LASERLAB-EUROPE

The Integrated Initiative of European Laser Research Infrastructures III

Grant Agreement number: 284464

WP33

European Research Objectives on Lasers for Industry, Technology and Energy (EURO-LITE)

Deliverable number D33.26

Report on thermal effect/amplification on a parallelepiped ceramic amplifier module

Lead Beneficiary:

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE - LOA

Due date: 30/10/2015

Date of delivery: 30/10/2015

Project webpage: www.laserlab-europe.eu

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

This report concerns the modelling and design of an amplifier module based on ceramic material. During the Eurolite program, we have performed experiments to validate an innovative amplifier design for which the pumping is made by passing the pump beams through the coolant. Our choice was fixed on the use of Yb:YAG ceramics which were diode-pumped at 940 nm in order to enjoy better performance stability over the long term. The amplification of ns and fs pulses in single pass with gains of up to 3.2 was obtained. Different types of ceramic (single one and hybride one) with different width and different doping level have been tested. Double pass has also been proved to be possible and to enable to double the gain. A significant improvement in performance in terms of gain relative to a conventional cooling was observed. Both the pump beams and the signal beam, when the proper alignment is realized, do not show disturbances in terms of spatial profile and pointing stability despite passing through the water flow. With or without amplification, the spatial profile of the 1030 nm beam remains unchanged.

B. Deliverable Report

1 Introduction

The current trend in laser development focuses primarily on the femtosecond sources of high peak power. These sources are particularly interesting for many areas of fundamental physics and also have great potential for many civilian and military applications. However, these sources delivering high peak power suffer from a lack of compactness and a lack of average power (that means a low repetition rate), which significantly limited the potential applications. The attainment of average powers beyond kW, while keeping short pulse duration (<500 fs), would conduct to an unprecedented expansion of the domain of these applications. In order to overcome these limitations, the development of femtosecond laser sources at high repetition rate appears to be an interesting challenge.

The fact that the current fs laser sources are limited in repetition rate is related to two major factors. First, the optical pumping systems for their gain media are themselves limited in frequency. Thus the source couldn’t have a repetition rate greater than the one of the system giving it its energy. The second limitation comes from the thermal effects occurring in amplifying media when one brings the pump energy. Under the Eurolite project, we want to implement various technical solutions to overcome these limitations and in particular to develop a new amplifier design. Its purpose is to achieve a significant improvement in performances and compactness of high speed and high average power femtosecond pulses amplifiers which are at this moment rather small.

2 Objectives

Thermal problems observed in the gain media of high repetition rate systems are the direct consequence of the large amount of pump power deposited therein. They also arise from the multi-pass architecture which is conventionally chosen to achieve the amplification power in these systems, especially with techniques known as "Thin disk." In recent years, the "Thindisk" technique developed by Trumpf (Germany) for continuous laser sources used in industry was used for pulsed sources. This technique is applied to both nanosecond sources (LUCIA LULI program) and for picosecond or femtosecond duration. The latter is treated in a German program at the Max Born Institute in Berlin. Its purpose is to obtain pulses of a few hundred milliJoules at a rate greater than 100 Hz and with a picosecond duration. The disadvantage of this technique is its use of a cryogenic cooling which results in a reduction of the spectral bandwidth of the laser gain material and limits the duration of the pulse. A second approach to obtaining high average power is the technique of Innoslab. This approach seeks to maximize the extraction of the heat load compared to the ThinDisk technique. In doing so the use of a cryogenic technique seems no longer necessary and shorter pulses are possible. This approach is considered by the "Fraunhofer Institute for Laser Technology" which allowed them to get some 400 watts in continuous mode [1] or 5 µJ 1 ps pulses at a repetition rate of 74 MHz. More recently, they have obtain amplification of an oscillator delivering pulses of 636 fs using this technique to an average power of 1.1 kilowatts [2] keeping the pulse duration.

Our approach is distinguished by three key points. First, we propose to achieve amplification in several gain media (amplification modules) to distribute the pump power and thus reduce consistently the thermal effects. Each of these amplifier modules can be seen as the equivalent of a passage in a conventional multipass configuration in terms of gain level. However, this does not mean that it is itself one-pass. Next, we consider a design for the amplification modules based on "Innoslab" architecture and using fibered single emitter diode instead of traditional "stacks" laser diodes as pump sources. These diodes have the advantage of being controllable by simple and cost-effective power supplies. As fibered, we can position them away from the laser head and have a stable beam quality over time. Moreover, they offer an arrangement modularity that does not offer the "stacks". It is thus possible to develop designs both flexible and robust. Finally, we use ceramics as laser gain medium. Such ceramics are available in sizes up to 10 x 10 cm ^{2} which potentially can reach a few hundred joules. On the other hand, ceramics are polarization insensitive materials, for both the pump beam and the signal beam. This fact frees us from typical problems with polarized beams (including induced depolarization) and provides additional flexibility in the design.

As part of this research program, we want to design, build, study and model a ceramic-based diode pumped amplification module in order to achieve the amplification of sub-200fs pulse with a repetition rate around 70 MHz.

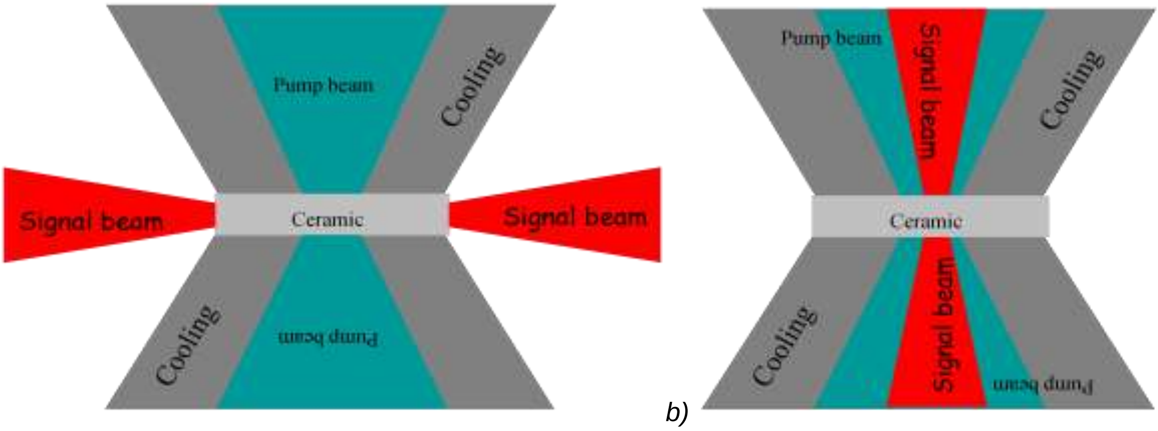
3 Work performed / results / description

Initially, we planned to work in two separate phases, the experimental one to deliver concrete results in support of the second phase on the modelling of the amplifier. Unfortunately, due to the departure of a part of our research team, we have had to abandon the modelling aspect and concentrate on the experimental aspect.

As it was explained in previous report, we have opted for the Yb:Yag in a ceramic version as gain medium. This choice was motivated by the excellent thermo mechanical properties of the YAG (especially its thermal conductivity), its hardness and its high damage threshold. Ytterbium is itself an interesting dopant having already demonstrated its ability to generate and amplify femtosecond pulses. Its different absorption bands also belong to the domain of wavelengths used in telecommunications diodes, which ensures the availability of powerful diodes, reliable pumping and reasonable cost. The Yb: YAG therefore is an appropriate material for our purposes.

The choice of ceramic version for Yb: YAG instead of single crystal allows us to consider that the pumping of the material and the signal amplification could be done thanks to beams pass through any surface of the ceramic. Thanks to this particularity, it was then possible to explore an original configuration which was very promising in terms of optimisation of the heat extraction : the direct pumping through the coolant fluid.

In this configuration, inspired from the Innoslab technology, the gain medium is a Yb:YAG ceramic plate with cooling water circulated over its large faces. The pumping is realized directly through the water. The cooling would be then more effective thanks to the fact that the extraction of heat would be through direct contact between the pumped area and the cooling liquid. These particulars conditions should limit sufficiently the different thermal effects (thermal lens, distortion wave forehead etc ...) without using cryogenic cooling. In addition, with regard only pump beams, any turbulence generated by the fluid flow on the beam wavefront would have no impact on the quality of the amplified beam. The signal beam would pass by the edge of the ceramic plate. In this configuration (see fig 1), it is also possible to homogenize the gain region by performing a pumping on either side of the ceramic and to produce multiple passages in the gain region like it is practiced with the technique "Innoslab."



a) b)

Figure 1: Architecture of proposed cooling a) Final configuration (transversal configuration), b) low pump power configuration (longitudinal configuration)

Depending of the pump power available, the pump beams will be focused with a ribbon shape or a spot shape in order to achieve the appropriate pump power density. And the amplification of the signal will be realized either in longitudinal configuration (see figure 1b) or by passing through the slice of the ceramic plate (see figure 1a).

As the length of the gain region is relatively small, a sufficiently high doping level is necessary. In the case of a quasi-3 levels gain medium such as Yb: YAG, a high doping level, in addition with a strong local heating, means more important thermo mechanical effects and leads to an important thermal settlement of the energy levels involved during the laser emission. This settlement results in a reduction of the population inversion and therefore a lower gain. It is the reason why we have conducted tests with different doping levels and thicknesses of ceramic to determine the most optimal configuration.

During our first tests of pumping through cooling water, we found that the presence of a very hot spot at the entrance of ceramic associated with low water flow generated small air bubbles right on the pumped area, bubbles that adhered to the surface and made dangerous the fact to pump the amplifying medium. In order to avoid this problem, different solutions have been implemented.

First, we have developed a specific cooling mount based on the technique of the nozzle where a copper pipe is used for the flow of water to an area where it was crushed. Then the pipe is drilled at said pinch region and a window and the ceramic are bonded (see figure 2). The narrowing of the tube causes a sharp increase in pressure at the face of the ceramic which allows to remove bubbles from the surface. The flow takes place on a relatively large thickness with a better guidance than in the case of a jet. There is no evidence of changes in the positioning of the pump beams (not signal beam when it pass also through the coolant). Achieving a cooling of this type on the two sides of the ceramic has been performed and the results are presented below.

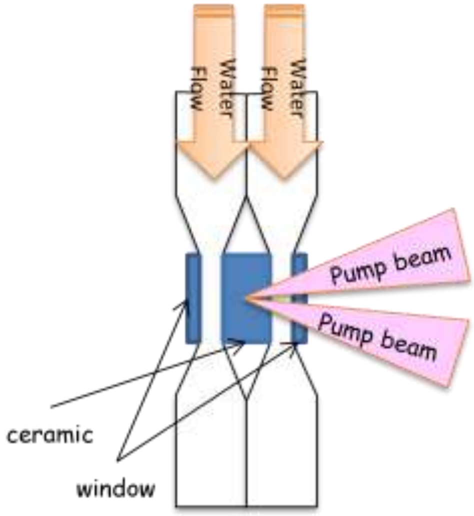


Figure 2: Schematic representation of the cooling of the 2 sides of the ceramic

We have also combined this technique with the use of hybrid ceramic. These ceramics are composed of three parts: two undoped YAG areas surrounding an ytterbium-doped YAG area [3]. This configuration allows to enjoy an excellent thermal coefficient of the undoped portions which facilitates the removal of heat from the doped region while pushing the hot spot at a place where the water is not flowing.

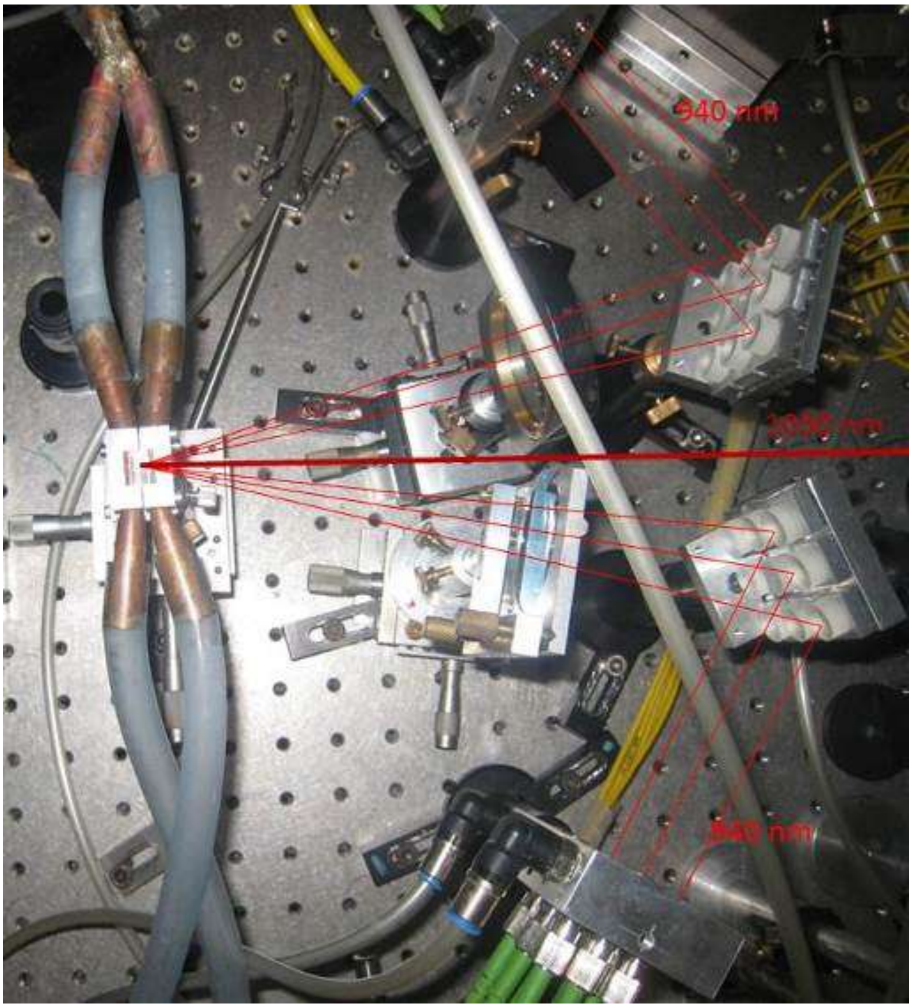


Figure 3: Photograph of the experimental setup for longitudinal configuration

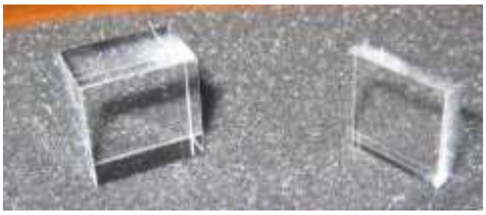


Figure 4: Photograph of a hybride and a single ceramics

Results for different types, doping level and thickness of ceramics in longitudinal configuration :

The table 1 present the absorption of each sample used in our experiment. Those results are really important because they show that there is a strong disparity between the doping level announced and the real absorption. This disparity explains some of the surprising results we have obtained at the begging of our research program.

Dopage(%)/Thickness	*2% 3mm*	*2% 4mm*	*5% 3mm*	*5% 4mm*	*5% Composite*	*7% Composite*
Absorption (%)	*39.7*	*48.2*	*42*	*71.1*	*63.7 3mm doped*	*71.6 3mm doped*

Table 1: Absorption in percentage for our different samples

The figure 5 presents the amplification results obtained for different doping level single ceramics. As we can see, the amplification performances are correlated with the absorption level and not with the doping level. The best results are obtained for the highest absorption (5% doped, 4 mm long ceramic). This fact indicates that the optimum doping level is not reached yet.

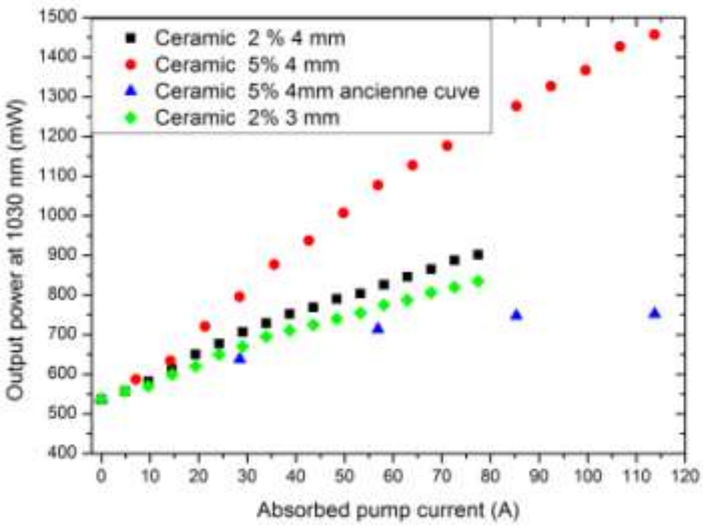


Figure 5: Gain curve obtained for different single ceramics

A gain up to 3 for 1035 nm 20nJ 100fs laser pulses with a repetition rate of 73 MHz pumped by 320 W of pump power has been observed, gain which can be double thanks to a second pass in the gain medium. In the case of the single ceramic which gave us the best results, we have also tested the amplification for different signal beam diameter (for the pump beam diameter, we are limit to the focal length of our focusing lenses).

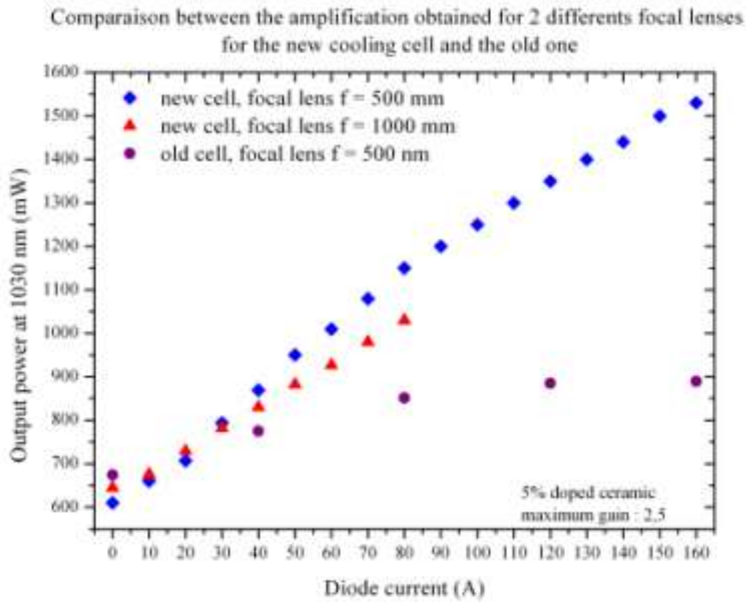


Figure 6: Gain curve obtained for different signal beam diameter (adjusted thank to different focal lenses)

We have also performed measurement of the spatial profile of the 1035 nm beam and of its wavefront in order to evaluate the possible perturbation and distortion due to thermal effect and water coolant. The spatial profile with and without amplification shows that, when everything is well-aligned, there is no perturbations nor distortions of the amplified beam.

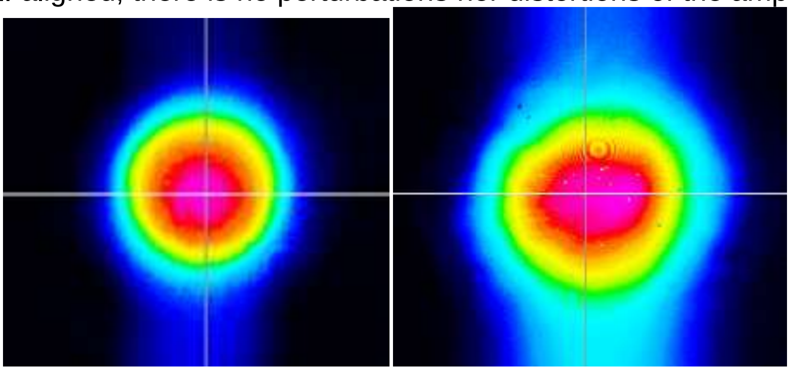


Figure 7: Spatial profile of the signal beam without and with amplification

It is more difficult to conclude on the wavefront distortion because of the strong deformation observed. This deformation is not due to the pumping but to stress inside the glass windows of the cooling mount.

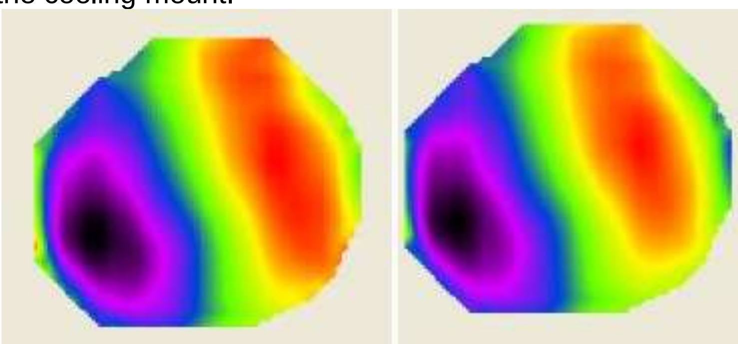


Figure 8: Wavefront of the signal beam without and with amplification

We also observed that, under the action of a much larger gain than previously, the spectrum of femtosecond pulses undergoes a spectral reduction of about 2 nm associated with a spectral blue shift (see figure 12) . This offset is adequately explained by the fact that the central wavelength of our femtosecond oscillator is 1035 nm while the center wavelength of the gain spectrum of the ceramics of Yb: YAG laser is 1030 nm. A short calculation also reveals that the spectral reduction should be essentially due to this difference of central wavelength.

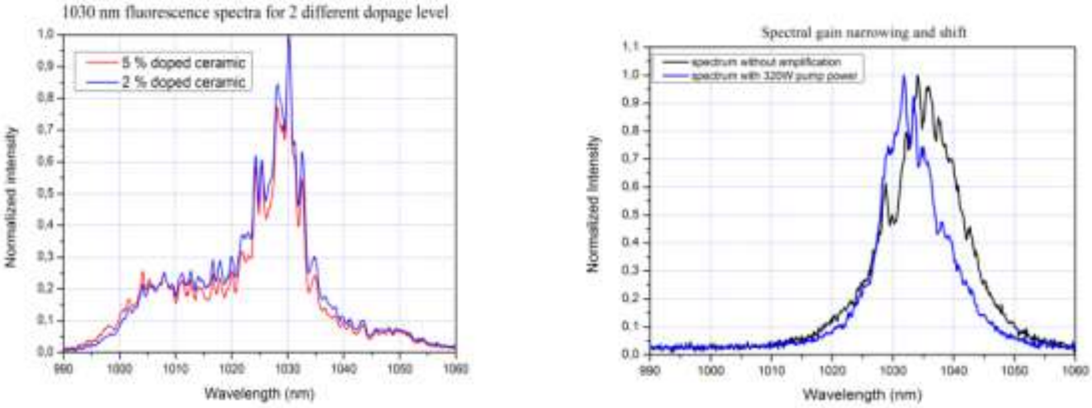


Figure 9: fluorescence spectrum of the ceramic and spectrum of the 1030nm beam before and after amplification

As our goal was to increase the pump power in order to test the transversal configuration, but also to have an idea of the performances that we can expect from our hybrid ceramics, we have also made some experiments in the longitudinal configuration. As expected from the absorption measurements, 7% doped hybrid ceramic gave us similar results to the 5% doped 4 mm long single one (see figure 10). Saturation of the gain seems to begin faster for this 7% doped sample which indicates that 7% should be an optimum concerning the doping level. With such high doping level, the impact of the cooling temperature is obvious. Even a low decrease of the water coolant temperature reduces the gain saturation (see figure 11).

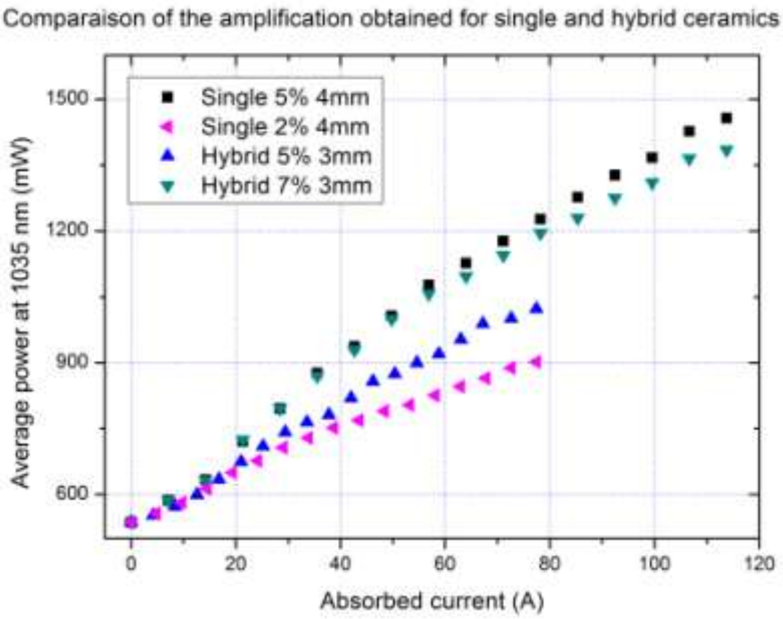


Figure 10: comparison of the amplification performances between single and hybrid ceramics

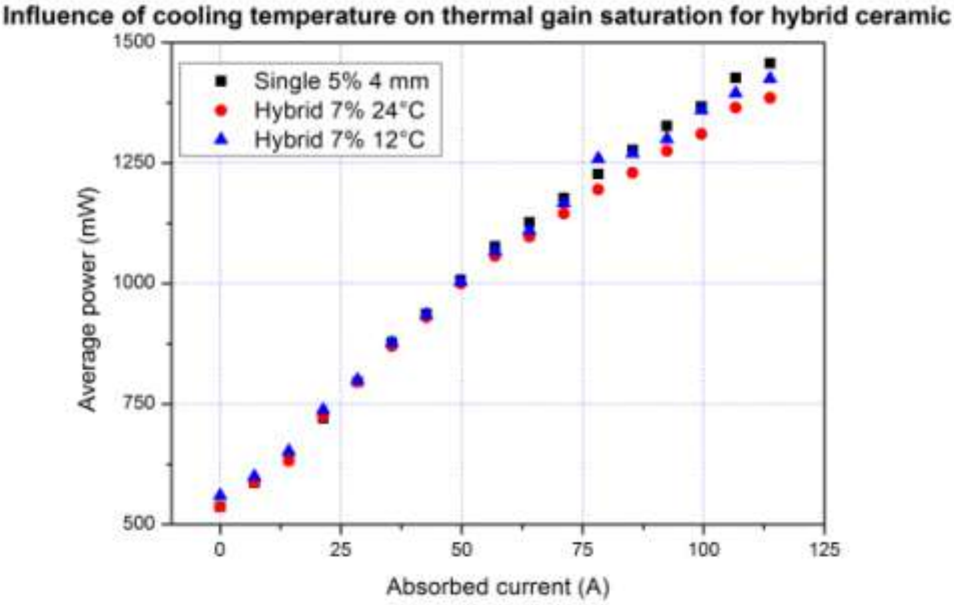


Figure 11: Influence of water temperature on the gain saturation

Some experiments on the transversal configuration have also been realized. Unfortunately, despite the supply of new more powerful pump diodes, it was not possible to obtain a sufficient pump power density on the ceramic to observe a phenomenon of amplification. But the measurements of the wavefront distortions show the absence of deformation related to thermo mechanical effects (fact to be controled with a higher pump power). This fact, combined with performances obtained in the longitudinal configuration, is quite promising.

4 Conclusions

Finally, at the end of this research program, the amplification module design that we choose looks very promising, both for amplification and for the control of thermal effects. Although amplification levels remain low, they are very high when you take into account of the weak pump power density on the ceramic. Increasing the density of pump power should provide quite easily very interesting levels of amplification. The spectral narrowing observed is readily explained by the difference in wavelength between the fluorescence spectrum and the signal spectrum. It should therefore be readily correctable by conventional techniques without generating an excessive decrease in the level of amplification.

5 References/Publications

[1] « Compact diode-pumped 1.1 kW Yb :YAG Innoslab femtosecond amplifier », P. Russbueldt et al., optics letters, vol 35, n°24, décembre 2010.

[2] « High efficency diode-pumped fentosecond Yb :YAG ceramic laser », B. Zhou et al., Optics Letters, vol 35, n°3, février 2010.

[3] « The Physical Properties of Composite YAG Ceramics », H. Yagi et al., Laser physics, vol 5, n°5, 2005