Performances of cryogenic cooled laser based on Ytterbium doped sesquioxide ceramics

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Abstract. With the goal to study laser chain for IFE application, preliminary investigations and experiments have been conducted. We report here experiments based on cryogenic cooled Yb doped cubic sesquioxides that are now available as ceramics.

1. Introduction.
Diode-pumped solid state lasers have the potential efficiency and repetition rate required for power production. One current candidate for laser materials is an Ytterbium doped material. Yb doped sesquioxydes seem to be good candidate for high average power diode pumped lasers: their saturation fluence is around 15 J/cm². At an aperture scale of only 10-15 cm, now possible using ceramics, it is possible to extract as much as 1 kJ per beam line opening new fields during the research phase to demonstrate ignition and fusion gain (including the fast ignitor concept). Cryogenic cooling brings several advantages for quasi-three-level systems compared to room temperature and we think that cryogenically cooled diode pumped Yb doped ceramic laser is the best way to operating at high average power. It increases the emission and absorption cross sections. On the other hand, for longitudinal pumping, the thickness is optimized for efficient extraction. For high doping concentration, thin amplifier must be used and the non-linear refractive index doesn't matter for setting the breakdown integral to a safety level, say B < 1.5 radians.

2. Figure of merit.
We first define two new figures of merit (FOM) for characterising the amplifier medium in term of material thermo-mechanical parameters. The first one is $R_p$ which characterise the capability of the material to support high pump power without breaking. The second one, $R_f$, characterises the resistance to thermal lensing.

$$R_p = \frac{\kappa^2}{\alpha \eta_Q} \propto P_{\text{max}}$$
$$R_f = \frac{\kappa}{\eta_Q \frac{dn}{dT}} \propto f$$

where $\kappa$ is the thermal conductivity, $\alpha$ is the thermal elongation coefficient, $\eta_Q$ is the quantum defect and $\frac{dn}{dT}$ is the thermal dispersion.
On Fig. 1 are reported the values of $R_p$ and $R_f$ for various undoped laser crystals. The factors have been computed for two pump transitions: the zero phonon line which connects the lower sublevel of the fundamental level to the lower sublevel of the excited state (1-5) and the one connecting the lower sublevel of the fundamental level to the second sublevel of the excited state (1-6). Usually, the first transition is stronger than the second one but it is also very narrower. The difference between the FOM values reported in Fig. 1 for the two pump transitions is the result of the quantum defect variation.

With respect to Fig. 1, the sesquioxides seems to be a good choice for high average power laser chain amplifier. In both factors, the thermal conductivity plays an important role.

Nevertheless, it is well known that the thermal conductivity drastically reduces with doping concentration as a result of the disorder created in the crystal by introducing foreign ions and the resulting slackening of the phonons velocity [1, 2, 3]. In order to limit the thermal conductivity reduction, the foreign ion must be as close as possible to the one it will be substituted. By comparing the atomic weight and ionic radius of different ions usually used in laser amplifier medium, we conclude that the best ions are Lu$^{3+}$ (LuAG, Lu$_2$O$_3$) and Gd$^{3+}$ (GGG). On Fig. 2 is plotted the thermal conductivities of 3 at % Yb doped and undoped YAG and cubic sesquioxides crystals.

### 3. Dependence of the thermo-mechanical parameters with temperature.

We now investigate the effect of temperature on the thermo-mechanical parameters. The thermal conductivity depends drastically on the temperature. Several works have been devoted to this effect [4, 5]. Between 160 K and 500 K, thermal conductivity varies as $\kappa \approx 1/T$ and between 30 K and 160 K, good agreement is found with a curve varying as $\kappa \approx 1/T^2$. For temperature lower than 30 K, the thermal conductivity decreases (Fig. 3). Both the elongation coefficient and the thermal dispersion reduce when decreasing the temperature [6]. We then conclude that, decreasing temperature enhance both $R_p$ and $R_f$.

### 4. Spectral temperature dependence.

![Fig. 2](image2.png)

Fig. 2 Thermal conductivity of 3 at % Yb doped cubic sesquioxides and YAG to undoped crystals.

![Fig. 3](image3.png)

Fig. 3 Thermal conductivity dependence on temperature for YAG. Crosses: experimental data, squares: $1/T$ approximation, circles: $1/T^2$ approximation, unfilled: undoped YAG, filled: 10 at % Yb doped YAG.

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The fifth International Conference on Inertial Fusion Sciences and Applications (IFSA2007) IOP Publishing
Journal of Physics: Conference Series 112 (2008) 032054
doi:10.1088/1742-6596/112/3/032054
We first notice that Yb doped materials are quasi-three-level systems in which the terminal level of the laser transition is thermally populated. Decreasing temperature depopulates this level making it possible to work as a four-level-system and thus, to avoid minimum pump intensity for inverting the amplifier medium. At the same time, the cross sections of both absorption and emission increase and the corresponding saturation fluences decrease [7]. However, the line bandwidth reduces with temperature lowering the efficiency of pulsed diode pumping [9] because the diode bandwidth is large (2 nm) and the wavelength shifts during pumping as a result of junction heating during the pulse [8].

- Then, cryogenic cooling of Yb doped crystals makes it possible:
  - Higher thermal conductivity ⇒ lower thermal strength.
  - Lower thermal dispersion ⇒ lower thermal lensing and OPD.
  - Lower thermal expansion ⇒ lower thermal strength.
  - Four level system ⇒ higher efficiency even with low pumping.
  - Larger cross section for stimulated emission ⇒ higher gain and lower saturation fluence.
  - Higher thermal shock parameter.

These characteristics are appropriated for high intensity, high average power laser and amplifiers.

5. Transparent laser ceramics and experimental results.
Sintered transparent laser ceramics are now available making possible large size amplifiers with high quality and good homogeneity [10, 11, 12]. In addition, it has been demonstrated that the fracture toughness of ceramics is five time higher than for single crystals [12, 13]. Sintering is now possible for cubic crystals like YAG, Y₂O₃, Lu₂O₃ and Sc₂O₃.

Fig. 4 Experimental setup
The experimental setup is shown in Fig. 4. The pump source is as stack of diodes delivering 2.5 kW in 600 µs at 10 Hz. The beam is shaped by one spherical lens and two cylindrical lenses. On the crystal, the pump spot is quasi Gaussian.

Fig. 5 Experimental results with Y₂O₃.

Fig. 6 Experimental results with Lu₂O₃.

Fig. 7 Experimental results with Sc₂O₃.
In order to avoid narrow absorption line at low temperature, the 1-6 pump transition centered at 940 nm has been chosen. On Fig. 5, 6 and 7 appear the experimental results obtained with 10 at % Yb doped 1.5 mm thick Y$_2$O$_3$, Lu$_2$O$_3$ and Sc$_2$O$_3$ respectively.

As the laser is free running with pump pulse of 600 µm, the pulse length depends on the pumping rate and the laser threshold. As not expected, the worst results have been obtained with Sc$_2$O$_3$ in spite of the best spectroscopic data. It seems that our Sc$_2$O$_3$ ceramic has crystallized differently than cubic (still under investigation).

Best results have been obtained by optimizing the cavity parameters for Y$_2$O$_3$ leading to an output energy of 520 mJ with an efficiency as high as 52.5 % at 80 K heat sink temperature.

6. Conclusion.
We have compared the figures of merit of several Yb doped materials. Following our classification, cubic sesquioxides seem to be promising hosts for Yb ion. Preliminary experiments of cryogenic cooled Yb doped sesquioxide ceramics have been conducted in free running laser. Very good performances have been obtained with Yb:Y$_2$O$_3$ ceramic.

References
[1] Romain Gaumé, Bruno Viana, Daniel Vivien, Jean-Paul Roger, Danièle Fournier “A simple model for prediction of thermal conductivity in pure and doped insulating crystals” Applied Physics Letters 83, 7 (2003)
[2] V. Peters, A. Bolz, K. Petermann, G. Huber “Growth of high-melting sesquioxides by the heat exchanger method” J. Crystal Growth 237-239, 879-883 (2002)
[3] Gilbert L. Bourdet, Olivier Casagrande “Theoretical comparison of Ytterbium doped sesquioxides under pulsed diode pumping” Optics Communications 244/1-6, 327–332 (2005).
[4] T. Numazawa, O. Arai, Q. Hu and T. Noda “Thermal conductivity measurements for evaluation of crystal perfection at low temperatures” Meas. Sci. Technol. 12 (2001) 2089–2094 PII: S0957-0233(01)26694-6.
[5] Gilbert L. Bourdet, Haiwu Yu “Longitudinal temperature distribution in a end-pumped solid state amplifier medium: Application to a high average power diode pumped Yb:YAG thin disk amplifier” Applied Optics, 46, 22, 6033-6041 (2007).
[6] Xiaodong Xu, Zhiwei Zhao, Jun Xu, Peizhen Deng “Thermal diffusivity, conductivity and expansion of Yb$_3$Y$_{3(1-x)}$Al$_{12}$O$_{12}$ (x= 0.05, 0.1 and 0.25) single crystals” Solid State Communications 130, 529–532 (2004)
[7] Jun Dong, Michael Bass, Yanli Mao, Peizhen Deng, Fuxi Gan "Dependence of the Yb$^{3+}$ emission cross section and lifetime on temperature and concentration in yttrium aluminium garnet" J. Opt. Soc. Am. B 20, 9 1975-1979 (2003).
[8] Gilbert L. Bourdet, Olivier Casagrande “Effect of the diode wavelength broadening in diode end-pumped solid state amplifier” Applied Optics 46, 14 2709-2716 (2007).
[9] Tadashi Kasamatsu, Hitoshi Sekita, and Yasuhiko Kuwano “Temperature dependence and optimization of 970-nm diode-pumped Yb:YAG and Yb:LuAG lasers” Applied Optics 38, 24 5149-5153 (1999).
[10] Konoshima Chemical Company Ltd., 4-1-1 Koraibashi, Chuo-ku, Osaka, Japan
[11] Ken-ichi Ueda “Scalable Ceramic Lasers: New Possibility of Solid State Lasers” EPS-QEOD, EPFL, Lausanne, Switzerland, Aug. 29, 2004
[12] 2nd Laser Ceramic Symposium, Univ. Electro-Communications, Tokyo, November 10 to 11, 2006.
[13] Baikowski, http://www.baikowskichimie.com/fr/technical_markets/tm_ceramicYAG.shtml, Technical Data Sheet.