. Although, very efficient to prevent parasitic lasing, it proved to carry

a too high Cr^{4+} doping concentration due to a 6 cm^{-1} linear absorption coefficient (Table 1). The absorption power was indeed too strong and the resulting heat load located at the $\text{Cr}^{4+}/\text{Yb}^{3+}$ interface generated internal stress [21, 25]. A second generation of 3 disks (Fig. 3, right) was then processed with a 4x larger Cr^{4+} doped radial thickness of 20 mm coupled to ~4x reduction in absorption coefficient (Table 1). The actual doping level, very likely below 0.1at%, was not made available by the manufacturer. Whereas one side is AR coated, the other (in contact with Helium) is HR coated, both for pump (940 nm) and extraction (1030 nm) wavelengths.

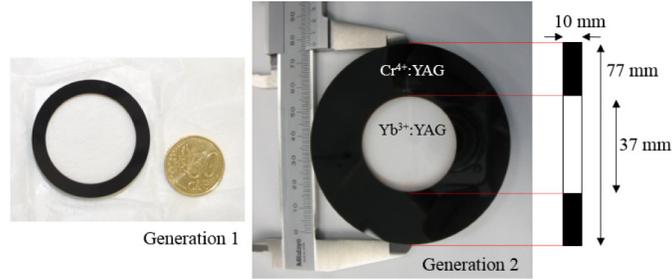


Fig. 3. Illustration of both generations of $\text{Cr}^{4+}/\text{Yb}^{3+}:\text{YAG}$ co-sintered ceramics.

Table 1. Co-sintered ceramics specifications.

Ceramics	Thickness	Yb^{3+} doped \emptyset	Cr^{4+} doped \emptyset	Cr^{4+} doped radial thickness t	Yb^{3+} doping	Cr^{4+} doping	Absorption coefficient	Transmission over t
Unit	mm	mm	mm	mm	at%	at%	cm^{-1}	%
Generation 1	7	35	45	5	2	0.25	6	4.98
Generation 2-A	10	37	77	20	1	not known	2.92	0.29
Generation 2-B							1.65	3.71
Generation 2-C							1.58	4.24

2.3. Laser head description

The Lucia water cooled first laser head used to reach the 14 J milestone [7] is pumped at a rather high intensity level (15 to 20 kW/cm^2) [32]. The high emission cross section of $\text{Yb}:\text{YAG}$ at low temperature [33, 34] allows a significant reduction in pump budget and this second laser head requires therefore only 5.5 kW/cm^2 (~1 ms pulse duration) within a 6 cm^2 homogeneously filled elliptical footprint (43 kW Lastronics pump engines with 76% efficiency).

Figure 4 details the head where a first copper block, as heatsink, is brazed on a LN_2 filled Dewar. For operation/maintenance purpose, a second removable copper element is screwed onto the first one; a ~100 μm layer of Indium ensures an efficient thermal contact. The other face of that copper element is carefully rectified and acts as one wall of the low pressure helium gas gap. The second wall is the HR coated side of the YAG disk. The pressure in the helium gas gap is adjusted to the required one with a vacuum pump and a source of helium gas. The thickness of the helium layer is fixed by the thickness of a thermal insulating element made of polyimide (VESPEL[®]) and the torque applied to the disk mount screws applying pressure on a pair of metallic seals. These later seals (HELICOFLEX[®]) are specifically designed to prevent any helium leaks even at low temperature. The removable copper element hosts also a set of heating cartridges giving an extra degree of freedom for

temperature control. For instance these cartridges can be used to set the initial temperature at the desired value (i.e. above the $\sim 90\text{K}$ at which the gain medium is usually thermalized before pumping starts).

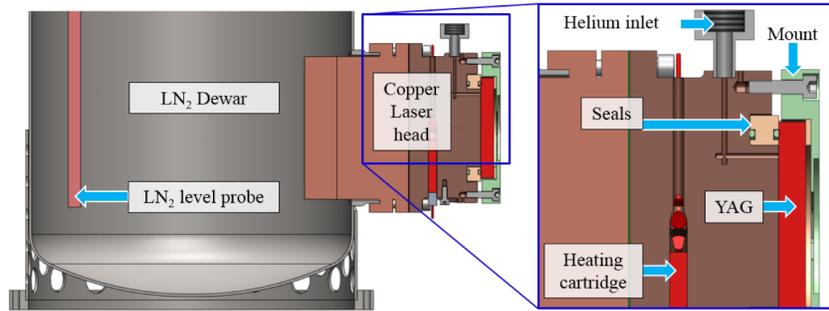


Fig. 4. CAD section view of the low temperature laser head.

3. Experimental qualifications

3.1 Thermal

In order to validate the thermal management concept exposed in section 2.1 and [26], it was necessary to have access to the gain medium surface and inner temperatures. For this purpose, two 15 mm deep holes were drilled at 3 and 7 mm depth on the periphery of a 77 mm diameter 2 at% doped Yb:YAG crystal of 10 mm thickness. Platinum PT100 probes were inserted in both holes while a thermocouple was strapped onto a thin annular copper disk placed on the top (altitude 0 mm i.e. AR coating surface) of the YAG crystal as illustrated on Fig. 5.

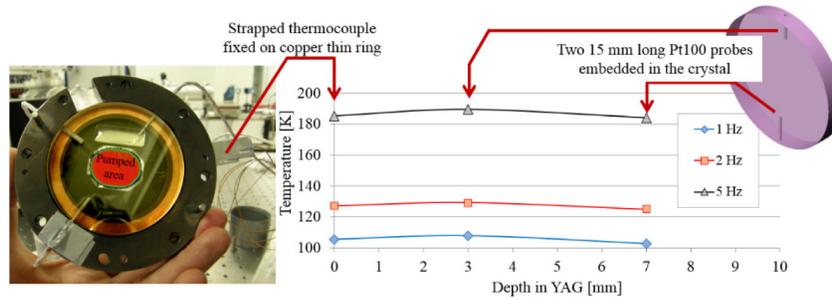


Fig. 5. Left, picture of a Yb:YAG crystal in its mount. The three thermal probes allow temperature measurement at 0, 3 and 7 mm depths. While the amplifier is operated at 1, 2 and 5 Hz, a below 5K axial gradient is observed. Helium pressure is set at 700 mbar, gap thickness at $400\ \mu\text{m}$ while pump intensity reaches $5.5\ \text{kW}/\text{cm}^2$ homogeneously distributed over the pump area illustrated in red on left picture.

An axial temperature gradient below 5K was observed. However it must be kept in mind that these measurements are performed a couple of centimeters away from the central illuminated part. It therefore does not give information about the gradient experienced by the crystal where the heat load is at its maximum, i.e. at its center. But the main purpose of this experiment was to identify the optimum range of pressure sensitivity as illustrated on Fig. 6.

We confirm a sensitive pressure range between 1 and 10 mbar. Above that level, the helium layer thermal conductivity is not evolving anymore as illustrated in Fig. 2 and therefore allows cooling control around 130K for a 2 Hz pump rate. Similar experiments were performed with a much thinner gas gap of $55\ \mu\text{m}$ and an identical pump intensity of 5.5

kW/cm^2 for which a minimal cooling temperatures of 110K (5Hz, 27.5W/cm^2) and 150K (10 Hz, 55W/cm^2) were achieved.

It should also be pointed out that this experimental configuration allowed us to record Yb:YAG absorption cross sections between 80 and 300 K as illustrated on Fig. 2 of [31].

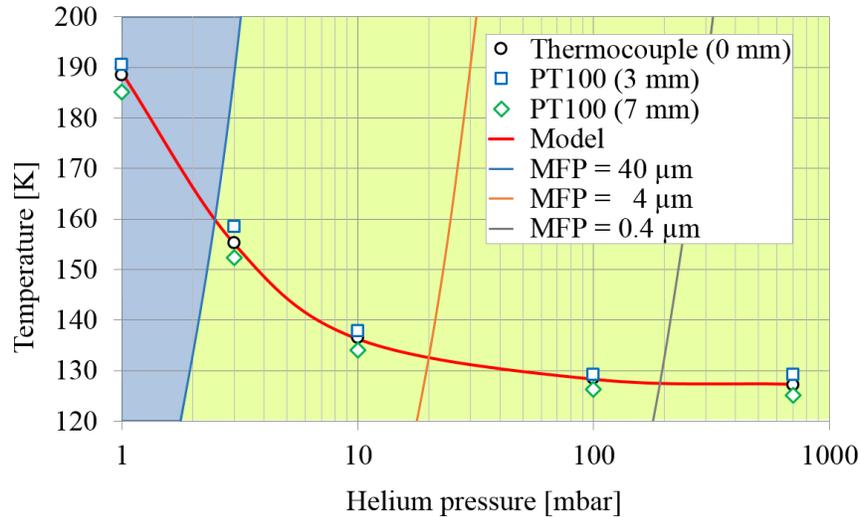


Fig. 6. Yb:YAG ceramic temperature versus helium pressure in a static $400\ \mu\text{m}$ thick cell. Iso-mean free path (MFP) curves are displayed for 40 , 4 and $0.4\ \mu\text{m}$. The first one defines the limits between transition (blue) and viscous (green) regimes as defined in section 2.1. Data points were collected while the $5.5\ \text{kW/cm}^2$ pump intensity was delivered at $2\ \text{Hz}$ with a $1\ \text{ms}$ pulse duration.

3.2 Gain

[25] was dedicated at cross evaluation of $45\ \text{mm}$ diameter co-sintered ceramics (Generation 1) and crystals at room temperature. This new prototype allows us to extend that study by comparing $77\ \text{mm}$ disks operated at low temperature. A narrow ($<0.1\ \text{nm}$) $1030.3\ \text{nm}$ CW $60\ \text{mW}$ laser source was first used as a probe beam. Experimental conditions were identical for both disks.

The Yb:YAG crystal performances are clearly affected by the lack of ASE control scheme (no $1030\ \text{nm}$ absorption of Yb at these temperatures and absence of Cr ions playing a similar role). After a few hundreds of microseconds, strong gain saturation takes place. Even at relatively high ($200\ \text{K}$) temperature, the gain never exceed a value of 2 (left, Fig. 7). These ASE plateaus are not observed on the $\text{Cr}^{4+}/\text{Yb}^{3+}$:YAG co-sintered ceramic gain curves and a 50% increase in single pass gain can be attained (right, Fig. 7). For these graphs and the followings, the reported temperatures are recorded through a peripheral copper ring in contact with the AR coated surface of the YAG disk.

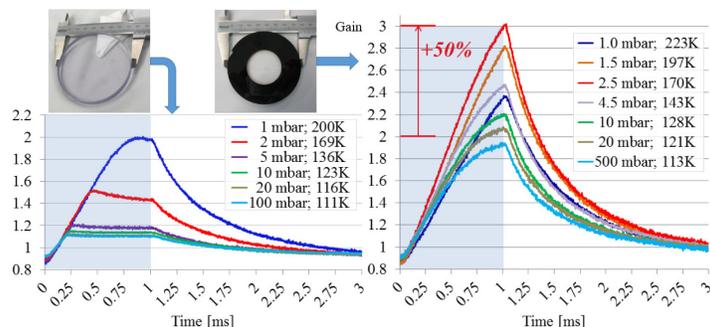


Fig. 7. Single pass gain temporal behavior for two 1 cm thick, 77 mm in diameter Yb:YAG disks operated in the low temperature Lucia amplifier. The 5.5 kW/cm² pump is limited at 1 ms duration (blue area) with a 2 Hz repetition rate. The left graph pictures gain curves obtained in the crystal case while the right graph is dedicated to the co-sintered ceramic. The Helium gas gap thickness is 150+/-5 μm.

Maximum gain values recorded with the ceramics are reported on Fig. 8 for different adjusted pressures in the gas gap (i.e. temperature control). The blue squares are the maxima of Fig. 7 right graph curves (2 Hz, 150 μm) whereas the red circles have been obtained similarly while operating the amplifier at 5 Hz with a 55 μm thickness Helium gap). The single pass gains increase with decreasing temperature until a temperature in the 160-190 K range where it somehow saturates and then decreases. In order to explain this behavior, one could invoke ASE losses but, although likely to play a negative role, ASE does not appear to play a significant one when carefully looking at build-up phase at Fig. 7 (right image). The reason has in fact to be linked to the nature of the source used for this experiment, i.e. a 1030.3 nm narrow one.

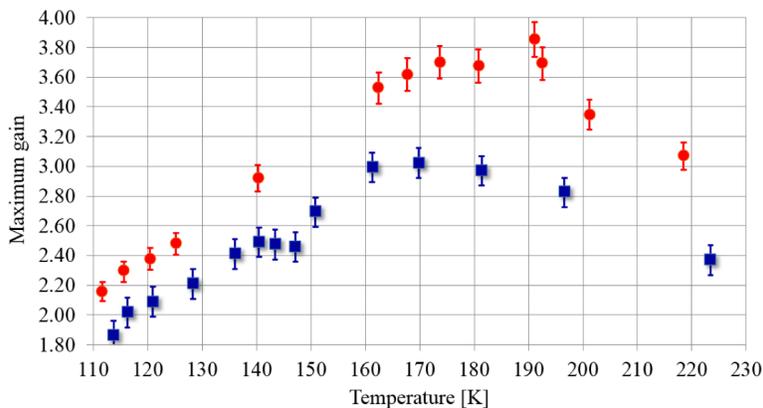


Fig. 8. Maximum gain observed versus Cr⁴⁺/Yb³⁺:YAG co-sintered ceramic temperature. Extraction wavelength is 1030.3 nm. Pump intensity is 5.5 kW/cm² with 1 ms pulse duration. The blue squares are the maximum values observed on Fig. 7 (right), i.e. obtained at 2 Hz with a 150+/-5 μm Helium gas gap thickness. The red disks are gain maxima obtained at 5 Hz with a 55+/-5 μm gap.

Figure 9 shows that, in order to reach much higher gains, a source tunable down to 1029.5 nm is requested.

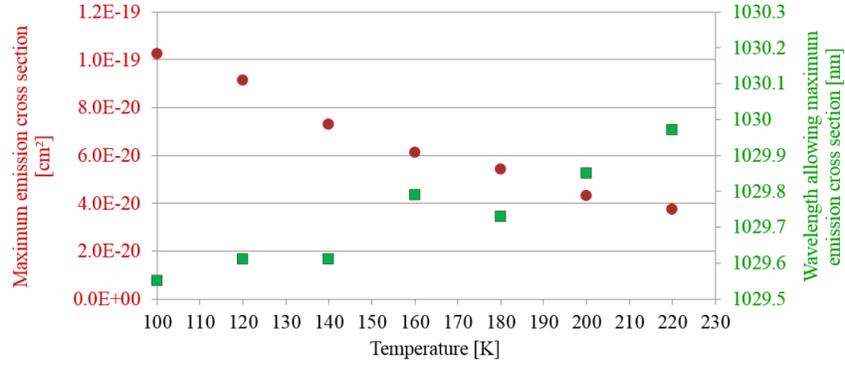


Fig. 9. Maximum emission cross section (red, left scale) and wavelength allowing to reach that maximum (green, right scale) versus temperature. Reaching high cross section values around 1.10^{-19} cm^2 requires a 1029.5 nm source. This graph was derived from data kindly shared by [35].

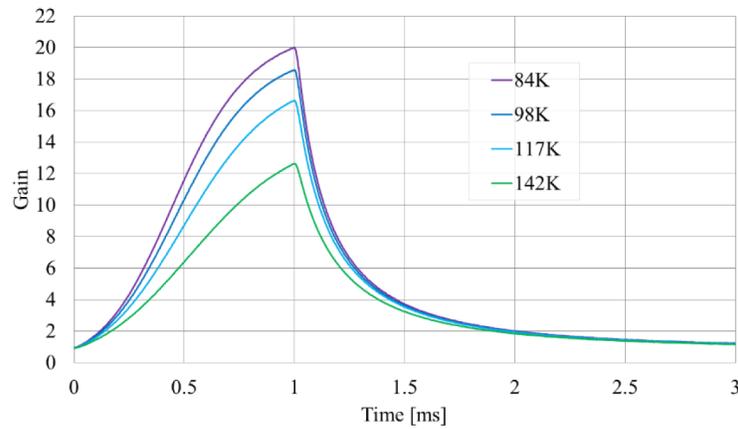


Fig. 10. Small signal gain recorded at 1029.7 nm while pumping the $\text{Cr}^{4+}/\text{Yb}^{3+}:\text{YAG}$ co-sintered ceramic at $5.5\text{kW}/\text{cm}^2$ intensity and single shot, 0.5, 1 and 2 Hz repetition rate. Respective temperatures are 84, 98, 117, 142 K. Helium pressure is 1 bar.

Gain measurements were then performed while adjusting the wavelengths to better match emission cross section maxima. Figure 10 displays single pass gain obtained with a 1029.7 nm narrow (100 pm) 35 mW CW source. Gain values vary between 12 and 20 with YAG temperatures across the 142 to 84 K range.

Similar experiment where performed with Lucia front end nominal configuration with a 20 mm diameter beam of 10 ns pulses at 2 Hz at 1029.7 nm; maximum energy per pulse being half a Joule. Figure 11 shows that single pass gain stays above 6 in the 100 to 460 mJ explored energy range. The YAG temperature was close to 140K.

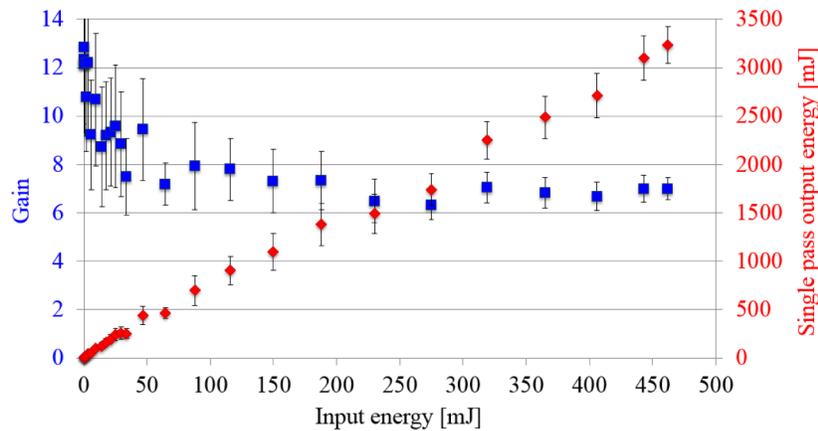


Fig. 11. Left, blue: single pass gain recorded in pulse mode (10 ns / 2 Hz) with the $\text{Cr}^{4+}/\text{Yb}^{3+}$:YAG co-sintered ceramic. Right, Red: Amplified energy in a single pass.

Any Helium pressure adjustment imposes a temperature stabilization period which depends of the operating pressure range (1, 10 or 100 mbar). A ~1% stabilization can require up to half an hour. As soon as the point of operation is defined (helium gap thickness, pressure, pump load...), it should not be necessary to adjust the helium pressure.

6. Conclusions

We have experimentally validated at low temperature the static helium gas gap heat switch concept for active mirror laser amplifier. A prototype was built and integrated into the Lucia laser chain. It can host YAG disks up to 77 mm in diameter in an active mirror configuration. A simple helium pressure adjustment between 1 and 10 mbars allows us to explore the amplifier behavior over a 100K wide temperature range around 140K. Colder or warmer operating temperatures could be achieved easily by adjustment of the VESPEL ring thickness allowing the helium layer to be tuned from tens of μm to hundreds of μm .

Thanks to Konoshima optimization work in terms of ultralow Cr^{4+} doping concentration, a new generation of co-sintered $\text{Cr}^{4+}/\text{Yb}^{3+}$:YAG disks were used allowing a 2x single pass gain improvement from 3 to around 7. Foreseen evolution of this low temperature amplifier will be devoted to a 2nd generation amplifier able to operate in the same temperature range without the need of LN_2 .

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