Laser and Particle Beams (2007), *25*, 219–223. Printed in the USA.

DOI: 10.1017/S0263034607000043

High-power Ti:Sapphire lasers: Temporal contrast and spectral narrowing

M. KALASHNIKOV,[1] K. OSVAY,[1,2] AND W. SANDNER[1]

[1]Max Born Institute for Nonlinear Optics and Ultrafast Spectroscopy, Berlin, Germany
[2]Department of Optics and Quantum Electronics, University of Szeged, Szeged, Hungary

(RECEIVED 5 November 2006; ACCEPTED 31 January 2007)

Abstract

New extensions of the chirped pulse amplification (CPA) scheme designed specially for petawatt Ti:Sapphire lasers are considered. The two new schemes support a spectral bandwidth sufficient for 20 fs pulses and a temporal contrast of 10^{12}. The Double CPA scheme consists of two CPA stages with an intermediate temporal pulse filtering for temporal contrast improvement. The scheme of Negative–Positive CPA amplification takes advantage of consecutive saturated amplification of down chirped and up chirped pulses. This allows a suppress imprint of gain narrowing, which usually limits the spectral bandwidth at the multi-terawatt power level, and reach the bandwidth in excess of 50 nm without using any direct spectral shaping of the pulse.

Keywords: High power lasers; Saturation; Spectral narrowing; Temporal contrast

1. INTRODUCTION

The advantages of chirped pulse amplification (CPA) together with the unique properties of Titanium doped Sapphire medium, has lead to the availability of 100-terawatt (TW) power Ti:Sapphire (Ti:S) lasers with a relatively small size. Recently, such a system became capable to approach the focused intensity of $\sim 10^{22}$ W/cm^2 (Bahk *et al.*, 2005). Current developments in Ti:S crystal growth techniques, have reached a level where Ti:S crystals with diameters larger than $\sim$120 mm and of very high optical quality became accessible. As a result, several scientific laboratories worldwide have already started petawatt (PW) Ti:S laser projects (Aoyama *et al.*, 2003; Danson *et al.*, 2005; Hein *et al.*, 2004; Peng *et al.*, 2006; Perry *et al.*, 1999; Pittman *et al.*, 2002). There have been proposals (Ross *et al.*, 1999) and even nice results for construction of PW class lasers based on optical parametric CPA (Lozhkarev *et al.*, 2006; Ross *et al.*, 2000; Yang *et al.*, 2002). However, the problems with the construction of reliable pump lasers having appropriately shaped pulses (Hugonnot *et al.*, 2006; Waxer *et al.*, 2003), and concerns about the temporal contrast (Divall & Ross, 2004; Osvay *et al.*, 2005) are still to be resolved.

Since most PW lasers are expected to be used for laser-matter interaction experiments, especially at high intensity, high temporal contrast becomes a point of great importance. The dominant source of pre-pulse formation in Ti:S CPA laser systems are amplified spontaneous emission (ASE). One of the main features of CPA is that the amplified pulse is temporally stretched, but the ASE is not. Since the ASE cannot be recompressed after the compressor, shortening the duration of the CPA pulse would increase the peak power and contrast simultaneously.

In this paper, we present new schemes of CPA laser architecture developed at the Max-Born-Institute, which support temporal ASE contrast exceeding 10^{12}, and allow to suppress narrowing of the pulse spectrum during amplification. These are the Double-CPA (DCPA) (Kalashnikov et al., 2005*a*) laser, and the scheme that implements successive amplification of laser pulses first with negative then with positive chirp (NPCPA) (Kalashnikov *et al.*, 2005*b*).

2. IMPROVEMENT OF TEMPORAL CONTRAST

High peak power Ti:S lasers have an ASE background typically ranging around 10^{-7}–10^{-5} of the peak laser intensity. Most of the modern high power Ti:S CPA lasers use similar architecture, which consists of a short-pulse master oscillator,

Address correspondence and reprint requests to: M. Kalashnikov, Max Born Institute for Nonlinear Optics and Ultrafast Spectroscopy, Max-Born-Strasse 2/A, Berlin 12489, Germany. E-mail: kalashnikov@mbi-berlin.de

a stretcher, a pre-amplifier, a power amplifier, and a compressor. Common laser oscillators deliver laser pulses of rather low energy ~1 nJ, but can exhibit high temporal intensity contrast as 10^{10}. The first amplifier has the highest gain in the system, which ranges around 10^6–10^8, resulting in an output energy around 1–5 mJ. Low energy levels of the master oscillator losses in the stretcher and additional equipment for spectral phase correction etc. result in a low starting signal level and thus high noise (ASE) in the first amplifier. Thus, the output contrast value is reduced by three, or sometimes even more orders of magnitude.

2.1. Double chirped pulse amplification

It was reported that direct amplification of laser pulses preceding the pulse stretching allows substantial improvement of temporal contrast (Itatani *et al.*, 1998). We measured the dependence of temporal contrast on the seed energy for our nine-pass Ti:S pre-amplifier (Kalashnikov & Osvay, 2006). The experiment shows a linear increase of the output contrast depending on the seed energy. If an intensity level of 10^{22} W/cm^2 is expected from a PW Ti:S system, the prepulse free interaction with solid targets requires a temporal contrast of ~10^{12}. Assuming that the dependence of the intensity contrast on the seed energy will further grow linearly, this will require input energy of tens of microjoules (μJ). Such a large value of energy can definitely not be possible with cavity dumped oscillators, especially delivering pulses of 10–20 femtosecond (fs). In addition, comparing the experiment presented in Figure 1, a PW laser will have several additional amplifiers running at saturation, which will additionally increase the output ASE level. Thus even higher seed energy is demanded to reach the required contrast value.

One of the most promising ways to improve temporal contrast of CPA lasers is the DCPA laser scheme (Kalashnikov *et al.*, 2005*a*). It consists of two complete CPA stages, and between them, a nonlinear temporal filter to subtract the ASE pedestal. The filtering system has to support the mJ energy level, have a uniform spatial mode for further amplification, extinction of 10^5, and have high transmittance (higher than 10%).

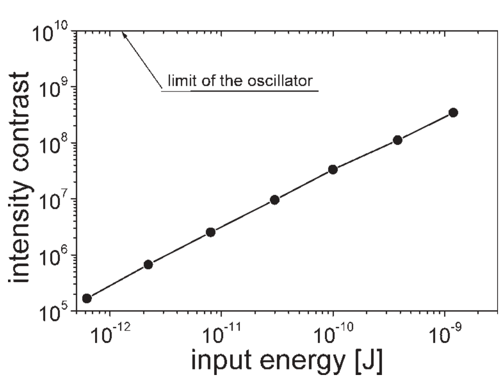

Fig. 1. Dependence of temporal intensity contrast of the nine-pass Ti:S amplifier on the seed energy.

The experimental scheme of the DCPA laser is presented in Figure 2. The first CPA stage (master oscillator, stretcher, multi-pass amplifier, and compressor) delivers ~1 mJ recompressed pulses of ~30 fs. The nonlinear temporal filter follows after the first compressor. We used a nonlinear filter based on rotation of the polarization ellipse in air (Kalashnikov *et al.*, 2004). Optical components supported the maximum extinction of ~10^5. The transmitted pulse exhibits a good spatial mode, which is especially important for further amplification in the second CPA stage. We found that the filter works efficiently with mJ pulses, exhibiting a rather high transmission (~0.5).

The second CPA stage consisted of a stretcher, multi-pass amplifier, and a compressor. Since the energy stability of the 10 Hz multi-pass amplifier preceding the nonlinear filter was not perfect (peak to peak fluctuation ~20%), the shape of the pulse spectrum injected in the second CPA stage varied slightly from shot to shot. This resulted in ±15 fs fluctuations in the pulse duration of the recompressed DCPA pulse around an average value of 50 fs.

The temporal contrast was characterized by a third order cross-correlator with a dynamic range of ~10^{10}. Results of the measurement are shown in Figure 3. The substantial improvement of temporal contrast with the DCPA laser is evident. With our cross-correlator, we did not observe any noticeable ASE signal at the leading edge of the laser pulse. This allows us to conclude that the ASE contrast at this edge is at least 10^{10}, which is also the limit of our correlator. Taking into account that the ASE level at the first CPA stage has the value of 10^7 and the fact that the nonlinear filter has an extinction of ~10^5, allows us to estimate the expected

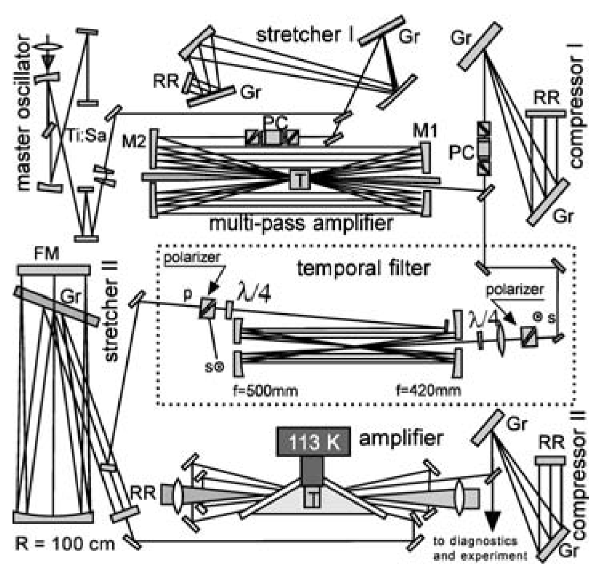

Fig. 2. Schematic of the DCPA laser. Gr, diffraction gratings; RR, retro-reflectors; PC, Pockets cells; M1, M2, mirrors of the multi-pass amplifier f = 42 cm and 50 cm; FM, flat mirror of the stretcher.

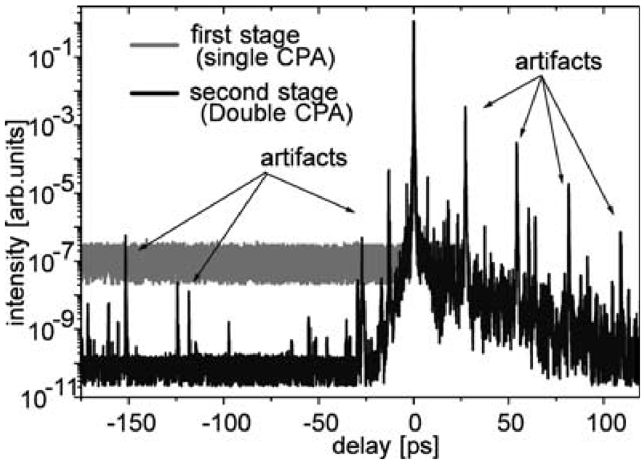

Fig. 3. Comparison of the recompressed pulses of the 2 mJ CPA laser (grey curve) and the 20 mJ DCPA laser pulses (black curve). Low intensity pulses appearing at the leading edge of the pulse are artifacts generated by the cross-correlator.

value of contrast at the front edge of 10^{12}, which could not be measured with our cross-correlator.

3. SUPPRESSION OF GAIN NARROWING IN TI:S LASERS

The main limitations of the pulse spectrum and thus duration of modern Ti:S CPA laser are coming from the non flat-top spectral gain of the amplifier material (gain narrowing, GN) and saturated pulse amplification (SA). Similarly to the temporal contrast, the main source of spectral reduction is the first amplifier. The extent of gain narrowing is of highest importance in the pre-amplifier, which to be reminded, typically possesses the highest gain in the laser system. Since the total gain required for a PW Ti:S laser exceeds a value of 10^{10}, it becomes difficult to achieve pulses of ~30 fs and shorter. Upon saturated amplification, the leading edge of the pulse experiences higher amplification, which makes the leading front steeper. In the case of chirped pulses, this works oppositely to pulses with different chirp sign, resulting in an effective red (for positive chirp) (Cha *et al.*, 1999; Chu *et al.*, 2004; Kalashnikov *et al.*, 2002) and blue (for negative) shift of the pulse spectrum. Thus, utilization of the combination of negatively CPA in pre-amplifier and positively CPA in power amplifiers can lead to a broader spectrum than that provided by a usual positive CPA laser.

3.1. The NPCPA laser system

To validate the considerations mentioned above, we have accomplished a conventional CPA laser with a positively stretched pulse and a laser, which implements a combination of positively and NPCPA using one set of optical elements (Kalashnikov *et al.*, 2005*b*). Since the NPCPA laser (Fig. 4) requires first a negatively chirped pulse, an extra stretcher was installed in addition.

An fs oscillator generated the seed laser pulses with duration of ~15 fs. The first stretcher of the CPA and NPCPA lasers was a positive and a negative stretcher, respectively. The positive stretcher lengthened the laser pulses to ~200 ps (for 60 nm spectral width). The negative stretcher of the NPCPA laser provided negatively chirped pulses with duration of about 50 ps. The stretched pulses were then amplified in a nine-pass Ti:S pre-amplifier up to an energy level of 3 mJ. While for the conventional CPA laser, the pulse goes straight to the second amplifier, in the NPCPA scheme, it is directed first to a positive stretcher, that one which was used in the CPA configuration. Since its stretching factor is nearly four times higher than that of the negative stretcher, the sign of the pulse chirp was changed to a positive, and the duration of the stretched pulse remained around ~150 ps. Note that in the NPCPA scheme, the positive stretcher is placed after the pre-amplifier. The following scheme practically remains unchanged. The next power amplifier was assembled with a 20 mm long Ti:S crystal. The active medium was cryogenically cooled to cancel thermal lens appearing in the Ti:S crystal. This amplifier provided laser pulses with energy up to 150 mJ.

3.2. Comparison of experimental results for CPA and NPCPA schemes

The spectral operation of the nine-pass pre-amplifier depending on the chirp sign is shown in Figure 5. In case of the CPA setup, the 62 nm bandwidth of the oscillator pulses is reduced to around 45 nm due to gain narrowing. The central peak is shifted slightly toward 800 nm, close to the emission peak of Ti:S. Although the major physics behind

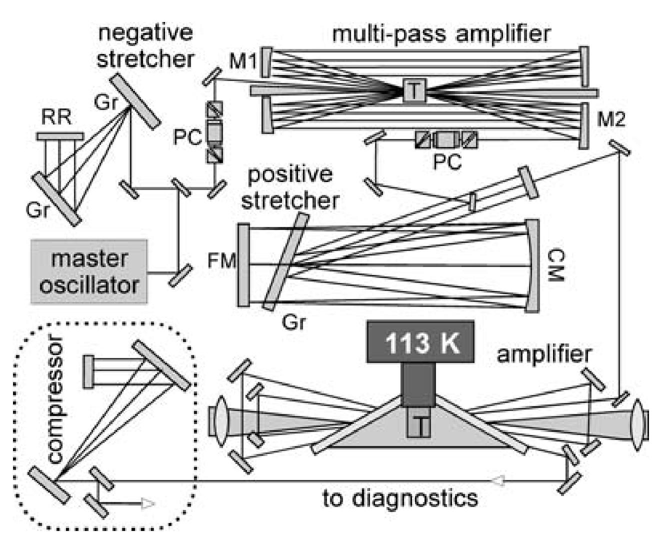

Fig. 4. Experimental scheme of the NPCPA laser. Gr, diffraction gratings; PC, Pockets cells; FM, flat mirror; CM, concave mirror of the stretcher; M1, M2, cavity mirrors of the multi-pass amplifier.

https://doi.org/10.1017/S0263034607000043 Published online by Cambridge University Press

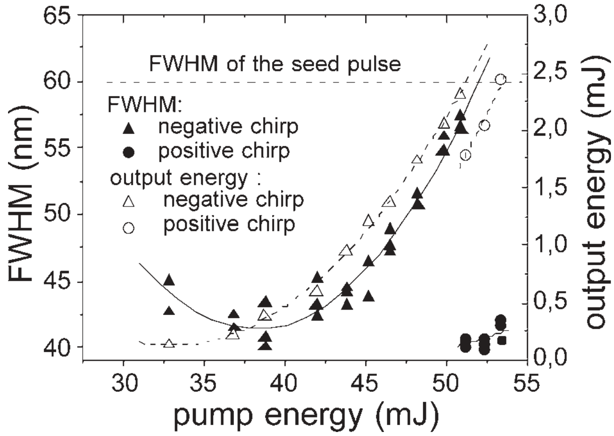

Fig. 5. Width of the pulse spectrum and output energy measured after the nine-pass amplifier for positively and negatively chirped pulses.

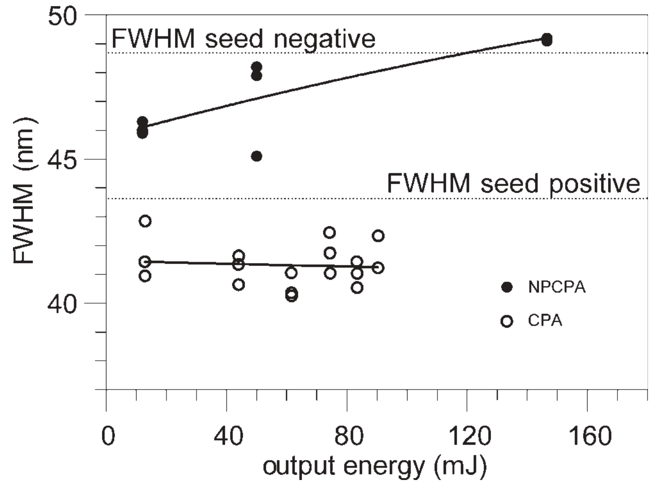

Fig. 6. Comparison of spectral bandwidth at the output of a conventional CPA and the NPCPA lasers.

it is the same, the spectral behavior of the negatively chirped pulse is substantially different. Namely, saturation now affects the leading blue edge, causing a large blue shift in the central wavelength by 25 nm. This could also lead to an extreme broadening of the bandwidth but the effect of gain narrowing counteracts, resulting in a bandwidth of almost 50 nm. Although this is somewhat narrower than the bandwidth of the oscillator pulses, but is still broader than that in the conventional CPA case. Further increase of the pump energy leads to higher saturation and broadens the pulse spectrum to ~57 nm, that is, close to the bandwidth of the seed pulse. The maximum output energy exceeds 2.5 mJ, but in order to keep the pre-amplifier in the safe operation region, the output energy was restricted to 1.5 mJ. This corresponds to the bandwidth of 50 nm. It is worth mentioning that the same level of the output energy in the case of the NPCPA laser is achieved at a lower pump. The reason for that is a higher throughput of the negative stretcher and thus higher energy of the seed pulse. This leads also to a higher temporal contrast of the output pulse (see Fig. 1).

The behavior of the power amplifier is different for both schemes. For the CPA scheme, at a lower level of pumping, the bandwidth of the pre-amplified pulses starts being reduced by GN (Fig. 6). When the pump level is raised, the saturation of the amplifier increases and counteracts stabilizing the bandwidth (and of course, the output energy) at around 42 nm. For the NPCPA setup, GN at a lower pump level makes again the bandwidth slightly narrower than its input one. This is, however, already broader than that obtained from the CPA scheme.

At a high level of pumping, moreover, saturation is more beneficial for the red leading front, and hence, for the NPCPA, this results in a bandwidth in excess of 50 nm (this corresponds to ~20 fs of a transform limited pulse), which is even broader than the input spectrum. It is worth noting that such a broad spectrum of the power amplifier has never been achieved before without using any direct spectral shaping of the pulse. Please also note that the original oscillator bandwidth of 60 nm (15 fs) was almost conserved in our NPCPA scheme after amplification by a factor of 2.5×10^7.

4. DISCUSSION AND CONCLUSION

We have accomplished two new advanced laser schemes based on the CPA principle to enhance temporal contrast of recompressed laser pulses and suppress gain narrowing. The DCPA experiment has demonstrated a principal possibility to improve the temporal contrast of high peak power Ti:S lasers to a value of at least 10^{10}. The DCPA architecture supports devices for temporal filtering of different types. In our experiment, the nonlinear polarization rotation in air was used. The very recently developed method of generation of cross-polarized waves in crystals (Jullien *et al.*, 2005), however, conserves the full spectral content of the laser pulse, so its implementation in the DCPA laser can bring even better performance. Thus the contrast ratio of 10^{11} has just been demonstrated (Chvykov *et al.*, 2006). The reliable operation of the DCPA laser with nonlinear temporal cleaning requires a very stable front end, which could be better accomplished at a kilohertz repetition rate. The use of the DCPA scheme with temporal filtering at an mJ energy level can allow temporal contrast exceeding 10^{12}, that will be sufficient for pre-plasma free interaction at intensities of 10^{22} W/cm^2. Further increase of the temporal contrast will require temporal filtering at the energy level exceeding an mJ, or use of a plasma mirror (Doumy *et al.*, 2004) at the laser output.

We have demonstrated that the amplification scheme using the NPCPA concept is a beneficial expansion of the traditional method of positive-only CPA. Due to saturation, it substantially reduces the effect of gain narrowing and effectively reshapes the spectrum within the amplifier chain, hence providing a possibility of shorter laser pulses.

Because of higher throughput of the negative stretcher and the shorter duration of the recompressed pulses, a higher temporal contrast related to ASE is anticipated with the NPCPA scheme. One needs to mention also, that the NPCPA laser is fully compatible with the DCPA option. Namely, the first negative stretcher and the positive stretcher can be designed in a way that allows complete pulse recompression inside the positive stretcher, where a nonlinear temporal filter has to be installed, or recompression of the pulse in the first stage can be accomplished with a bulk material. The NPCPA scheme completed with the double CPA method offers hence an additional possibility of substantial enhancement of temporal contrast.

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