PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Preliminary design of a Tm:Lu2O3-based amplifier for J-scale ultra-short pulses at a kW average power

Cellamare, Gianluca, Labate, Luca, Baffigi, Federica, Palla, Daniele, Gizzi, Leonida Antonio

Gianluca Cellamare, Luca Labate, Federica Baffigi, Daniele Palla, Leonida Antonio Gizzi, "Preliminary design of a Tm:Lu2O3-based amplifier for J-scale ultra-short pulses at a kW average power," Proc. SPIE 11777, High Power Lasers and Applications, 117770K (18 April 2021); doi: 10.1117/12.2586967

SPIE.

Event: SPIE Optics + Optoelectronics, 2021, Online Only

Preliminary design of a $Tm:Lu_2O_3$ based amplifier for J-scale ultra-short pulses at a kW average power

Gianluca Cellamare, Luca Labate, Federica Baffigi, Daniele Palla, Leonida Antonio Gizzi
Intense Laser Irradiation Lab., Istituto Nazionale di Ottica (INO), Consiglio Nazionale delle Ricerche (CNR), Pisa, Italy

ABSTRACT

We report on the conceptual design of a 2 µm, ultrashort pulse laser system including power amplification based [1] on Tm-doped gain medium. We consider ceramic [2] $Tm:Lu_2O_3$ with a direct diode-pumping architectures to develop a solid-state laser technology for high-efficiency, high repetition rate and ultra-short pulse laser, with high peak power and kW-scale average power.. A CW pumping (duty cycle of the diodes 100%) and a multi-pulse extraction mode [3] scheme are considered with a multipass scheme with thin disk $Tm:Lu_2O_3$ doped at 4% and with lateral (edge) [5] pumping (EPDL).

Here we show the preliminary results of the modelling of a two-stage amplifier operating at a repetition rate of 1 kHz, output energy of >500mJ, with a maximum fluence of about 1.5 J/cm2 for the first stage and of about 2 J/cm2 for the second stage. The optical model of the two-stages is based on a multi-pass configuration and designed for a gain of 50x and 12x respectively. Each stage consists of two gain media in active mirror configuration. This conceptual design represents the best balance between constructive complexity and efficiency in terms of energy gain.

Keywords: ultra-short pulse laser, Tm-doped, high intensity laser, diode-pumping

1. INTRODUCTION

High-power ultrashort pulse lasers are widely used in several fields and are key tools for laser-plasma acceleration [24], where systems based on Titanium-Sapphire (Ti:Sa) technology are commonly used [23]. Ti:Sa lasers, in turn, require frequency-doubled Neodymium (Nd) lasers as optical pumping sources. This double-step in pumping architecture sets a cap to maximum overall wall-plug efficiency and limits the average power currently reachable by this class of lasers, typically not exceeding a few tens of Watts. This limitation is essentially due to the optical pumping technology, usually based on flash lamps, that requires significant heat dissipation in the amplifier medium. Recently, the development of pulsed lasers with diode pumping have made possible the delivery of high energy (100 J per pulse) and high average power (kW) Neodymium sources for pumping titanium-sapphire lasers [1, 24], although, severe constraints remain in the management of the thermal budget in the Ti:Sa amplifiers for scaling at higher average power levels.

Direct diode pumping of lasing media capable of broadband amplification is the most obvious solution to this issue, potentially leading to much higher efficiency and compactness. Several materials have been proposed and tested in this context and significant progress has been demonstrated for kW amplification dow to the ps level, using Yb:YAG [26,27], while similar performances for tens of fs pulses is still lacking. Architectures based on Tm-doped crystals (Tm: YLF, Tm: YAG and $Tm:Lu_2O_3$) have been recently proposed for the potential advantages of energy efficiency and scalability at very high average power levels with emission around 2 µm [2]. The crystal is pumped directly using stacks of commercially available diodes with emission around about 800 nm. Pumping takes place in quasi-CW, duty cycle of the diodes close to 100%, and the extraction scheme that is exploited is so-called "multi-pulse extraction mode"[2,3], enabled by the relatively long lifetime of the lasing transition, typically several milliseconds.

Here we report on the conceptual design of a laser amplification chain based on Tm-doped gain medium[1]. We consider ceramic $Tm:Lu_2O_3$ with a direct diode-pumping architecture to develop a solid-state laser technology for high-efficiency, high repetition rate and ultra-short pulse laser, with high peak power and kW-scale average power, at an emission wavelength around 2 µm.

High Power Lasers and Applications, edited by Joachim Hein, Thomas J. Butcher, Pavel Bakule, Constantin L. Haefner, Georg Korn, Luis O. Silva, Proc. of SPIE Vol. 11777, 117770K
 doi: 10.1117/12.2586967

2. THULIUM DOPED MATERIAL PROPERTIES

The energy level scheme of Tm3+ with the relevant energy transfer processes for this laser transition is shown in Figure 1. Thulium (Tm) doped gain media exhibit emission around 2.0 μm, resulting from a transition that starts in the $^3F_4$ manifold level and ends in a thermally populated Stark level of the $^3H_6$ ground state. The first Tm:YAG laser at 2 μm using this transition was demonstrated in 1965 with a flash lamp pumped laser which operated at 77 K [7]. The first pulsed laser operation at room temperature was demonstrated in 1975 using Cr,Tm:YAG [8], and after few years the first laser diodes in the wavelength range around 800 nm continuous wave diode pumped laser operation at room temperature was developed [9,10]. Until now thulium laser emission around 2 μm was demonstrated in many different host materials and there are several thulium based laser systems commercially available (LISA laser products OHG; IPG Photonics Corp.). [6]

Thulium ions can be excited around 800 nm from the ground state to the $^3H_4$ energy level. Interestingly, the upper laser level $^3F_4$ is then populated by the cross-relaxation process (CR) that occurs between two Tm ions. In this non-radiative process, for one ion an electron relaxes from the $^3H_4$ level to the $^3F_4$ level and for a second ion an electron is excited from the ground state to the $^3F_4$ level [10-11]. This excitation process yields two excited ions for each absorbed pump photon. Therefore the quantum efficiency is nearly two when the cross relaxation process is highly efficient. Thus, instead of a maximum efficiency of 41 %, one can obtain an efficiency of 82 %, in theory. Indeed, lasing of Tm:Lu_2O_3 with a slope efficiency of 68 % has been demonstrated[15]. The efficiency of the cross-relaxation process depends on the doping concentration of the Tm ions since the involved dipole-dipole interaction depends on the ion spacing. [6]

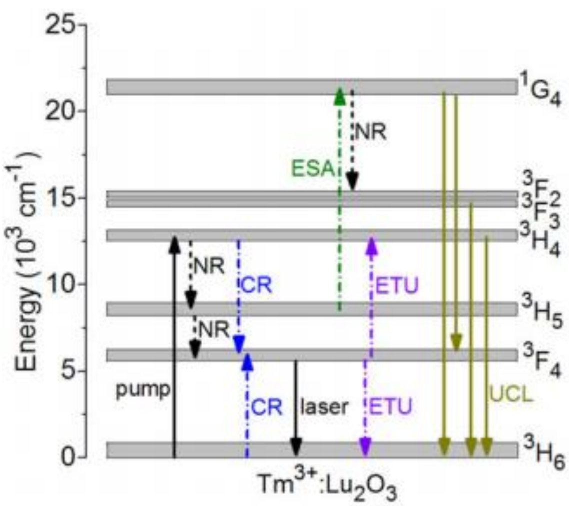

Figure 1. Scheme of energy levels of the Tm^{3+} ion (on the example of Tm^{3+} : Lu_2O_3,C_2 site) showing relevant processes (CR: cross-relaxation, ETU: energy-transfer upconversion, ESA: excited-state absorption, UCL: upconversion luminescence, NR: non-radiative relaxation). The grey rectangles correspond to the total Stark splitting [22].

The Tm atomic structure allows for doping into both crystal and glass hosts used for high power lasers. In Figure 2, important parameters for the 2 μm laser transition are listed for a selection of crystals used for high power lasers. The broad emission spectra of Tm-doped crystals offers broad-band amplification of stretched femtosecond pulses in a CPA potentially capable of compression down to 50 fs as required in some applications [5] including laser-plasma acceleration.

Lu_2O_3 has a cubic crystal lattice structure that enables the use as gain medium in the ceramic form. The key advantage of ceramic hosts is their size scalability, which is necessary to attain high pulse energies. Another advantage of ceramics is easy fabrication of complex compositions enabling improved laser performance. In particular, ceramics are amenable to advantageous forming of composite laser gain media by cosintering doped and undoped sections and/or sections with different doping. Such composites are beneficial for efficient concentration of pump radiation [12,13], mitigation of amplified spontaneous emission (ASE) [14], and reduction of thermal stresses at disk edge, while having comparable mechanical strength of a monolithic unit [5].

laser host material	σ_{abs} (10^{-21} cm^2)	λ_{em} (nm)	σ_{em} (10^{-21} cm^2)	λ_{th} (W m^{-1} K^{-1})	τ (ms)
YAG	7.5	2013	1.8	13	10
YLF	σ pol 3.6 π pol 8.0	1910 1880	2.35 3.7	6	15.6
Lu_2O_3	3.8	2070 1945	2.3 8.5	13	3.8
Sc_2O_3	5.0	1994	8.4	17	4.0
Y_2O_3	5.0	2050 1932	2.1 8.1	14	
LuAG	5.7	2023	1.66	13	10.9
$YAlO_3$		1936	5.0	11	4.8
silica fibre	4.5	1860	3.9		6.6
germanate f.	6	1840	4.1		5.3

Figure 2. Properties of widely used thulium doped laser crystals for high power applications. Absorption cross section σabs; free running laser emission wavelength λem; emission cross section σem; thermal conductivity λth; lifetime of the upper laser level τ. [6]

3. EDGE-PUMPED DISK LASER AMPLIFIER

Edge-pumped disk laser (EPDL) [4] configuration uses a composite disk having undoped material around the doped laser disk. This construction improves coupling between the pump diodes and the gain medium, aids in concentration of the pump radiation, and provides cooling to the doped disk edge in the active mirror configuration. EPDL pump diode arrays are arranged around the circumference of the composite disk and generally point toward its center. Diode pump light is delivered directly or via fibers, to the perimetral edge to ensure good coupling efficiency into the material as shown conceptually in Figure 3. Pump radiation is first concentrated in the tapered portion of the undoped edge, followed by injection into the doped disk where it is channeled between the disk faces of the thin disk and gradually absorbed. Arrangements of the diodes and disk doping allows for tailoring the gain profile for optimal BQ and extraction [1, 12].

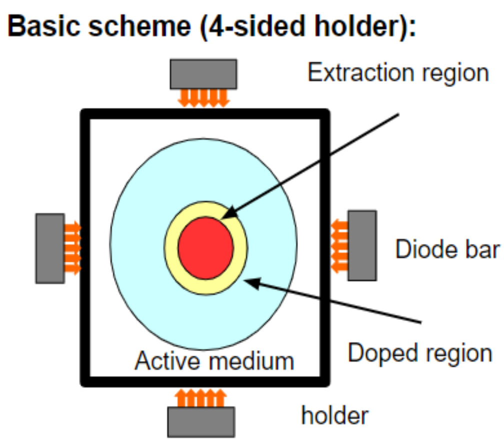

Figure 3 Basic scheme (4-sided holder) edge-pumped disk laser module.

In the active mirror configuration, the EPDL laser disk is made reflective at one of its faces (so as to reflect back the beam having passed through the disk) and is cooled by a liquid-based heat sink. By placing the diodes in an appropriate configuration around the perimeter of an appropriately doped disk, the desired profile, e.g. near-perfectly uniform or tailored, of absorbed power density can be produced. More in detail, the spatial profile of the power density in the doped portion of the active medium is strongly influenced not only by the global geometry of the pumping system, but also by the absorption coefficients, by the angular divergences of the individual emitters and their linear power distribution, and by the local focusing set-up of the diode array (or bars). For these reasons, numerical modeling is generally required to define optimized or flexible pumping configurations for both tailored or uniform power distributions. Tailoring the gain profile can increase optical extraction and efficiency by better matching the optical gain to the optical mode. The combination of uniform or tailored gain, avoidance of transverse temperature gradients, and the ultra-flat surface of the heat sink enable amplification of a laser beam. These features make EPDL an excellent candidate for use in ultrafast lasers with high average power.. The EPDL architecture was selected in view of its potential scalability to high average power and high-pulse energies, and robustness as for induced thermo-optical aberrations[1,5].

4. LASER SYSTEM ARCHITECTURE

A conceptual scheme of the laser chain is shown in Figure 4. The front-end is based on a commercial system, essentially consisting of an Optical Parametric Amplifier (OPA) pumped by a short pulse laser and capable of a mJ level pulse at 2 μm at 1 kHz, with a bandwidth matched with the $Tm:Lu_2O_3$ amplifier gain bandwidth. The pulse produced by the front-end is then stretched up to the sub-ns level to allow the subsequent chirped pulse amplification {CPA}. A telescope is used to adjust the pulse diameter in order to obtain the required values of the fluence of the single pulse that we need as input of the amplifier (<2 J/cm2).

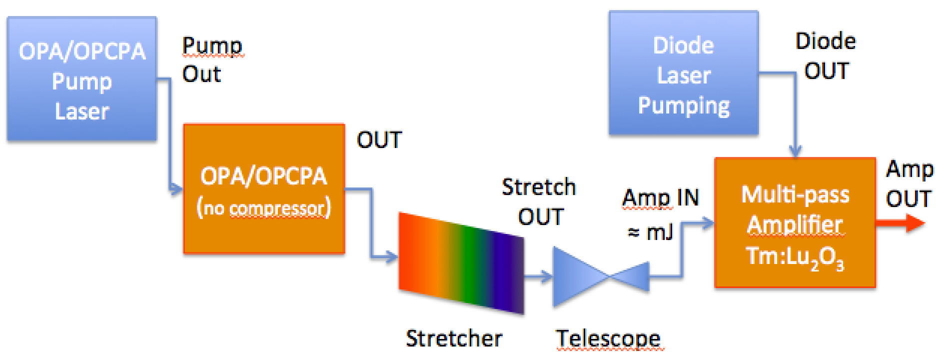

Figure. 4. Optical architecture of laser system, including the front-end and the main amplifier.

In our system the front-end is expected to provide approximately 1 mJ energy pulses at a rep rate of 1 kHz, with a wide spectral band compatible with ultrashort pulses (<50 fs) and a tunable central wavelength.. We consider a multi-pass scheme with thin disk $Tm:Lu_2O_3$ doped at 4% in configuration of active mirror and with lateral (edge) diode pumping at 800nm. The doping of each disk is tailored along the radial direction in order to optimize the pump energy absorption and minimize unwanted thermal load. The amplifier energy design goal is > 500 mJ, starting from the input seed energy of 1 mJ. We consider a two-stage, multi-pass amplifier, with a preamp and a main amplifier, with 2 gain media for each stage. The first stage is seeded with the pulse from the front-end to reach an energy output of 50 mJ per pulse. The second stage allows for further amplification of the pulses up to an energy > 500 mJ. The number of passes of each amplifier was determined by setting a maximum output fluence from each stage equal to 2 J/cm^2.

An optical model and a thermal model have been developed for the design of the amplifier. The optical simulations were carried out with the aim of reducing the thermal budget while keeping the gain high [6]. A modified 4f relay imaging (4f) [16] from active medium (AM) to active medium structure is considered. Commonly this structure is used to realize a multi-pass amplifier where the output power is independent of the thermal lens of the active medium because the beam is imaged from pass to pass [16, 19]. The 4f-design exhibits various advantages: It sustains equal beam size at each pass on the active medium independently of the dioptric power of the active medium and independently of the beam size at the active medium. Moreover, multiple passes can be realized with only a few optical elements [17–19].
Optical simulations were carried out also considering second-order nonlinear refractive index effects. Compared to glasses, Lu_2O_3, as all ceramics in general, shows a higher nonlinear index of refraction. We considered n2 $=8.6 \times 10^{-16}$ cm^2 W^{-1}. Compared to Ti:Sa, one of the most common active medium used for this kind of laser, the value of n2 of Lu_2O_3 is almost three-fold. [20]

For our simulations, we considered the configuration with the initial Gaussian seed profile and the SuperGaussian pump profile of order n=5. This is the configuration that, having fixed the Gaussian distribution for the seed, allows for the maximum amplification and output energy. At the first stage the beam has a radius of 1.5 mm and the seed energy is set to 1 mJ. The input of the second stage, obtained from the output of the first stage with a telescope, has a beam radius of 4.5 mm and the seed energy of about 40 mJ. The output beam profile of the first stage is a Supergaussian of order n=2. After the second stage, we obtain a flat-top profile. In the Figure 5 we can see, respectively, the seed profile as input of the first stage (a), output of first stage (b) and output of second stage (c).

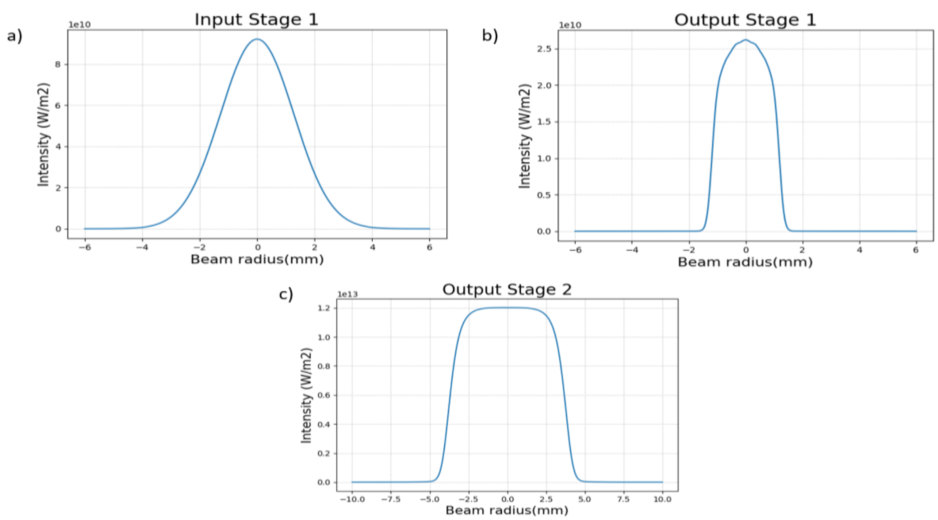

Figure 5. Respectively, first stage input beam profile (a), first stage output beam profile (b), second stage output beam profile (c)

Preliminary results of the modelling of a two-stage amplifier operating at a repetition rate of 1 kHz show an output (i.e., after the second stage) energy of >500mJ, with a maximum fluence of about 1.5 J/cm2 for the first stage and of about 2 J/cm^2 for the second stage. The optical model of the two-stages is based on a multipass configuration and designed for a gain of about 50x and 12x respectively (see Fig. 6). This represents a balance between constructive complexity and efficiency in terms of energy gain.

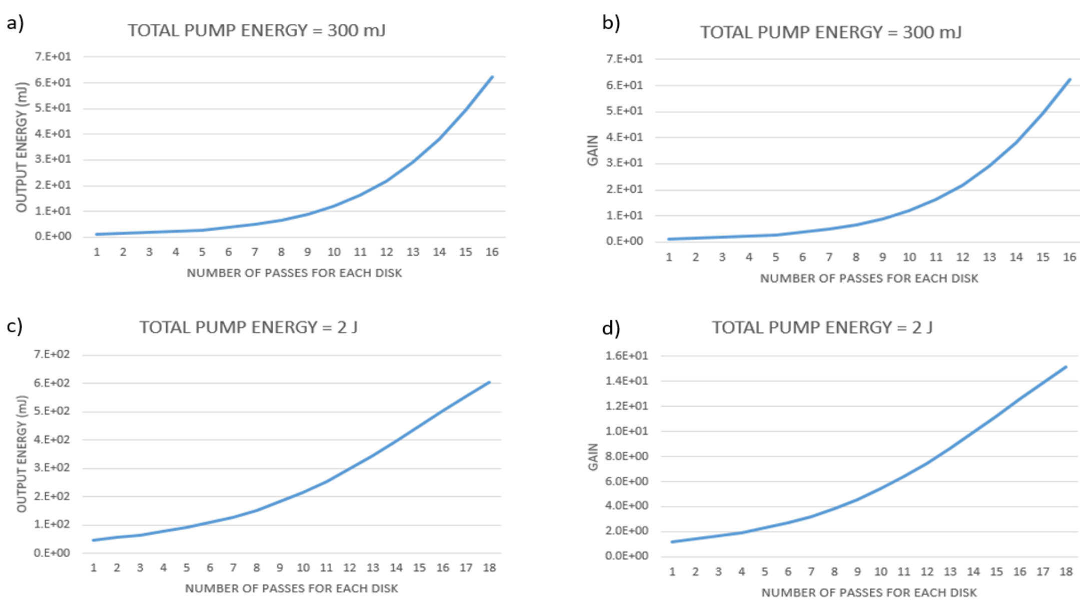

Figure 6. Energy gain and output energy as a function of the number of passes, for the 1st stage (a, b) and for the 2nd stage (c-d).

Thermal simulations were also carried out, aimed at studying mechanical parameters, such as stresses, strains and deformations, which ultimately give rise to beam aberrations. The input of such a simulations is represented by the power density distribution obtained once defined the appropriate edge-pump configuration. Then, starting from the nonlinear 3-D heat transport equation it is possible to define the spatial temperature distribution as a function of time.
The thermal model provides information on the management of the thermal budget aimed at dissipating excess heat in the active medium due to the effect of optical pumping, under conditions of maximum possible thermal load. Our calculations show the temperature distribution that is established in the active medium and the time required to reach this distribution, of the order of a few seconds. In the case of the first stage, the ultimate requirements on the thermal load were found to be compatible with conventional water-cooling schemes. In the case of the second stage, cryogenic cooling was explored in view of the greater thermal conductivity of the active medium at low temperatures (90 ° K).
The thermal model shows that the adoption of the active mirror configuration involves a distribution of highly asymmetrical (along the disk axis) temperatures, with the uncooled surface reaching maximum temperatures and with the establishment of a significant longitudinal thermal gradient. Nevertheless, a careful optimization of the doping profile, pumping scheme and beam sizes allowed a safe configuration to be identified. Furthermore, the thermal modelling carried out so far doesn’t include a possible reduction in the required pump energy (and thus average thermal load) due to the mechanism of multi pass extraction (at the 1kHz rep rate); an estimate of the impact of this effect on the thermal load is still under study.

Preliminary, we have also estimated the thermal lensing effect from equation [21]:

$$f_{th}(r) = \frac{2\pi K_c w_p^2}{P_p \gamma \eta_{abs} (dn/dT)}$$

where Kc is the thermal conductivity of the gain medium, *wp* is the radius of the doped area of the gain medium, *Pp* is the total incident pump power, η_{abs} corresponding to the fraction of the absorbed pump power, γ is the part of the absorbed pump power dissipated as heat and *dn/dT* represents the temperature dependence of the refractive index [22]. A value around 0.5m is expected.

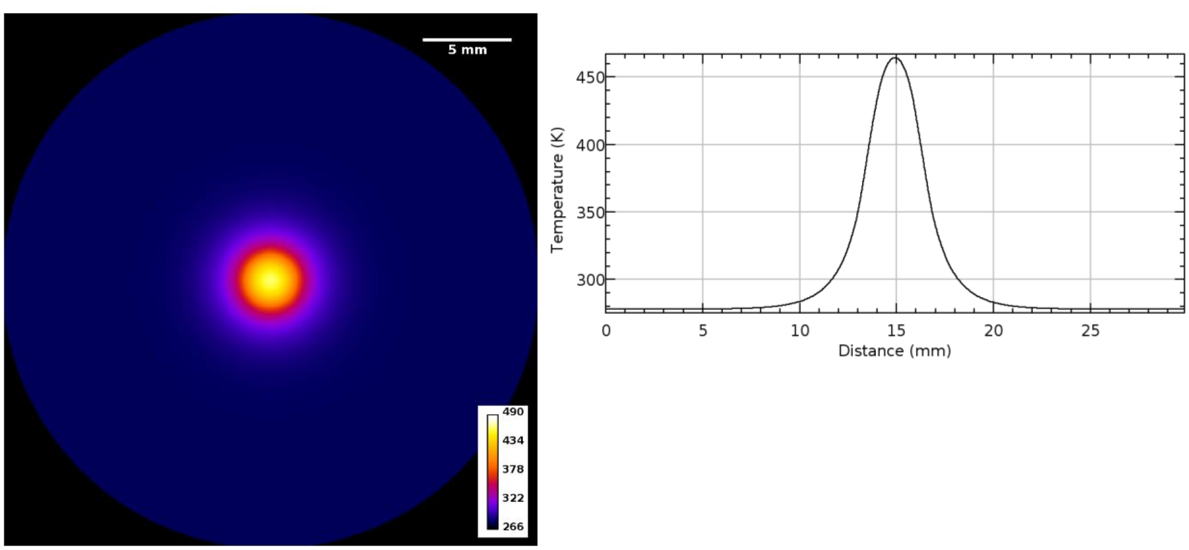

Figure 7. Graphical representation of the temperature distribution on the front face and corresponding lineout for the active medium of the first stage obtained assuming 278°K heat exchanger on the back face.

5. CONCLUSIONS

A preliminary design of a $Tm:Lu_2O_3$ based amplification chain at around 2 µm for J-scale ultra-short pulses at a kW average power is reported. A multi-pass configuration with two stages with 2 ceramic thin disk of $Tm:Lu_2O_3$ 4% doped as gain medium for each stage allows to obtain an output energy of >500mJ from an input energy of 1 mJ with a relatively high number of passes. The final design of the amplifier should consider a trade-off between the need of high gain and the thermal budget.

REFERENCES

[1] D.A.Copeland et al., "Wide-Bandwidth Tm-Based Amplifier for Laser Acceleration Driver",Proc. of SPIE Vol. 9729, 97290I, (2015)· doi: 10.1117/12.2220010

[2] E.V. Ivakin et al., "Laser ceramics Tm:Lu2O3. Thermal, thermo-optical, and spectroscopic properties", Optical Materials 35 499–503 (2013). doi:10.1016/j.optmat.2012.10.002

[3] T. C. Galvin, et al., "Scaling of petawatt-class lasers to multi-kHZ repetition rates", Proc. SPIE 11033, 1103303 (2019); doi:10.1117/12.2520981

[4] J. Vetrovec, et al., "Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier", Proc. SPIE 9834, 983407 (2016); doi:10.1117/ 12.2224411

[5] J. Vetrovec, et al., "2-micron lasing in Tm:Lu2O3 ceramic:initial operation", Proc. SPIE 10511, 1051103 (2018); doi:10.1117/ 12.2291380

[6] Scholle, K., et al., "2 µm Laser Sources and Their Possible Applications," Chapter 21 in [Frontiers in Guided Wave Optics and Optoelectronics], Bishnu Pal (Ed.), www.intechopen.com, (2010).

[7] Johnson, L. F.; Geusic, J. E.; & Uitert, L. G. V. (1965). Coherent oscillations from Tm3+, Ho3+, Yb3+ and Er3+ ions in yttrium aluminum garnet, Appl. Phys. Letters, 7 (5), 127

[8] Caird, J. A.; DeShazer, L. G. & Nella, J. (1975). Characteristics of room-temperature 2.3-µm laser emission from Tm3+ in YAG and YALO3. IEEE J. Quantum Electron. , 11

[9] Huber, G.; Duczynski, E. W. & Petermann, K. (1988). Laser pumping of Ho-, Tm-, Er-doped garnet lasers at room temperature, IEEE J. Quantum Electro., 24, pp. 924-933

[10] Becker, T.; Clausen, R. & Huber, G. (1989). Spectroscopic and Laser Properties of Tm-doped YAG at 2 µm. OSA Proceedings on Tunable Solid-State Lasers, 5, 150

[11] French, V. A.; Petrin, R. R.; Powell, R. C. & Kotka, M. (1992). Energy-transfer processes in Y3Al5O12:Tm,Ho, Phys. Rev. B, 46, p. 8018

[12] D. A. Copeland and J. Vetrovec, "Gain Tailoring Model and Improved Optical Extraction in CW Edge- Pumped Disk Amplifiers," Proc. SPIE 8235, Solid State Lasers XXI: Technology ard Devices, 82350U (15 February 2012); doi: 10.1117/12.910301; https://doi.org/10.1117/12.910301.

[13] R. J. Beach et al., "High-Average-Power Diode Pumped Yb: Y AG Lasers ," UCRL-JC-133848 (1999)

[14] J. Vetrovec and R. Clark, "High-gain solid-state laser," U.S. Patent No. 7,477,674 (2009).

[15] Wu, J., Yao Z., Zong, J., and Jiang, S., Optics Letters, Vol. 32, No. 6, pgs 638–640 (2007).

[16] J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, "Suppression of self-focusing through low-pass spatial fil[1]tering and relay imaging," Appl. Opt. 17, 2053–2057 (1978).

[17] P. Georges, F. Estable, F. Salin, J. P. Poizat, P. Grangier, and A. Brun, "High-efficiency multipass Ti:Sapphire amplifiers for a continuous-wave single-mode laser," Opt. Lett. 16, 144 – 146 (1991).

[18] S. Banerjee, K. Ertel, P. D. Mason, P. J. Phillips, M. Siebold, M. Loeser, C. Hernandez-Gomez, and J. L. Collier, "High efficiency 10 J diode pumped cryogenic gas cooled Yb:YAG multislab amplifier," Opt. Lett. 37, 2175 – 2177 (2012).

[19] Karsten Schuhmann, Klaus Kirch, Miroslaw Marszalek, François Nez, Randolf Pohl, et al.. Multipass amplifiers with self-compensation of the thermal lens. Applied optics, Optical Society of America, 2018, 57 (35), pp.10323. ff10.1364/AO.57.010323ff. ffhal-01980145f

[20] Daniel ALBACH, "Amplified Spontaneous Emission and Thermal Management on a High Average-Power Diode- Pumped Solid-State Laser- The Lucia Laser System", Thesis 2010

[21] W.A. Clarkson, Journal of Physics D: Applied Physics 34, 2001

[22] P. Loiko, P. Koopmann, X. Mateos, J.M. Serres, V. Jambunathan, A. Lucianetti, T. Mocek, M. Aguilò, F. Diaz, U.Griebner. V.Petrov and C. Krankel, IEEE Journal of Selected Topics in quantum electronics, Vol.24, N°5, 2018

[23] L.A. Gizzi, P. Koester, L. Labate, F. Mathieu, Z. Mazzotta, G. Toci, M. Vannini, “A viable laser driver for a user plasma accelerator”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 909, 2018, Pages 58-66, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2018.02.089.

[24] F. Albert, M E Couprie, A. Debus, M. C. Downer, J. Faure, A. Flacco, L. A. Gizzi, T. Grismayer7, A. Huebl, C. Joshi, M. Labat, W. P. Leemans, A. R Maier, S. P. D. Mangles, P Mason, F. Mathieu, P. Muggli, M Nishiuchi, J Osterhoff, P. P. Rajeev, U. Schramm, J. Schreiber, A. G. R. Thomas, J.L. Vay, M. Vranic and K Zeil, “2020 roadmap on plasma accelerators“New J.Phys. 23 (2021) 3, 031101, DOI: 10.1088/1367-2630/abcc62

[25] Mason, P., Banerjee, S., Smith, J., Butcher, T., Phillips, J., Höppner, H. Collier, J. (2018). Development of a 100 J, 10 Hz laser for compression experiments at the High Energy Density instrument at the European XFEL. High Power Laser Science and Engineering, 6, E65. doi:10.1017/hpl.2018.56

[26] Thomas Nubbemeyer, Martin Kaumanns, Moritz Ueffing, Martin Gorjan, Ayman Alismail, Hanieh Fattahi, Jonathan Brons, Oleg Pronin, Helena G. Barros, Zsuzsanna Major, Thomas Metzger, Dirk Sutter, and Ferenc Krausz, "1 kW, 200 mJ picosecond thin-disk laser system," Opt. Lett. 42, 1381-1384 (2017)

[27] Yong Wang, Han Chi, Cory Baumgarten, Kristian Dehne, Alexander R. Meadows, Aaron Davenport, Gabe Murray, Brendan A. Reagan, Carmen S. Menoni, and Jorge J. Rocca, "1.1 J Yb:YAG picosecond laser at 1 kHz repetition rate," Opt. Lett. 45, 6615-6618 (2020)