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To cite this version:

Aurelien Dantan, Julien Laurat, Alexei Ourjoumtsev, Rosa Tualle-Brouri, Philippe Grangier. Femtosecond Ti:sapphire cryogenic amplifier with high gain and MHz repetition rate. Optics Express, Optical Society of America, 2007, 15 (14), pp.8864-8870. hal-00689672

HAL Id: hal-00689672
https://hal-iogs.archives-ouvertes.fr/hal-00689672
Submitted on 19 Apr 2012

Femtosecond Ti:sapphire cryogenic amplifier with high gain and MHz repetition rate

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Abstract: We demonstrate high gain amplification of 160-femtosecond pulses in a compact double-pass cryogenic Ti:sapphire amplifier. The setup involves a negative GVD mirrors recompression stage, and operates with a repetition rate between 0.2 and 4 MHz with a continuous pump laser. Amplification factors as high as 17 and 320 nJ Fourier-limited pulses are obtained at a 800 kHz repetition rate.

OCIS codes: (140.3280) Laser amplifiers; (140.3590) Lasers: titanium; (320.7090) Ultrafast lasers

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1. Introduction

High-energy femtosecond pulses are essential for many applications in biophysics, chemical spectroscopy, nonlinear optics and high-energy physics[1]. Despite recent progress in available powers, amplification of femtosecond oscillators is often required for these stringent applications[2]. On account of its high saturation fluence and thermal conductivity, broad gain bandwidth, and long fluorescence lifetime, titanium-doped sapphire is one of the most widely used materials for ultrashort pulses amplification[3]. Multi-pass or chirped-pulse regenerative amplifiers are commonly used, with repetition rates in the kHz range with pulsed pumping [4, 5, 6, 7, 8, 9, 10, 11].

Continuous pumping allows to reach higher repetition rates, and for instance Norris demonstrated fs-pulses amplification using Ti:sapphire with a cw regenerative amplifier at 250 kHz[12]. A simpler, double-pass amplifier was reported by Liu *et al.*[13, 14], at a much higher repetition rate (88 MHz). More recently, Huber *et al.* demonstrated efficient amplification between 10 kHz and 4 MHz, in a double-pass geometry using an adaptative prism recompression stage[15].

Another approach, useful in an *intermediate regime* where the repetition rate is of the order of the MHz, is to use cavity-dumped oscillators, which allow for the production of pulses in the tens of nJ energy range[16, 17, 18]. Increasing further the pulse energy of cavity-dumped commercial systems with simple optical setups would open promising possibilities for high-sensitivity lock-in techniques, pulse-shaping and nonlinear optics applications. For instance, generating 150 fs-pulses with up to several hundreds of nJ energy at a 1 MHz repetition rate

Received 30 Apr 2007; revised 25 Jun 2007; accepted 26 Jun 2007; published 2 Jul 2007

would be especially interesting for quantum optics experiments with thin nonlinear crystals[19, 20]. In particular, this may lead to the production of strongly nonclassical states of light by increasing the available parametric gain[21]. Such high energy pulses would also be suitable for fundamental quantum mechanics tests[22].

In this paper, we report on the realization of a continuously-pumped double-pass cryogenic Ti:sapphire femtosecond amplifier, designed for pulses from a cavity-dumped laser with repetition rates between 0.2 and 4 MHz. Cryogenic temperatures allow for the use of higher pump powers and therefore stronger amplification. Negative GVD mirrors are used for the recompression stage, allowing for a compact optical setup. At a repetition rate of 800 kHz we observe amplification factors up to 17 (pump on / pump off power ratio) for 18.5 W pump power and cooling temperatures in the 100 K range, allowing to produce up to 320 nJ Fourier-limited pulses. Amplification factors greater than 13 are still obtained at 4 MHz, yielding pulses with over 120 nJ energy and more than 0.5 W average output power. A non trivial behavior of the amplification with the crystal cooling temperature is also reported.

2. Setup

The setup is sketched in Fig. 1. A commercial cavity-dumped Ti:sapphire oscillator (Tiger-CD, Time Bandwidth) pumped by a 3W cw Verdi (Coherent) generates nearly-Fourier transform-limited pulses with 160 fs duration at 845 nm. Its repetition rate can be varied between 200 kHz and 4 MHz, yielding ~ 40 nJ pulses for repetition rates up to 1 MHz, and ~ 20 nJ pulses at 4 MHz. After passing through an optical isolator, the infrared beam is overlapped with the pump beam coming from a cw solid-state laser (18 W Verdi) delivering up to 18.5 W power at 532 nm. In order to get strong single-pass amplification both beams are tightly focused (beam waist diameter $\sim 20-25\mu$m) inside a Brewster-cut Ti:sapphire crystal by a 75 mm focal-length lens. The infrared beam is recollimated with another 75 mm focal-length lens and reflected back by a dichroic mirror to be amplified a second time. The focusing lenses are mounted on translation stages to optimize the beam size and overlap (see Sec. 4). In order to compensate for the astigmatism due to the propagation in the crystal, this second lens is tilted as shown in Fig. 1 and manually adjusted by looking at the collimated output beam. At the output of the optical isolator the pulses are recompressed back to their initial duration using 12 reflections on two pairs of negative group velocity dispersion mirrors (Layertec, GVD~ -1300 fs^2).

About 88% of the pump power is absorbed by the 3 mm-long highly doped crystal ($\alpha_{532} = 7$

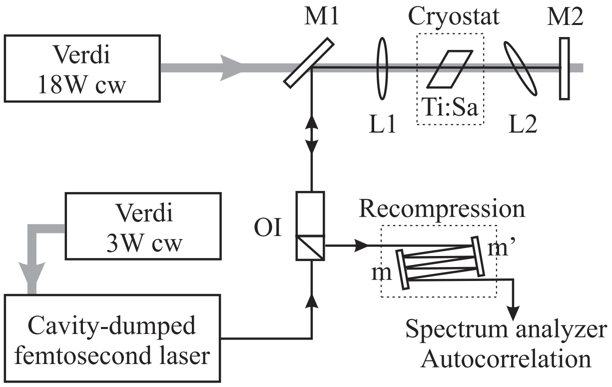

Fig. 1. Cryogenic double-pass amplifier setup with compact recompression stage. OI: optical isolator. M1, M2: dichroic mirrors. L1, L2: focusing lenses with $f = 75$ mm. Ti:Sa: Brewster-cut highly-doped crystal. The mirrors m, m' have negative GVD.

#82477 - $15.00 USD Received 30 Apr 2007; revised 25 Jun 2007; accepted 26 Jun 2007; published 2 Jul 2007

cm^{-1}, Crystal Systems, Inc.). Owing to the extremely tight focusing inside the crystal and intense cw pump power, the crystal needs to be cooled down efficiently to avoid damage and reduce beam distortion and thermal lensing effects[23, 24, 25]. It is thus enclosed in a vacuum chamber ($< 10^{-4}$ Pa) with antireflection-coated windows ($R < 0.5\%$ at both 532 and 845 nm) and cooled with a temperature-stabilized liquid nitrogen cryostat. At temperatures in the 100 K range the thermal conductivity of Ti:sapphire is increased by a factor ~ 30, and the refractive index temperature gradients are decreased by a factor 7 with respect to ambient temperature[26, 27]. Although it is more demanding, the use of a cryostat instead of a Peltier cascade[15] allows us to substantially improve the amplification by operating with higher pump powers, without damaging the crystal, and still maintaining a high output beam quality.

3. Experimental results

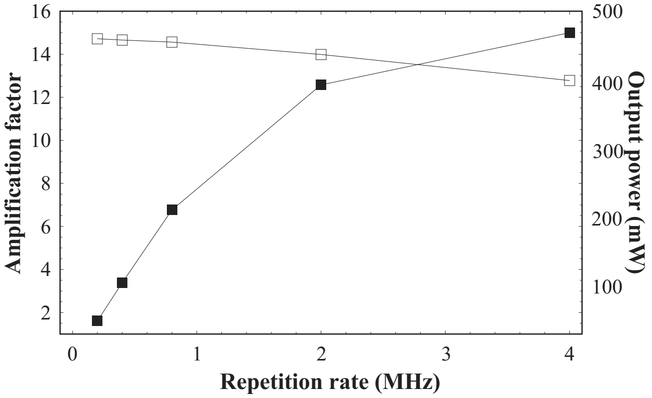

Fig. 2. Amplification factor (□) and average output power (■) as a function of the repetition rate, for 15 W pump power and a temperature of 110 K.

Typical variations of the average output power and the amplification factor (ratio of output power after recompression with and without amplification) with the oscillator repetition rate are shown in Fig. 2, for 15 W pump power and a temperature of 110 K. The amplification factor decreases from 14.7 in the 200-800 kHz range, corresponding to 270 nJ energy pulses, to 13 at 4 MHz for which 120 nJ pulses and 475 mW average output power are still obtained. Although the gain is slightly reduced, the saturation in output power is mostly due to the saturation in the input power delivered by the cavity-dumped oscillator above 800 kHz. Increasing the pump power up to 18.5 W allows to reach amplification factors of the order of 17, corresponding to a single-pass gain larger than 4, and produce pulses with up to 320 nJ energy at a repetition rate of 800 kHz (Fig. 3), with power fluctuations in the percent range over minutes.

For a fixed pump power and temperature the output infrared power scales linearly with the input power, so we always operate in the unsaturated gain regime. However, for high amplification levels we observe a slight pulse compression - from 160 to 135 fs as measured by nonlinear autocorrelation - as well as spectrum broadening - from 4.5 to 5.5 nm - on account of self-phase modulation in the crystal[1]. The pulses nevertheless stay Fourier transform-limited, and the effect is found to disappear when reducing either the infrared or the pump power, or when increasing the input pulses duration.

In addition, we observe non trivial variations of the amplification with the temperature, as shown in Fig. 3. The amplification factor and the average output power are represented for var-

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[1] The B-integral value is ~ 0.22 for the double-pass.

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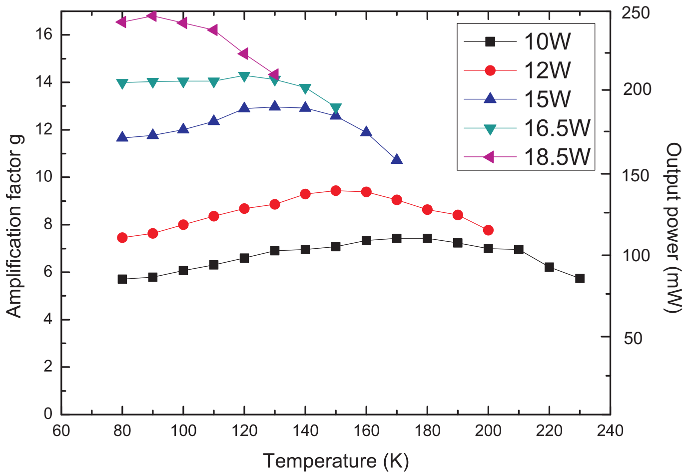

Fig. 3. Amplification factor and average output power as a function of the crystal mount temperature, for different pump powers and a fixed repetition rate of 800 kHz.

ious pump powers ranging from 10 W to 18.5 W and for a 800 kHz repetition rate. For a given pump power, the amplification increases when the crystal is cooled down, as expected, but there is an optimal temperature below which the gain starts to decrease. This behavior is attributed to a competition between thermal effects and the modification of the Ti:sapphire gain spectrum with the temperature[28].

More specifically, owing to the short Rayleigh ranges involved, the amplification is very sensitive to the modematching between seed and pump beams in the amplification zone, which is strongly affected by thermal lensing effects at high pump powers. As can be seen from Fig. 3, cooling the crystal down to cryogenic temperatures improves the amplification, all the more so that the pumping power is large. However, the existence of an optimal temperature is linked to the fact that the Ti:sapphire emission spectrum is blue-shifted when the temperature decreases from 300 K to 77 K[29]. Since our oscillator output pulses are centered at 845 nm we operate on the red side of the gain spectrum at room temperature. When going to lower temperatures, the intrinsic gain at 845 nm starts to increase (as well as the quantum efficiency[30]), but ultimately ends up decreasing. Amplification is thus optimal when the improvement due to the reduction of thermal effects is balanced by the decrease in gain at 845 nm at low temperatures.

4. Discussion and model

Although exact gain calculations are rather complex to perform, the dependence of the amplification with cooling temperature and pumping power can be explained by a simple toy model analyzing both the modematching and the blue-shift issues. In our case, the central wavelength is fixed, which means that the small signal gain in the absence of any thermal effects will be peaked around a certain temperature T_λ and width δT. On the other hand, thermal lensing will affect the pump-seed modematching $m(T,P)$, all the more so when the pump power is high and the temperature increases. We therefore assume an amplification factor of the form

$$g = \exp[G_\lambda(T)m(T,P)] \tag{1}$$

The thermal lens focal length is given by [23]

$$f = \frac{\kappa\pi\omega_{532}^2}{\rho P_{abs} dn_T} \tag{2}$$

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where $\kappa(T)$ and dn_T are the Ti:sapphire thermal conductivity and refractive index change, P_{abs} is the absorbed pump energy ($\sim$ 88%) and $\rho = 1 - \lambda_{532}/\lambda_{845} = 0.37$ the fraction of pump energy converted to heat. Taking a modematching term of the form

$$m(T,P) \sim \frac{1}{1+(f_0/f)^2} \sim \frac{1}{1+aP^2\exp(bT)} \tag{3}$$

and assuming that the small signal gain at 845 nm to be proportional to the pump power in the unsaturated regime and to have a broad Lorentzian temperature dependence

$$G_\lambda(T) \sim \frac{cP}{1+(T-T_\lambda)^2/\delta T^2} \tag{4}$$

one can reproduce the experimental results for $a = 0.02$ W^{-2}, $b = 0.006$ K^{-1}, $c = 0.285$ W^{-1}, $T_\lambda = 210$ K, $\delta T = 200$ K. The values of T_λ and δT are extrapolated from small gain spectra measured by Delaigue *et al.*[29], whereas a, b, c are obtained by fitting the experimental data. Let us note that the data shown in Fig. 3 is obtained by optimizing for each temperature the modematching and the focusing of both beams, by translating the crystal as well as the seed beam focusing lens. This simple optimization procedure allows for greatly reducing the thermal lensing effects and finding the best trade-off between amplification and thermal effects at a given temperature. If one were to take a *fixed* spot size for the beams and the values for κ and dn_T found in the literature[26, 27], the variation in the thermal lens focal length of Eq. (2) over the temperature range considered would be approximately 10 times larger than what can be deduced from the simple model presented above. This explains why our fitted value of b differs from the one ($b \sim 0.02$) which can be obtained from the data of Refs. [26, 27].

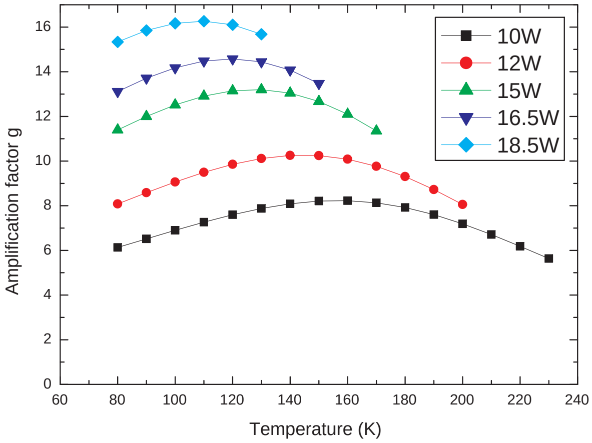

Fig. 4. Fit of the variation of the amplification factor with temperature for the same conditions as in Fig. 3.

5. Conclusion

As a conclusion, we have demonstrated efficient femtosecond amplification with a compact double-pass Ti:sapphire amplifier at 845 nm in the MHz regime. Cryogenic cooling allows

Received 30 Apr 2007; revised 25 Jun 2007; accepted 26 Jun 2007; published 2 Jul 2007

to use high cw pump power and obtain high amplification with repetition rates as high as 4 MHz. Gains as large as 17 and 13 are obtained at 800 kHz and 4 MHz, respectively. We have shown that the cooling temperature plays an important role in optimizing the gain for a given wavelength. We also point out that our cavity-dumped laser has been designed to operate at 845 nm in order to be used in experiments such as those described in Refs. [19, 20, 21], and cannot be tuned easily. However, Delaigue *et al.* observed a substantially higher increase in the small signal gain ($>$ 50%, for a crystal with lower dopant concentration) when operating at 770 nm rather than 850 nm and cooling from 260 K to 100 K[29]. We therefore expect that much higher output powers and gains should be easy to reach by tuning the wavelength of the input pulses closer to the peak of the Ti:sapphire gain profile[15].

We gratefully acknowledge useful discussions with Patrick Georges, Rupert Huber, Isao Matsushima, and Manuel Joffre. Warm thanks are due to Martin Delaigue for providing us with a copy of his PhD thesis. This work was supported by the European IST/FET project COVAQIAL and by the French ANR/PNANO project IRCOQ.