Broadband Yb:CaF2 regenerative amplifier for millijoule range ultrashort pulse amplification

Sandrine Ricaud, Martin Delaigue, Antoine Courjaud, Frédéric Druon, Patrick Georges, Patrice Camy, Jean-Louis Doualan, Richard Moncorgé, Eric Mottay

Broadband $Yb:CaF_2$ regenerative amplifier for millijoule range ultrashort pulse amplification

Sandrine Ricaud [1], Martin Delaigue [1], Antoine Courjaud [1], Frédéric Druon [2],
Patrick Georges [2], Patrice Camy [3], Jean-Louis Doualan [3], Richard Moncorgé [3], Eric Mottay [1]

1 Amplitude Systèmes, 6 allée du Doyen Georges Brus 33600 Pessac, France
2 Laboratoire Charles Fabry de l'Institut d'Optique,CNRS, Univ Paris-Sud, RD 128, 91127 Palaiseau, France
3 Centre Interdisciplinaire de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CNRS-CEA-ENSICAEN, Université de Caen, 6 Blvd Maréchal Juin, 14050 Caen, France

ABSTRACT

We report on a diode-pumped regenerative amplifier based on $Yb:CaF_2$ material, delivering pulses up to 1.8mJ pulse energy at a repetition rate of 100Hz. The crystal is pumped at the zero line at 978 nm with a 10W continuous wave (CW) fiber coupled laser diode. The pulses have a spectral bandwidth of 16nm centered at 1040 nm, which indicates a good potential for millijoule range sub 100fs pulse duration after compression. It is also a good candidate for seeding higher energy diode-pumped ytterbium lasers.

Keywords: Regenerative amplifier, Ytterbium doped material, Ultrafast laser

1. INTRODUCTION

More and more industrial applications require reliable, efficient and compact laser configurations. Industrial diode-pumped ultrafast lasers are very promising and offer high flexibility in energy and repetition rate. Ytterbium doped materials are popular since 10 years as active laser media, and show various advantages compared with their Nd^{3+} counterparts, for several applications around 1.05 µm. First of all, their broader absorption spectrum, which is suitable for direct diode-pumping, allows pumping with relaxed temperature regulation constraints. Their large emission bandwidth permits ultra short pulse generation, amplification, and broad tunability. Then, their simple electronic level structure based on only two manifolds, reduces thermal loads and prevents undesired effects such as upconversion and excited-state absorption. Thus, their low quantum defects allows high dopant concentrations while maintaining low fluorescence quenching and gives rise to high efficiencies even at high pump power.

For some specific applications, sub-100fs energetic pulses are required. Intensive work was done on the generation of short pulse duration with diode-pumped oscillators based on Ytterbium materials, however for millijoule range energy, broadband amplifiers suffer from thermal effect, leading to lower average power[1] and efficient amplifiers suffer from gain narrowing, leading to longer pulse durations, typically >350fs[2-3]. New materials are needed, with broad gain spectrum together with a high gain for good extraction efficiency.

A “new-old” laser material showed recently very promising results for short pulse generation in oscillators[4] as for short pulse high energy amplification up to the Terawatt level[5]. Indeed, $Yb:CaF_2$ offers a good thermal conductivity for undoped material, 9.7 $W\ m^{-1}\ K^{-1}$, comparable with that found for YAG, although the increasing Yb^{3+} concentration will reduce the thermal conductivity. For instance, the thermal conductivity decreases to 5.0 $W\ m^{-1}\ K^{-1}$ for a 5-at. .% doping level. Furthermore, it can be grown easily by use of the Czochralski and Bridgman technique, leading to very large size, up to diameters of about 200 mm. The crystals of a high-quality, show high damage threshold, low dispersion behavior and limited nonlinear effects under intense laser irradiation So, they are suitable for high-energy and high-power laser operation. In addition, the substitution of trivalent ytterbium for Ca^{2+} ions into the cubic structure of CaF_2, leads to charge compensation to maintain the electrical neutrality, creating thus a rich multisite structure. Broad absorption and emission bands are obtained, which makes it able to compete with glasses, and thus, to get broadly tunable continuous laser operation[6]. Finally, Yb:CaF_2 has a long fluorescence lifetime, 2.4 ms[7], which allows to use fewer pumping diodes to accumulate a certain amount of energy within the gain medium of a pulsed laser amplifier.

In this contribution, we report on a watt level regenerative amplifier based on Yb:CaF_2 laser material used at room temperature.

2. EXPERIMENTAL SET-UP

Our approach to study the potential of Yb:CaF_2 for short pulse amplification was to use the crystal in a regenerative amplifier cavity with a Pockels cell for Q-switching and a thin film polarizer centred at 1040 nm used at Brewster angle.
As depicted on the experimental set-up on figure 1, the crystal is a 5mm long crystal with 2.6 % doping concentration, used at Brewster angle, pumped through a dichroic mirror by a 10 W laser diode with a central wavelength of 978 nm. To optimize the overlap between the laser and the pump beams, the diode is coupled with a 200 µm diameter fiber, then collimated and focused by two 50 mm focal-length triplets to reduce optical aberrations. The pump spot diameter is estimated to approach 200 µm in the middle of the crystal. The cavity is designed in order to obtain diffraction limited laser beam at the output, with a cavity length of about 1.5 m.
The Pockels cell is adjusted for quarter waveplate at 45° in static state, *i.e.* without high voltage, and no birefringent effect with high voltage. We extract the intracavity pulse when its energy is maximal after about 2 µs in the cavity depending on amplifier repetition rate.
Thin film polarizer (TFP) is used in combination with the Pockels cell to extract the output pulse. Moreover we exploit the spectrally-dependent losses of the TFP in order to tune the output pulse spectrum. Indeed, as the polarizer acts on gain cavity spectrum as a high-wavelength pass, adjusting its angle between 55° and 59° allows to tune the spectrum of the laser. We assume that other component coatings (on mirrors and on Pockels cell) are almost flat on all crystal gain spectrum (at typical inversion).
Yb:CaF_2 spectral gain depends on the inversion of the laser showing mainly a maximum gain around 1045 nm for low inversion rate and around 1035 nm for high inversion rate. This behaviour allows to use such a material for various applications where central wavelength is an issue, i.e. injection of higher power amplifiers such as Yb:YAG or even Nd:glass, with relatively broad spectrum to fight against gain narrowing in the subsequent amplification stages.

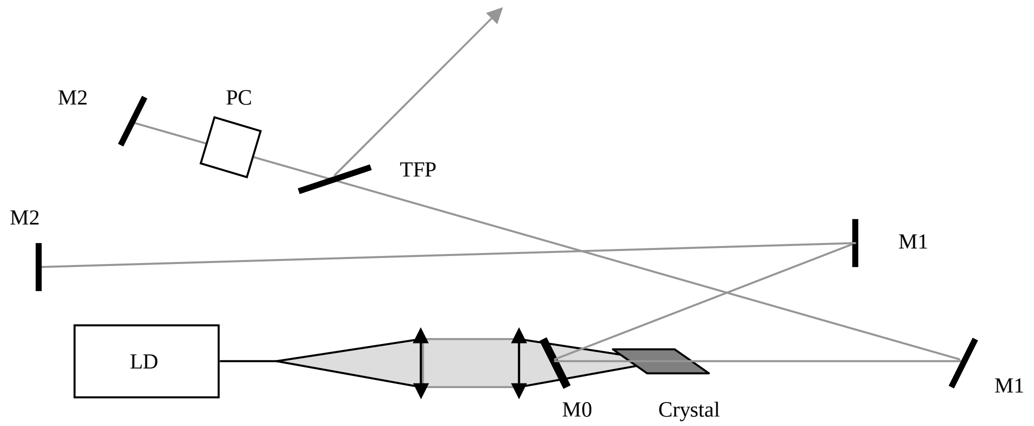

Figure 1 Laser Set-up, M0: dichroic mirror, M1: curved mirror, M2: end-cavity flat mirror, TFP: thin film polarizer, PC: Pockels cell, LD: Laser diode

3. Q-SWITCH RESULTS

As depicted on Figure 2 showing the dependence of the average power and energy versus the repetition rate, we achieved extracted energy as high as 1.8 mJ at 100 Hz repetition rate, and average power as high as 850 mW at higher repetition rate. The fluorescence lifetime of 2.4 ms of the crystal explains a decrease of the output energy for repetition rates higher than 300 Hz. However, the maximal average output power is reached at 800 Hz, due to a complex interplay between storage time and amplification time.

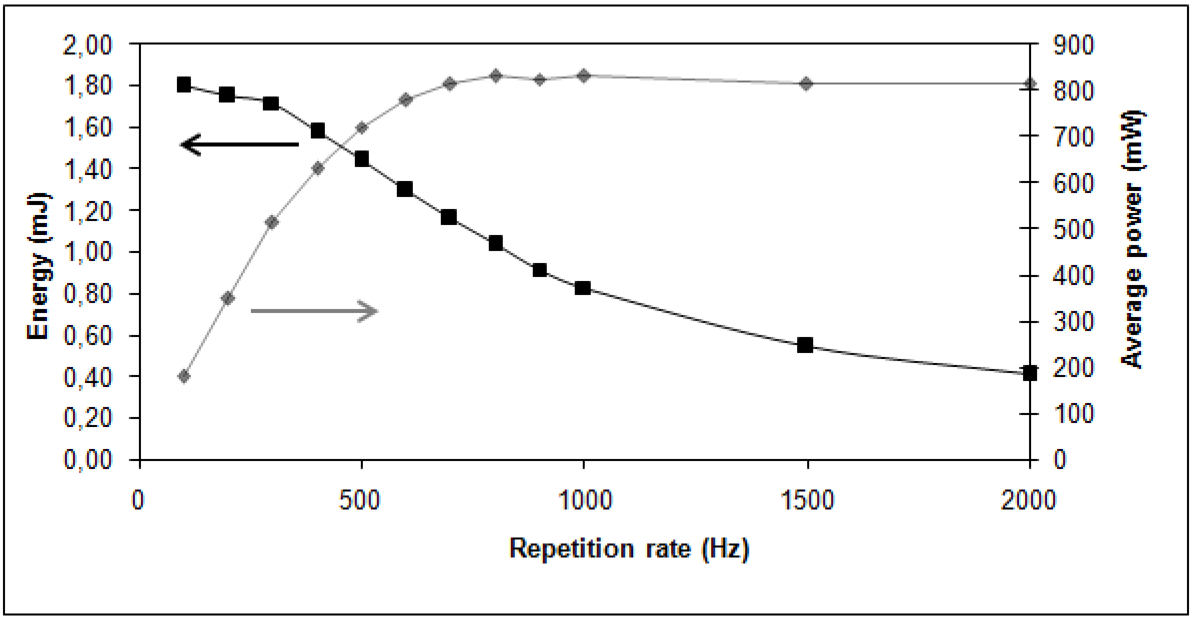

Figure 2 Evolution of average power and output pulse energy with repetition rate

We observed a significant influence of the polarizer alignment on the amplified spectrum, which allowed to tune and optimize the spectral shape for broadband amplification, necessary to achieve short pulses after compression in a chirped-pulse amplification architecture.

Figure 3 shows the spectrum obtained at a 500 Hz repetition rate and 1.5 mJ output pulse energy. The spectrum is centered at 1040 nm with a bandwidth of 16 nm FWHM, with a “camel” shape transcribing the valley at 1040 nm observable in the spectral gain profile.

This result clearly indicates a strong potential for sub 100 fs pulse duration in the millijoule range. In order to achieve millijoule range short pulses with this amplifier, seeding pulses are required with a central wavelength of 1040nm, and a bandwidth higher than 20nm, which is not available directly out of a purely soliton-based oscillator.

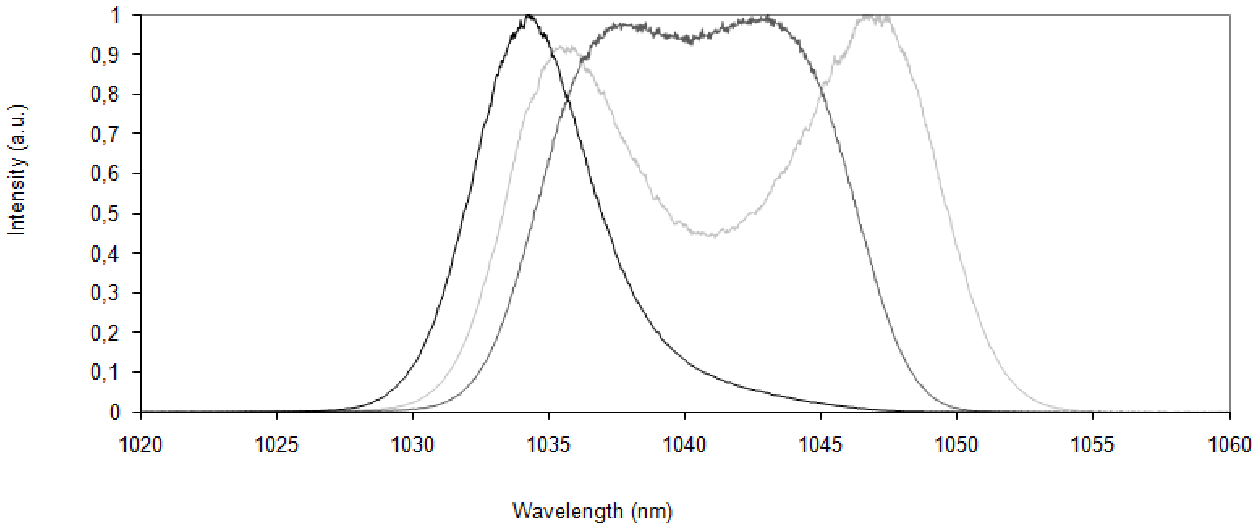

Figure 3 Normalized output pulse spectrum at 500 Hz (1,5 mJ), and dependence of the polarizer angle of incidence

4. SEEDING WITH A BROAD SPECTRUM

The experiment was then conducted using a standard oscillator combined with a spectral broadening system. The oscillator used for the injection is centered at 1029 nm, with 6nm broad spectrum.
So, we decided to inject the oscillator output into an undopped polarization maintaining large mode area fiber (PLMA) whose core diameter is 25 µm. The Yb^{3+}:KGW oscillator delivers transform-limited 180 fs pulses at a repetition rate of 30 MHz with an average power of 700 mW at the central wavelength of 1029 nm. Into the fiber, the action of self-phase modulation (SPM) leads to a considerable spectral broadening of the oscillator spectrum. Thus, we could select the attractive part situated between 1030 and 1050 nm.
This oscillator was then injected into a 4m long undoped polarization maintaining large mode area fiber (PLMA) with 25µm core diameter. Using such large mode area allows to achieve a smooth broadened spectrum, owing to the interplay of self-phase modulation together with positive dispersion. The pulse train delivered by the Yb^{3+}:KGW oscillator were transform-limited pulses with 180 fs pulse duration at a repetition rate of 30 MHz with an average power of 700 mW. The pulses at the output of the fiber showed a broadened spectrum of approximately 60 nm, allowing to select the proper spectrum region between 1030 and 1050 nm.
The spectrally broadened pulses were directly injected in the broadband regenerative amplifier, taking benefit of the stretching effect of the fiber. The amplified spectrum showed a bandwidth similar to the one achieved without seeding. Distortions appeared in the spectrum for 200µJ extracted pulse energy, indicating that stretching and subsequently compressing is required to achieve millijoule level. However, this result demonstrates that the regenerative amplifier supports a broadband spectrum, confirming the potential of such amplifier.

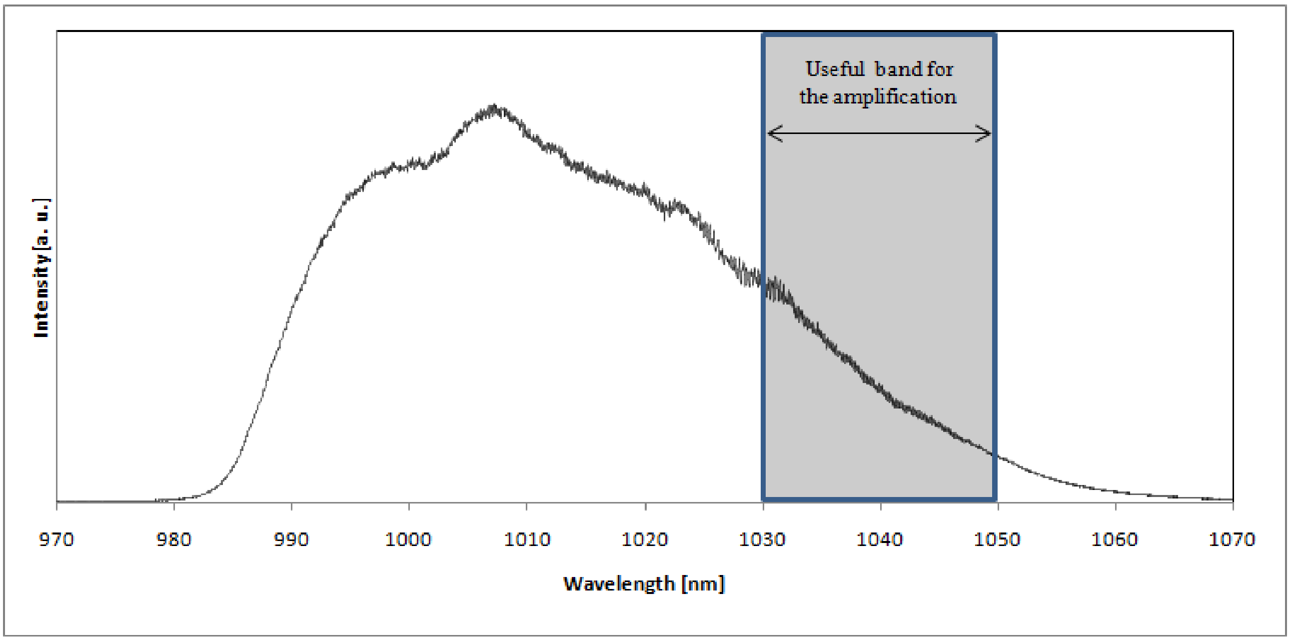

Figure 4 Output pulse spectrum of the PLMA fiber

5. CONCLUSION

We demonstrated broadband, high energy regenerative amplifier, based on Yb:CaF_2 single crystal. We obtained maximal output energy of 1.8 mJ, maximal output power of 850 mW and maximal spectral bandwidth of about 16 nm centered at 1040nm. This laser material offers a good combination of high energy storing capacity together with broad gain spectrum, indicating a good potential for sub-100-fs pulse amplification at millijoule energy level.

6. REFERENCES

[1] Liu, H., Biswal, S., Paye, J., Nees, J., Mourou, G., Hönninger, C. and Keller, U., "Directly diode-pumped millijoule subpicosecond Yb:Glass regenerative amplifier," Opt. Lett. 24 917-919 (1999)

[2] Liu, H., Nees, J., Mourou, G., Biswal, S., Spühler, G. J., Keller, U. and Kuleshov, N. V., "Yb:KGd$(WO_4)_2$ chirped-pulse regenerative amplifiers," Opt. Com. 203 315 (2002)

[3] Delaigue, M., Hönninger, C., Courjaud, A., Manek-Hönninger, I. and Mottay, E., "1mJ, multikHz, sub-500fs diode-pumped ytterbium laser amplifier," in Conference on Lasers and Electro-Optics/Quantum Electronics, OSA Technical Digest Series, (2007)

[4] Lucca, A., Debourg, G., Jacquemet, M., Druon, F., Balembois, F., Georges, P., Camy, P., Doualan, J. L. and Moncorgé, R., "High-power diode-pumped Yb3+:CaF_2 femtosecond laser," Opt. Lett. 29 2727-2729 (2004).

[5] Siebold, M., Hornung, M., Boedefeld, R., Podleska, S., Klingebiel, S., Wandt, C., Krausz, F., Karsch, S., Uecker, R., Jochmann, A., Hein, J. and Kaluza1, M. C., "Terawatt diode-pumped Yb:CaF_2 laser," Opt. Lett. 33 2770-2772 (2008)

[6] Petit, V., Doualan, J.L., Camy, P., Ménard, V. and Moncorgé, R., "Cw and tunable laser operation of Yb^{3+} doped CaF_2," Appl. Phys. B 78 681 (2004).

[7] Camy, P., Doualan, J.L., Benayad, A., Von Edlinger, M., Ménard, V. and Moncorgé, R., "Comparative spectroscopic and laser properties of Yb^{3+}-doped CaF_2, SrF_2 and BaF_2 single crystals," Appl. Phys. B 89 539 (2007)