High energy picosecond Yb:YAG CPA system at 10 Hz repetition rate for pumping optical parametric amplifiers

Sandro Klingebiel,[1,*] **Christoph Wandt,**[1] **Christoph Skrobol,**[1]
Izhar Ahmad,[1] **Sergei A. Trushin,**[1] **Zsuzsanna Major,**[1,2]
Ferenc Krausz[1,2] **and Stefan Karsch**[1,2]
[1] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1,*
D-85748 Garching, Germany
[2] *Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1,*
D-85748 Garching, Germany
[*] *sandro.klingebiel@mpq.mpg.de*

Abstract: We present a chirped pulse amplification (CPA) system based on diode-pumped Yb:YAG. The stretched ns-pulses are amplified and have been compressed to less than 900 fs with an energy of 200 mJ and a repetition rate of 10 Hz. This system is optically synchronized with a broadband seed laser and therefore ideally suited for pumping optical parametric chirped pulse amplification (OPCPA) stages on a ps-timescale.

OCIS codes: (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped; (320.5520) Pulse compression.

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1. Introduction

High-power, few-cycle light pulses are of great interest for studying laser-matter interactions at extreme conditions. Several applications such as the generation of mono-energetic electron beams by laser-wakefield acceleration in the “bubble” regime or higher-harmonic generation from solid surfaces have been demonstrated [1, 2] and theoretical predictions call for light sources delivering ever shorter and more powerful pulses in order to drive these processes more efficiently [3, 4]. The generation of Joule-class pulse energies combined with the few-cycle duration has yet to be demonstrated.

The PFS project aims at developing a light source delivering Petawatt-scale carrier-envelope phase controlled [5] pulses with pulse energies $> 3\,\text{J}$ in the few-cycle regime ($< 5\,\text{fs}$, 700…1400 nm) at a repetition rate of 10 Hz [6, 7]. The concept for reaching the ambitious parameters of PFS is based on the optical parametric chirped pulse amplification (OPCPA) technology, using a modified scheme as compared to existing facilities. In the PFS design short pulses are used to pump the OPA stages, i.e. on the order of 1 ps, in contrast to 100 ps – ns pulse durations in previous systems (e.g. in [8–10]). The short-pulse-pumped OPCPA approach improves the conditions for high-power few-cycle-pulse generation as compared to long-pulse-pumped OPCPA in several ways. Firstly, the significantly increased pump power permits the use of thinner OPA crystals while keeping the same level of gain, which implies an increase of amplification bandwidth as compared with OPA driven by longer pulses. Secondly, the short pump-pulse duration reduces the necessary stretching factor for the broadband-seed pulse, thereby increasing stretching and compression fidelity and allowing the use of simple, high-throughput stretcher-compressor systems, consisting of bulk glass and chirped multilayer mirrors. Finally, the short pump-pulse duration results in a short amplification time window and hence dramatically enhanced temporal pulse contrast outside this window. However, the drawback of ps-pumped OPCPA is that it requires a very accurate and stable synchronization between the pump and seed pulses. Therefore a special, synchronized pump delivering 1-2 ps pulses with $4\times5\,\text{J}$ pulse energy (frequency doubled at 515 nm) i.e. $4\times12\,\text{J}$ in the fundamental beam (1030 nm) at 10 Hz repetition rate is required. Such a system is not commercially available and therefore a challenge for development in its own right.

Recently Yb:YAG based CPA systems delivering sub-2 ps pulses with energies as high as 125 mJ at 100 Hz [11], and 25 mJ at 3 kHz [12] have been demonstrated. For the PFS pump laser we aim for higher pulse energies but limit our repetition rate to 10 Hz. We have developed Yb:YAG amplifiers and have shown up to 3 J pulse energy with ns-pulses at 1 Hz repetition rate [13], and for 200 mJ pulses we raised the repetition rate to 10 Hz [14]. In this paper we present a full characterization of a high energy CPA system generating the shortest high energy

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pulses in Yb:YAG and show its potential for OPCPA pumping. We implemented a spatial light modulator (SLM) for spectral amplitude shaping which counteracts gain narrowing and therefore pushes the limit for the compressed pulse length below 900 fs. Simulations show, that similar values can be reached for 50 J pulse energy.

2. Experimental setup

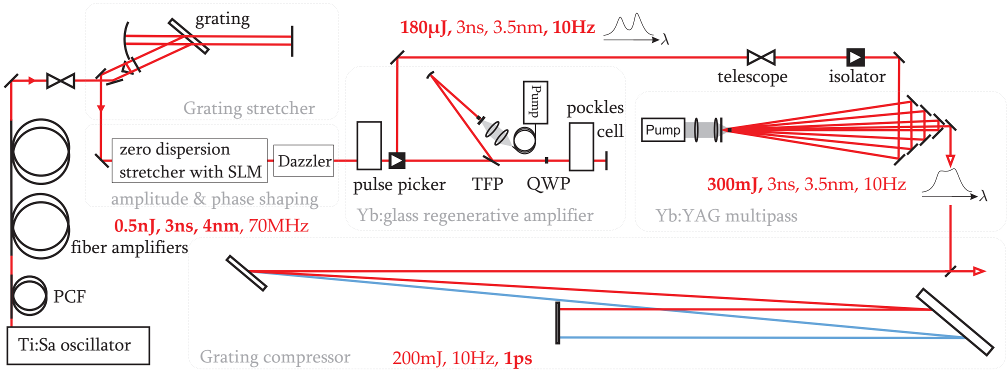

Fig. 1. Experimental setup: The seed pulses from the Ti:Sa oscillator are spectrally shifted to 1030 nm in a photonic crystal fiber (PCF), pre amplified in a double stage fiber amplifier, stretched to 3 ns and their spectral amplitude is shaped by an SLM in a zero-dispersion stretcher. The subsequent Dazzler shapes the spectral phase to improve the compression. The amplifier chain consists of a Yb:glass regenerative amplifier and a Yb:YAG multipass. After the main amplification compression is realized in a Treacy type compressor. TFP:thin film polarizer,QWP: quarter wave plate, SLM: Spatial Light Modulator.

As shown in Fig. 1(a) Ti:sapphire fs oscillator (Femtolaser rainbow) is used as front-end. The advantage of this approach is that the broadband OPCPA seed can be derived from the same oscillator and therefore will be optically synchronized. For the OPCPA pump a fraction of the oscillator output is spectrally shifted to 1030 nm in a photonic-crystal fiber. An interference filter selects a $\Delta\lambda = 10$ nm band centered at 1030 nm from the frequency spectrum with 3.4 pJ pulse energy. This output is then amplified in a two-stage Yb-doped fiber amplifier (designed by the Institute for Applied Physics, Jena, Germany) to 14 nJ pulse energy (70 MHz, 4.4 ps).

The seed pulses are temporally stretched in a compact all-reflective grating stretcher [15] to a FWHM pulse-duration of 3 ns with a spectral bandwidth of 4 nm centered at 1030 nm. It has been constructed using a 1740 lines/mm multilayer-dielectric reflection grating with an angle of incidence of 59°, a $f = 2.5$ m concave mirror, a flat mirror in the focal plane of the curved one, and two retroreflectors. This geometry provides a 4-times folded optical path, i.e. 8 reflections off the grating.

In Yb:YAG the bandwidth is normally limited by strong gain narrowing therefore we incorporated a spatial light modulator (SLM) which allows spectral amplitude shaping by changing the transmission for each wavelength. The SLM (CRI corporation) is located in the Fourier plane of an additional zero-dispersion stretcher, which is adapted to the aperture of the used SLM (12.8 mm × 5 mm). The losses of this setup are easily compensated by a few more round trips in the subsequent regenerative amplifier. Recently, a Dazzler (Fastlite Inc.) was implemented with the capability of simultaneously shaping the spectral phase and amplitude. Nevertheless the presented results were achieved using the SLM for spectral amplitude shaping.

The Yb:glass regenerative amplifier boosts the pulse energy to the 200 μJ-level without significant gain narrowing. The Yb:glass gain medium (8 mm long, 12 mm diameter, doping level $N_{Yb} = 6 \cdot 10^{20}\,\mathrm{cm}^{-3}$) is pumped by a fiber-coupled laser diode (5 W, 1.5 ms, 10 Hz, 976 nm) focused to a pump spot of 100 μm. Owing to the low average power, no cooling is needed and the glass is mounted in a standard mirror mount. The cavity is 1.6 m long and consists of two plane end mirrors and a focusing mirror with 200 mm focal length, which generates a focus of 100 μm diameter next to the amplifying medium on one of the end mirrors. A thin film polarizer, a quarter wave plate and a Pockels-cell are used for coupling the beam in and out of the cavity. After approximately 100 round trips this amplifier reaches saturation. Seed-energy fluctuations cause only a small variation in output energy and lead to a very stable output (1% standard deviation) with a nearly diffraction limited beam profile ($M^2 = 1.2$) as shown in Fig. 2(a).

For reaching the final output energy, we apply an 8-pass, diode-pumped, Yb:YAG amplifier, which is an upgraded version of the amplifier presented in [14]. The AR-coated Yb:YAG crystal rod (8 mm long, 6mm diameter, 3 at.% -doped) is connected to a copper heat sink with indium foil over its lateral area and is pumped by a diode-laser stack (Jenoptik Laserdiode GmbH) with an output power of 3 kW (1.5 ms, 10 Hz) at a center wavelength of 940 nm. In order to provide a small signal single pass gain of approximately 3 a pump intensity of 35 kW/cm^2 is needed and the pump is focused to an area of 0.086 cm^2. For a fixed pump power, the length of the individual passes in this non-imaging amplifier setup can be chosen in such a way that the beam size on the crystal stays 2.5 mm for all passes. This amplifier boosts the energy from 180 μJ to 300 mJ (3% standard deviation) with the beam profile shown in Fig. 2(b). In order to quantify the beam quality, we measured the strehl ratio of the compressed 1030 nm beam. The beam profile is measured in the near- and far field. Additionally the far field distribution for a perfect gaussian beam with the same size in the near field is simulated. Thereafter, the encircled energy on the area of $\pi\omega_0^2$ was calculated for the calculated focus and compared to the encircled energy on the same area for the measured focus. With this method the strehl ratio was measured to be 0.82±0.05.

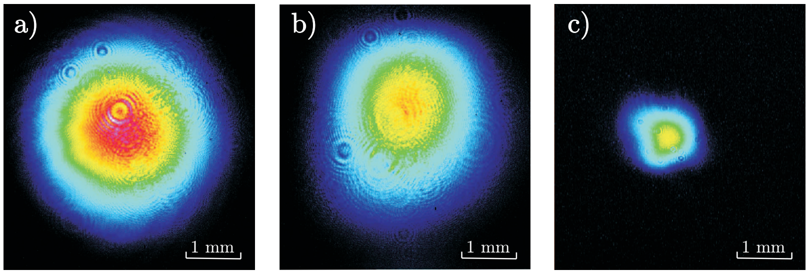

Fig. 2. Measured beam profiles: a) output beam profile of the regenerative amplifier (2.5mm diameter), b) output beam profile of the 8-pass amplifier (2.5mm diameter) and c) beam profile of the frequency doubled beam down collimated to 1.3 mm diameter at the position of the first OPA stage. The diffraction rings originate from dust on the filters in front of the camera.

3. Results and discussion

The high gain of 1500 in the main amplifier would lead to a gain-narrowed bandwidth of 1.5 nm (cf. Figure 4 a) and thus to a shortened pulse duration for stretched pulses which would increase the risk of optical damage significantly. In order to counteract this effect and to preserve the maximum bandwidth we applied spectral amplitude shaping. The final output spectrum and the corresponding shaped input spectrum are shown in Fig. 3(b).

We also investigated the effect of gain narrowing numerically. The calculations used a simple model based on the rate equations as described in [14]. There it was shown, that the simulation of the amplification in Yb:YAG fits well to the experimental data. For spectral shaping we carry out the reverse calculation, in order to find a suitable input spectrum for the desired output spectrum.

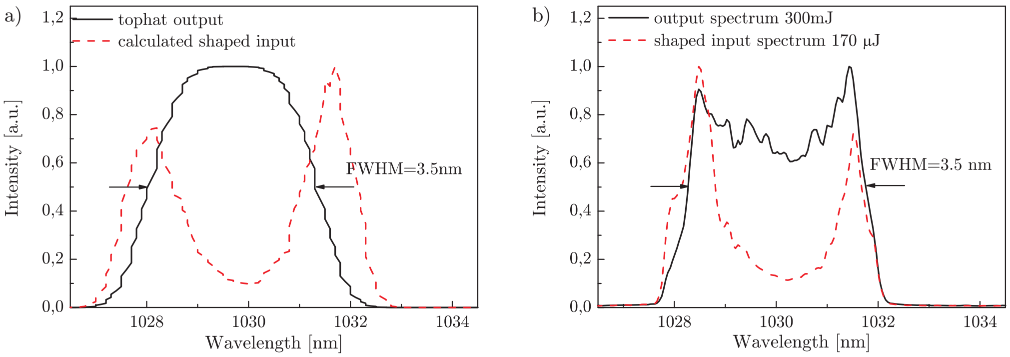

Fig. 3. (a) The input spectrum (red, dashed) which supports a broad flattop spectrum (black, solid) after amplification is calculated. In b) measured spectra for the maximum amplification are shown. The amplified spectrum (black, solid) is still suppressed in the center, showing that further amplification is possible without significant gain narrowing.

As an example, we calculated the input spectrum for 3.5 nm FWHM top-hat output profile, as shown in Fig. 3(a). The major feature is the dip at 1030 nm. Compared to the spectrum predicted by our model, the real input spectrum (Fig. 3(b) has narrower wings due to clipping in the stretcher, and we choose it in such a way, that the output spectrum is still suppressed in the center to enable further amplification without significant gain narrowing.

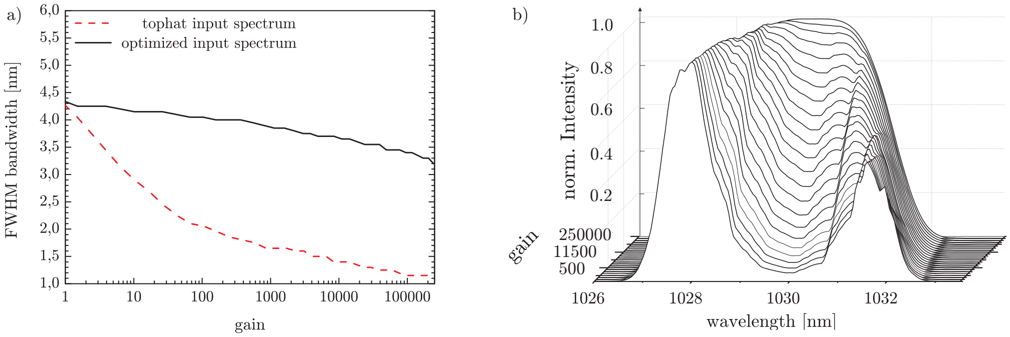

Fig. 4. Results of the simulation: a) gain narrowing for a top-hat input spectrum (red), and the reduced effect for the spectrally shaped spectrum (black). Figure b) shows the normalized spectra at different amplification levels for shaped pulses and illustrates, how the input spectrum with a dip in the center evolves to a tophat spectrum during amplification while the bandwidth is preserved large.

Furthermore the bandwidth for our final gain factor of $2.5 \cdot 10^5$ was simulated by subsequently raising the pump power. The results are shown in Fig. 4(a), which illustrates the change of the FWHM bandwidth of the shaped input spectrum with overall gain. Compared to a top-hat shaped input spectrum our calculation predicts a threefold increase in bandwidth. Fig. 4(b)

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shows the calculated spectral shape and illustrates how this shape evolves into a smooth top-hat spectrum with increasing gain.

We succeeded in compressing these spectrally shaped, amplified pulses with 66 % efficiency to 900 fs with 200 mJ. In a Treacy type grating compressor [16] with 6 m grating separation, gratings with the same grating period as in the stretcher are utilized. As shown in Fig. 1 we use a reverse configuration, meaning that the incident beam has a smaller angle to the grating normal than the diffracted one. The grating angles were optimized for shortest pulses and the implemented Dazzler enables us to correct for higher order phases.

The compressed pulse duration is measured by a home-built single-shot second-order autocorrelator with a tuning window of 6 ps and a pixel resolution of 22 fs. This device is designed to measure 700 fs pulses with 6 % accuracy. For 1000 shots the autocorrelation traces are measured the mean width is 1.21 ps with a standard deviation of 0.04ps. The measured autocorrelation trace is shown in Fig. 5.

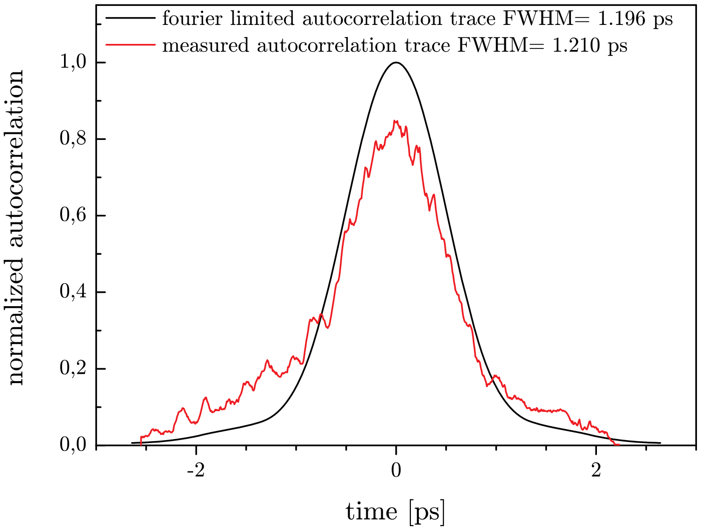

Fig. 5. Calculated autocorrelation trace for the Fourier-limited pulse (black) and measured autocorrelation trace (red). The latter one is normalized to to enclose the same area as the calculated autocorrelation trace. The corresponding pulse length is 884 fs and 895 ps, respectively.

The fourier limited pulse shape and the corresponding autocorrelation trace are calculated from the measured spectrum. From this we have inferred a deconvolution factor between the pulse duration and the width of the autocorrelation trace of 1.3518 for this particular case. Using this factor we can obtain a realistic estimate for our compressed pulse duration which turns out to be 895 fs (transform limit 884 fs) with a measurement uncertainty of 40 fs. As can be seen in Fig. 5 the autocorrelation trace is slightly asymmetric, which is most likely caused by an imperfect beam profile in the autocorrelator. Although the main pulse is close to fourier limited FWHM, there are large side wings which could be explained by uncompensated higher order dispersion. Another possibility could be spatio-temporal coupling caused by B-integral issues when the compressed pulse propagates in several meters air after the last grating. This problem will be solved by a vacuum chamber for the compressor, which is currently under construction.

In a 5 mm type 2 DKDP crystal frequency doubling with 40% conversion efficiency is achieved so far. We therefore have 80 mJ pulse energy in the green, which is sufficient for pumping the first two to three OPA stages. The beam profile of the frequency doubled beam at

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the position of the first OPA stage is shown in Fig. 2(c).

Another important aspect for short pulse pumped OPCPA is the timing jitter between pump and seed pulses. In our case the pulse length is 1ps and therefore a timing jitter at least 100 fs is desired for reliable operation of the OPCPA process. We measured the timing jitter in a single-shot cross-correlation experiment between the 30 fs, 800 nm pulse (representing the timing of the OPCPA seed) and the compressed pulses (1030 nm) in a 1 mm BBO crystal. The relative position of the correlation traces on the camera can be converted to a relative timing between the pulses. On a 10 s timescale, a jitter of 273 fs standard deviation was measured. We believe, these timing fluctuations mainly originate from air turbulences, and the mechanical instability of different optical components in the pump laser chain. A more extensive analysis of the jitter is under way in order to find out where exactly this jitter originates from. Preliminary results show, that active stabilization allows for a timing jitter of less than 100fs.

4. Summary

In summary we showed amplification in Yb:YAG up to 300 mJ pulse energy at 10 Hz repetition rate with an unprecedented spectral bandwidth of 3.5 nm. This was realized by spectral amplitude shaping using a SLM to counteract gain narrowing. In our system we demonstrated the operation of a sub-ps CPA laser system based on Yb:YAG at an energy level of up to 200 mJ for the first time. We have therefore demonstrated, to our knowledge, the highest-peakpower pulses ($\approx$160GW) generated in a Yb:YAG laser to date. From a gain-narrowing point-of-view, these results can be scaled to the 50 J-level, as predicted by our simulations. In order to obtain the best possible efficiency for the frequency doubling stage and therefore the highest possible pulse energy in the green, some additional optimization will have to be performed. The laser system described in this manuscript fulfills the requirements and is currently being used to drive the next important step in the PFS-project, namely the development of the first OPA-stage.

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