Pulsed operation of a high average power Yb:YAG thin-disk multipass amplifier

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Abstract: An Yb:YAG thin-disk multipass laser amplifier system was developed operating in a 10 Hz burst operation mode with 800 µs burst duration and 100 kHz intra-burst repetition rate. Methods for the suppression of parasitic amplified spontaneous emission are presented. The average output pulse energy is up to 44.5 mJ and 820 fs compressed pulse duration. The average power of 4.45 kW during the burst is the highest reported for this type of amplifier.

OCIS codes: (140.3280) Laser amplifiers; (140.3580) Lasers, solid-state; (140.3615) Lasers, ytterbium.

References and links

1. S. Hädrich, J. Rothhardt, M. Krebs, F. Tavella, A. Willner, J. Limpert, and A. Tünnermann, "High harmonic generation by novel fiber amplifier based sources," Opt. Express **18**(19), 20242–20250 (2010).
2. F. Krausz and M. Ivanov, "Attosecond physics," Rev. Mod. Phys. **81**(1), 163–234 (2009).
3. S. Pekarek, T. Südmeyer, S. Lecomte, S. Kundermann, J. M. Dudley, and U. Keller, "Self-referenceable frequency comb from a gigahertz diode-pumped solid-state laser," Opt. Express **19**(17), 16491–16497 (2011).
4. H. Rabitz, R. de Vivie-Riedle, M. Motzkus, and K. Kompa, "Whither the future of controlling quantum phenomena?" Science **288**(5467), 824–828 (2000).
5. C. Emmelmann and J. P. Calderón Urbina, "Analysis of the Influence of Burst-Mode Laser Ablation by Modern Quality Tools," Phys. Proc. **12**, 172–181 (2011).
6. I. Will, G. Koss, and I. Templin, "The upgraded photocathode laser of the TESLA Test Facility," Nucl. Instr. Meth. Phys, Research A **541**, 467–477 (2005).
7. H. Redlin, A. Al-Shemmary, A. Azima, N. Stojanovic, F. Tavella, I. Will, and S. Düsterer, "The FLASH pump-probe laser system: Setup, characterization and optical beamlines," Nucl. Instr. and Meth. in Phys, Research A **635**, 88–93 (2011).
8. G. Lambert, T. Hara, D. Garzella, T. Tanikawa, M. Labat, B. Carre, H. Kitamura, T. Shintake, M. Bougeard, S. Inoue, Y. Tanaka, P. Salieres, H. Merdji, O. Chubar, O. Gobert, K. Tahara, and M.-E. Couprie, "Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light," Nat. Phys. **4**(4), 296–300 (2008).
9. B. Faatz, N. Baboi, V. Ayvazyan, V. Balandin, W. Decking, S. Düsterer, H.-J. Eckoldt, J. Feldhaus, N. Golubeva, K. Honkavaara, M. Körfer, T. Laarmann, A. Leuschner, L. Lilje, T. Limberg, D. Nölle, F. Obier, A. Petrov, E. Plönjes, K. Rehlich, H. Schlarb, B. Schmidt, M. Schmitz, S. Schreiber, H. Schulte-Schrepping, J. Spengler, M. Staack, F. Tavella, K. Tiedtke, M. Tischer, R. Treusch, M. Vogt, A. Willner, J. Bahrdt, R. Follath, M. Gensch, K. Holldack, A. Meseck, R. Mitzner, M. Drescher, V. Miltchev, J. Rönsch-Schulenburg, and J. Rossbach, "Flash II: Perspectives and challenges," Nucl. Instr. Meth. A **635**(1), S2–S5 (2011).
10. I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," Opt. Commun. **144**(1-3), 125–133 (1997).
11. S. Adachi, H. Ishii, T. Kanai, N. Ishii, A. Kosuge, and S. Watanabe, "1.5 mJ, 6.4 fs parametric chirped-pulse amplification system at 1 kHz," Opt. Lett. **32**(17), 2487–2489 (2007).
12. J. Rothhardt, S. Hädrich, E. Seise, M. Krebs, F. Tavella, A. Willner, S. Düsterer, H. Schlarb, J. Feldhaus, J. Limpert, J. Rossbach, and A. Tünnermann, "High average and peak power few-cycle laser pulses delivered by fiber pumped OPCPA system," Opt. Express **18**(12), 12719–12726 (2010).

#159113 - $15.00 USD Received 2 Dec 2011; revised 13 Jan 2012; accepted 27 Jan 2012; published 14 Feb 2012

13. S. Hädrich, S. Demmler, J. Rothhardt, C. Jocher, J. Limpert, and A. Tünnermann, "High-repetition-rate sub-5-fs pulses with 12 GW peak power from fiber-amplifier-pumped optical parametric chirped-pulse amplification," Opt. Lett. **36**(3), 313–315 (2011).
14. E. Seise, A. Klenke, S. Breitkopf, M. Plötner, J. Limpert, and A. Tünnermann, "Coherently combined fiber laser system delivering 120 μJ femtosecond pulses," Opt. Lett. **36**(4), 439–441 (2011).
15. P. Rußbüldt, T. Mans, G. Rotarius, D. Hoffmann, R. Poprawe, T. Eidam, J. Limpert, and A. Tünnermann, "Hybrid 400W Fiber-Innoslab fs-Amplifier," in ASSP, OSA technical Digest Series (CD) (Optical Society of America, 2009), paper MF4.
16. P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," Opt. Lett. **35**(24), 4169–4171 (2010).
17. M. Schulz, R. Riedel, A. Willner, T. Mans, C. Schnitzler, P. Rußbüldt, J. Dolkemeyer, E. Seise, T. Gottschall, S. Hädrich, S. Düsterer, H. Schlarb, J. Feldhaus, J. Limpert, B. Faatz, A. Tünnermann, J. Rossbach, M. Drescher, and F. Tavella, "Yb:YAG Innoslab amplifier: efficient high repetition rate sub-ps pumping system for optical parametric chirped pulse amplification," Opt. Lett. **36**, 2456–2458 (2011).
18. T. Metzger, A. Schwarz, C. Y. Teisset, D. Sutter, A. Killi, R. Kienberger, and F. Krausz, "High-repetition-rate picosecond pump laser based on a Yb:YAG disk amplifier for optical parametric amplification," Opt. Lett. **34**(14), 2123–2125 (2009).
19. A. Antognini, K. Schuhmann, F. D. Amaro, F. Biraben, A. Dax, A. Giesen, T. Graf, T. W. Hänsch, P. Indelicato, L. Julien, C.-Y. Kao, P. E. Knowles, F. Kottmann, E. Le Bigot, Y.-W. Liu, L. Ludhova, N. Moschüring, F. Mulhauser, T. Nebel, F. Nez, P. Rabinowitz, C. Schwob, D. Taqqu, and R. Pohl, "Thin-Disk Yb:YAG Oscillator-Amplifier Laser, ASE, and Effective Yb:YAG Lifetime," IEEE J. Quantum Electron. **45**(8), 993–1005 (2009).

1. Introduction

High repetition rate ultrashort pulse laser systems are essential in many fields of modern physics, for example, high harmonic generation [1], attosecond metrology [2], frequency comb spectroscopy [3] and coherent control [4]. A special subset of applications requires high repetition rate bursts of pulses such as materials processing [5] and laser applications at free-electron lasers (FEL) [6]; most important is the long term stability of operation. Among the possible applications at FELs, pump-probe laser systems [7] require high pulse energies at high repetition rates, high stability of the system and ultrashort pulse durations. Laser amplifiers with similar parameters can also be used as a high harmonic generation (HHG) driver for direct FEL XUV seeding [8]. The system described here is part of a planned seed laser system for FLASH2 [9]. The parameters desired are pulse energies of up to 2 mJ at burst repetition rates of 100 kHz to 1 MHz with pulse durations below 10 fs. A promising way to achieve these parameters is optical parametric chirped-pulse amplification (OPCPA) [10]. OPCPA has emerged as a powerful tool for the generation of ultrashort few-cycle laser pulses. So far, few-optical-cycle amplifiers with mJ-level output pulse energy have only been demonstrated at repetition rates of a few kHz [11]. Recent studies on a fiber pumped OPCPA system have reached pulse energies of tens of μJ with sub-10 fs pulse durations at a repetition rate of 96 kHz [12] and 5.6 fs at 30 kHz [13]. Different approaches are possible for the realization of high power pump sources for OPCPA systems. Multiple fiber CPA systems can be coherently combined to increase the output pulse energy as shown in ref [14]. To further increase the pulse energy from fiber based sources, hybrid systems with a fiber amplifier in combination with a solid-state laser amplifier are under investigation [15]. Recent results have shown the possibility to generate pulses with 20 mJ pulse energy at a repetition rate of 12.5 kHz with an Yb:YAG Innoslab amplifier [16] combined with a fiber amplifier system [17]. Another promising technique to achieve high pulse energies at high repetition rates is the use of an Yb:YAG thin-disk amplifier [18] in multipass configuration [19], also with a fiber amplifier front-end system.

In this paper we explore two different setups for the amplification of laser pulses to tens of millijoules. In the first approach, a fiber amplification system was used to generate the seed for an Yb:YAG thin-disk multipass amplifier. In the second approach, a combined fiber and Yb:YAG Innoslab amplifier was used to seed the thin-disk amplifier with a higher energy.

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2. Experimental setup

A schematic overview of the experimental setup is shown in Fig. 1a. The seeder of the amplification system delivers a power of 1.9 mW at a pulse repetition rate of 2 MHz. These pulses are stretched in an Öffner-type stretcher to a pulse duration of 2.27 ns FWHM, and then coupled into a three stage fiber amplification chain consisting of a fiber preamplifier and two large-mode-area photonic crystal fiber amplifiers. The spectral width of the amplifier output is 6.8 nm FWHM. The repetition rate is set by two acusto-optic modulators (AOM), one AOM to reduce the repetition rate to 100 kHz and a second AOM to generate a 10 Hz burst of pulses (80 pulses per burst with 800 µs burst duration). The 375 µJ pulses resulting from this system are coupled into a thin-disk multipass amplifier for further amplification. The multipass geometry of the Yb:YAG thin-disk amplifier allows for 30 passes through the disk. Another possibility to generate the seed for the thin-disk amplifier is to further amplify the pulses provided by the fiber amplifier setup with an Yb:YAG Innoslab amplifier, delivering pulse energies of up to 5 mJ.

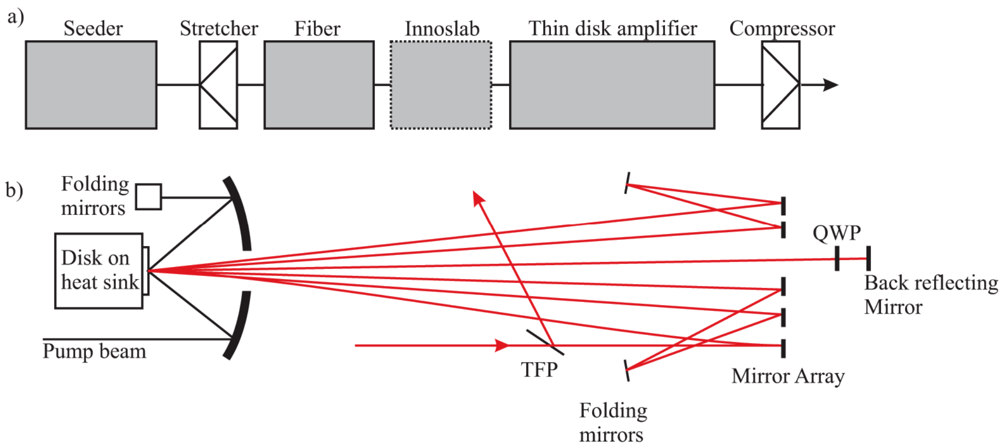

Fig. 1. Schematic of a) the experimental setup, b) thin-disk multipass amplifier geometry, QWP = quarter-wave plate, TFP = thin-film polarizer.

A schematic of the thin-disk amplifier is presented in Fig. 1b. The diode laser pump produced by 6 diode bars (λ_{diode} = 940 nm) with a total nominal pumping power of 10 kW is coupled onto the disk by a collimation optic and then folded 24 times through the amplification medium by a parabolic mirror and retro reflecting prisms (Trumpf Laser GmbH). The pump spot diameter on the disk with a uniform super Gaussian shaped beam profile can be changed between 9.6 mm and 7.35 mm FWHM by changing the collimation optics. The amplification medium is a 360 µm thick Yb:YAG disk with a diameter of 17 mm, a radius of curvature of 20 m and a doping concentration of 7%. It is soldered onto a heat sink cooled to a temperature of 20°C. The seed multipass geometry consists of 29 mirrors in an array for folding the beam on the amplifier medium and 16 folding mirrors to project onto a new beam path after every pass on the disk. Partly defocussing (R_{oc} = 8 m) and plane mirrors are used to counteract the divergence of the beam introduced by the 20 m radius of curvature of the thin disk. The distance between the disk and the mirror array is 1.5 m. A total of 15 passes can be realized, an additional 15 passes (total 30) can be achieved by returning the beam back through the multipass amplifier. A quarter-wave plate to rotate the polarization of the amplified beam and a thin-film polarizer are used to extract the beam from the amplifier.

The thin-disk multipass amplifier is primarily designed to be operated in a 10 Hz burst-mode as a pump amplifier for a seeding laser for FLASH2 [9] but can also be used with an increased burst repetition rate or for continuous operation with similar parameters. For this, modification of the multipass defocusing mirrors would be necessary, taking into account the

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increased thermal lensing of the thin disk introduced by cw-pumping. The burst-mode was extensively investigated to optimize the shape of the pulse train, the maximal amplification factor and the stability of the amplifier.

3. Experimental results

The amplification medium is pumped by the pumping diodes in a pulsed operation mode with a pump pulse duration of 1.3 ms. The delay between pump and seed pulse burst from the fiber amplifier is set to 150 µs. Due to the duty cycle of the pumping diodes, the nominal diode current of 200 A, corresponding to 10 kW pumping power, can be exceeded. A maximal pumping energy of 16 J (pumping power of 12.4 kW) during the burst is used in the experiment.

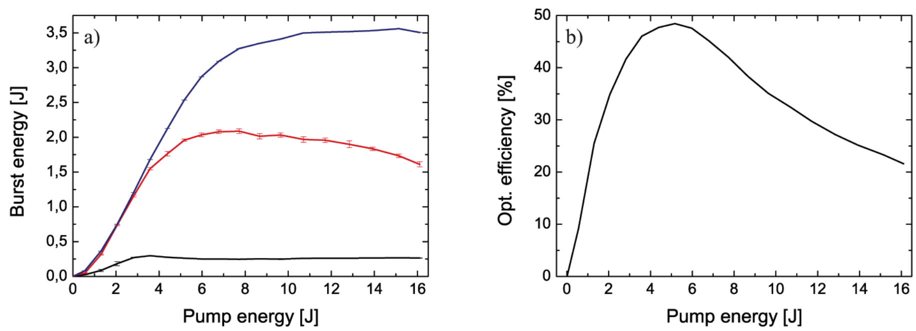

Fig. 2. Suppression of ASE during the amplification process: a) Gain curve for a 9.6 mm pump spot (black), gain curve for a reduced 7.35 mm pump spot (red), gain curve for a beveled disk and 7.35mm pump spot (blue). b) Optical to optical conversion efficiency for the beveled disk.

The development of the amplifier proves to be difficult due to parasitic amplified spontaneous emission (ASE), which limits the achievable total amplification. In the first approach, a diode pump spot diameter of 9.6 mm FWHM is used. As described in ref [19], ring type and transversal ASE modes develop in the amplification medium during the amplification process. These optical ASE modes are back reflected through total internal reflection at the boundaries of the disk and further amplified provided that the reflected ASE photons pass through the pumped volume. In our system, this causes depletion of the inversion by ASE, clearly visible in Fig. 2a (black line), where the amplified pulse energy reaches a maximum already at a pump pulse energy of 3.5 J (2.7 kW diode pump power). The pump spot diameter is reduced to 7.35 mm to reduce the coupling between the pump spot area and the back-reflected ASE photons, which results in a trifold gain increase (Fig. 2a, red line). Still, further amplification saturates at around 6 J of pump energy (4.6 kW diode pump power). The second approach to overcome the ASE is to use a disk with beveled boundaries, which suppresses back reflection of the ASE photons. Figure 2a (blue line) shows the amplification of the seed depending on the pump energy (gain curve) where ASE is suppressed and the full diode pump power (12.4 kW) can be used for pumping. The remaining limiting factor in this configuration is the limited average gain per pass in the multipass amplifier, which is measured to be G = 1.17, yielding a maximum amplification factor of 118 for the 30 passes.

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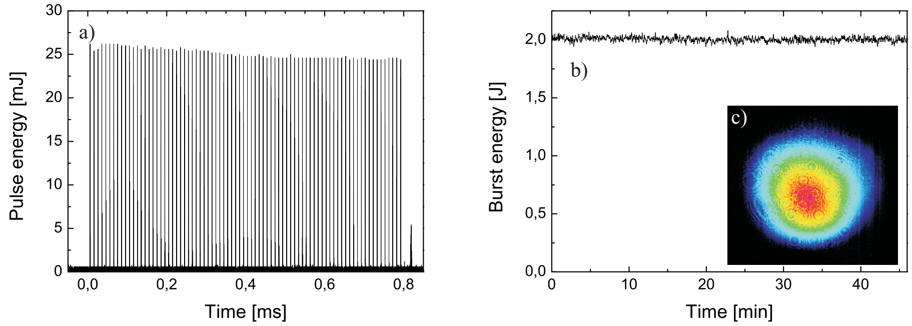

Fig. 3. Burst-mode operation of the amplifier: a) Temporal energy profile of a burst consisting of 80 pulses and b) measured burst energy with stability of 1.1% rms. c) Spatial beam profile.

The 375 µJ pulses delivered by the fiber amplification system are amplified to a maximum of 44.5 mJ pulse energy with the full pumping power of 12.4 kW, averaged over all 80 pulses in the burst, leading to an average intra-burst power of 4.45 kW. Due to the burst operation mode, the total average power of the laser system is 35.6 W. The optical to optical extraction efficiency of this operation mode is 21.5%. The envelope of the pulse train at this high pumping power has an asymmetric shape with decreasing pulse energies over the burst. One possibility to establish a flat and stable shape of the pulse train in the burst is by reducing the pump energy to 4 J (3.1 kW pump power), where the seed pulses are amplified to energies of about 25 mJ. The resulting amplification factor is around 67 and all pulses in the burst experience similar amplification. A typical shape of the bursts after the amplification to 25 mJ in the thin-disk amplifier is shown in Fig. 3a. The extraction efficiency in this case is 48.5%. A possibility of additional shaping of the burst can be a modulation of the pump diode current, which will be implemented in future. The output stability of the amplified bursts is measured to be 1.1% rms (Fig. 3b, measured with an Ophir Nova II energy-meter). The spatial profile of the amplified beam is shown in Fig. 3c.

The spectrum of the pulses is gain narrowed to 2.6 nm FWHM (Fig. 4a) during amplification. The pulses are compressed in a grating compressor with a transmission efficiency of 70%. The resulting autocorrelation trace has a width of 1156 fs FWHM (Fig. 4b), resulting in a pulse duration of 820 fs assuming a temporal Gaussian beam distribution (measured with a single-shot line autocorrelator).

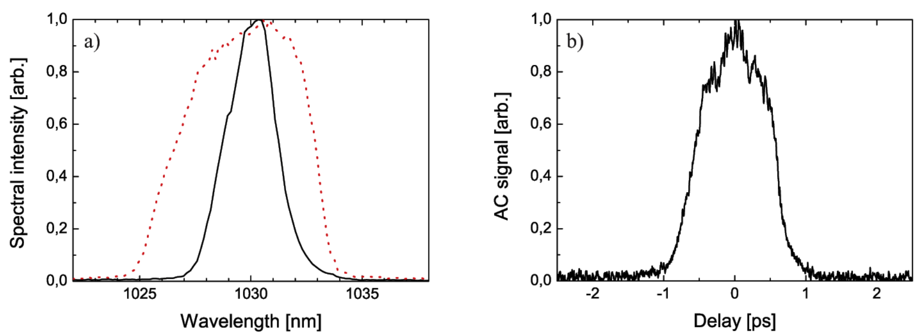

Fig. 4. a) Spectrum of the amplified pulses (solid line) and spectrum of the seed pulses (fiber amplifier, dotted line); b) pulse duration measurement by single-shot autocorrelation.

In a second experiment, a seeder with a higher output pulse energy of 5 mJ (Innoslab amplifier) is used. Therefore, a reduced number of passes (10) in the thin-disk amplifier can be set up. The final amplified pulse energy is 24 mJ at full pumping power leading to an

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amplification factor of 4.8 corresponding to an average single pass gain of G = 1.17. This observed gain is the same as measured in the previous experiment, where the thin-disk amplifier is seeded by the fiber laser. Additionally, the amplification is saturated at the same pump pulse energy as with the fiber seeder, leading to the same shape of the gain curve (see Fig. 2a, blue line). This approves that ASE can be suppressed with the beveled disk in the thin-disk amplifier. Due to the shorter beam path resulting from the lower number of passes, the stability of the system in this setup is improved to be 0.7% rms in the burst energy, measured over a time period of 15 minutes.

4. Conclusions

We have demonstrated the amplification of laser pulses from 375 µJ to 44.5 mJ average pulse energy in the burst with a single stage thin-disk multipass amplifier, leading to an amplification factor of around 118. The repetition rate of the pulses was 100 kHz in a 10 Hz burst operation mode with 80 pulses in the burst, resulting in an average burst laser power of 4.45 kW. This is to our knowledge the highest average power achieved at such high repetition rates. In addition, stable operation with a flat burst envelope was shown with reduced pump power and an output pulse energy of 25 mJ per pulse, yielding an amplification factor of around 67. Furthermore, the compression of the pulses to sub-ps pulse durations was demonstrated, which makes the system interesting as OPCPA pump laser, operating the system with a burst energy stability of 1.1% rms.

In a second design, a higher seed pulse energy of 5 mJ was amplified to a maximum pulse energy of 24 mJ, leading to an amplification factor of 4.8. Due to the higher seed energy, the length of the multipass geometry could be significantly reduced, obtaining an improved burst energy stability of 0.7% rms.

Compared to the results from reference [17], we managed to increase the pulse energy from 2 mJ to 25 mJ at 100 kHz repetition rate using either a fiber seeded or a fiber and Innoslab seeded single stage thin-disk amplifier. The system is capable of stable operation over longer time periods, which makes the laser suitable for long-term operation at the FLASH facility. For the future, we plan to implement a second Innoslab amplifier with 20 mJ output pulse energy. This can be used to seed the thin-disk amplifier to reach pulse energies above 50 mJ with a reduced number of passes on the disk medium, improving the stability of the system.

Finally, we have also discussed the problems arising from parasitic ASE in the thin-disk amplification medium. Different approaches have been shown to overcome the ASE problem for extracting the highest possible pulse energies and guarantee stable operation of the amplifier system. Suppression of the ASE was demonstrated by reducing the pump spot diameter and by beveling the boundaries of the thin-disk gain medium.

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