High-energy diode-pumped Yb:YAG chirped pulse amplifier

Mathias Siebold[a,b], Christoph Wandt[a], Sandro Klingebiel[a], Zsuzsanna Major[a], Sergei Trushin[a] Izhar Ahmad[a], Tie-Jun Wang[a], Joachim Hein[b], Ferenc Krausz[a], and Stefan Karsch[a]

[a]Max-Planck-Institute for Quantum Optics,
Hans-Kopfermann-Str. 1, 85748 Garching, Germany;
[b]Institute for Optics and Quantum Electronics, Friedrich- Schiller-University Jena,
Max-Wien-Platz 1, 07743 Jena, Germany

ABSTRACT

A diode-pumped chirped-pulse amplifier (CPA) system based on Yb:glass and Yb:YAG as a picosecond pump source for a future ultra-high peak-power optical parametric chirped-pulse amplifier (OPCPA) is currently under development. Pulses as short as 300 fs generated in an Yb:glass mode-locked oscillator have been stretched to the nanosecond level. The seed pulses are then amplified up to an output pulse energy of 100 mJ in a diode-pumped Yb:glass regenerative amplifier and a subsequent Yb:YAG booster. At a small-signal gain of 10^3 in Yb:YAG the initial pulse bandwidth of 4 nm (FWHM) has been gain-narrowed to 1.5 nm, which allows the re-compression to 1.1 ps. With a multi-pass Yb:YAG amplifier which has been seeded by a Q-switched sub-10-nanosecond laser an output pulse energy of 2.9 J has been achieved. In quasi-cw-mode a peak output power of 7.6 kW and a tuning range of 5 nm have been obtained. The foot-print-size of the multi-pass amplifier is $0.8\,\mathrm{m} \times 1.1\,\mathrm{m}$ which illustrates the degree of system compactness.

Keywords: Diode-pumped, Laser amplifier, Chirped pulse amplification

1. INTRODUCTION

The goal of the Petawatt Field Synthesizer (PFS) project[1] of the Max-Planck Institute for Quantum Optics (Garching, Germany) is the construction of a unique, few-cycle light source in the petawatt range with absolute phase stabilization. In order to achieve these ambitious goals, the PFS design is based on an optical parametric chirped pulse amplification (OPCPA) scheme[2,3] operating in the wavelength band between 800 and 1600 nm. The OPA stages employing DKDP crystals will be pumped by ultra-short pulses with a pulse duration of at least 1 ps at a center-wavelength of 515 nm. Therefore, a high energy, diode-pumped CPA[4] system as a powerful pump source is currently under development. A final output pulse energy of 15 J in one beam before frequency-doubling and a repetition rate of 10 Hz are desired. At least, four pump beams are required in order to scale the pulse energy of the four-stage OPA chain to the multiple-joule-level.

In terms of its output parameters the considered pump laser will be comparable to the high-energy-class diode-pumped solid-state lasers such as MERCURY,[5] LUCIA,[6] HALNA,[7] or POLARIS.[8] A prototype laser was constructed for a maximum pulse energy of 1.5 J at a center wavelength of 1030 nm and a pulse duration of 2 ns (stretched pulses of a CPA system), which represents a $1/10^{\mathrm{th}}$ scale of the pump laser.

For the power amplifiers of the considered pump laser system Ytterbium-doped Yttrium Aluminum Garnet (YAG) as one of the most developed laser materials for diode-pumped lasers with high-average-power has been chosen. Yb:YAG has been evolved to a laser material for applications up to the industrial scale such as thin-disk[9] and slab lasers[10] for several 100 W average power. Ceramic Yb:YAG[11] has been extensively developed in order to provide large volumes with optical quality, where the presented CPA system as well as future high-energy-class diode-pumped solid-state lasers will benefit from. Considering improved thermal behavior and increasing emission cross section at low temperature cryogenic Yb:YAG[12–14] has attracted interest in the field of high average power applications. However, the emission spectrum of Yb:YAG is narrowed with decreasing temperature, which in general complicates the CPA concept. With regard to high-energy-class lasers, microsecond pulse amplification

Further author information: (Send correspondence to M. Siebold or S. Karsch)
M. Siebold: E-mail: siebold@ioq.uni-jena.de, Telephone: +49-3641-947 286
S. Karsch: E-mail: stefan.karsch@mpq.mpg.de, Telephone: +49-89-32 905 322

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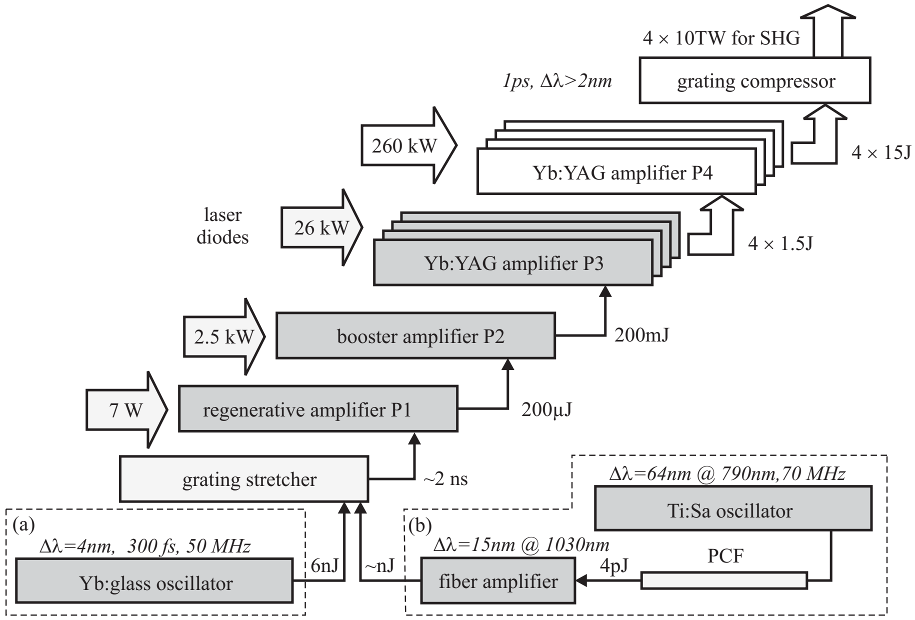

Figure 1. Outline of the PFS pump laser system, four-stage diode-pumped chirped-pulse amplifier chain, preliminarily seeded by front-end (a), Later, a broadband Ti:Sa oscillator serves as common front-end (b) for both OPCPA-chain and the pump laser, PCF: photonic crystal fiber for shifting the center-wavelength of the seed-pulses from 790 nm to 1030 nm.

to the joule-level with an optical-to-optical efficiency of 8.7% has already been demonstrated using an Yb:YAG slab.[15] To our knowledge the amplification of nanosecond pulses with an output pulse energy of more than 50 mJ has not been shown elsewhere.[16,17] With an emission bandwidth of nearly 10 nm mode-locking operation down to the sub-ps time-scale has also been reported,[18] which indicates enough gain bandwidth of Yb:YAG for picosecond pulse amplification. In terms of pumping optical parametric chirped-pulse amplifiers picosecond regenerative[19–21] and multi-pass amplification[14] with several mJ output energy has been demonstrated already. In general, due to its quasi-three level scheme the major drawback of Ytterbium-based gain media is the minimum pump intensity required to bleach out the absorption at the laser wavelength.[22] Therefore, efficient pulse energy extraction requires high fluences which tend to approach the damage threshold fluence for nanosecond pulses. Here, we present multi-pass amplification of nanosecond pulses to the 2.9 J-level employing Yb:YAG. Furthermore, we introduce a fully diode-pumped chirped-pulse amplifier system for OPCPA pumping.

2. AMPLIFIER SYSTEM

Fig. 1 shows the layout of the CPA-based pump-laser system. Preliminarily, the seed pulses are generated in a commercial Yb:glass oscillator (front-end a) with an average output power of 300 mW and a repetition rate of 50 MHz. A pulse duration of 300 fs and a pulse bandwidth of 4 nm at a center-wavelength of 1030 nm has been measured. Later, a broadband Ti:Sa oscillator serves as common front-end (b) for both OPCPA-chain and the pump laser system, in order to synchronize the pump and signal pulses. A photonic-crystal fiber (PCF) is then used to shift the center-wavelength from 790 nm to 1030 nm for the seed-pulse generation of the CPA system. Due to the low efficiency of the shifting process the PCF is followed by a diode-pumped Yb:silica fiber laser amplifier.

The seed pulses are stretched to 2 ns by an 8-pass grating stretcher which incorporates a 200-mm grating with 1740 lines per mm. After stretching the pulse energy of several nanojoules is boosted to the 50 J-level by four diode-pumped amplifier stages labelled P1 to P4. The amplifier P1 employing a low-gain broadband laser material (Yb:glass[24]) is designed as a regenerative amplifier.[8] After the booster amplifier (P2) the pulses are multiplexed (temporal pulse stacking) because of 4 pump beams, one for each OPA stage of the PFS. In addition, this technique allows a further increase of the stretched pulse duration while amplification and therefore reduced risk of laser induced damage.

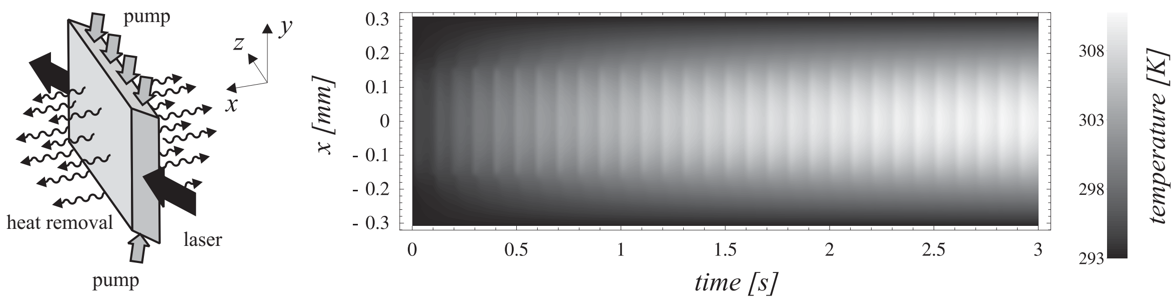

Figure 2. Yb:YAG crystal of multi-pass amplifier P3 and the simulated evolution of the temperature distribution inside the transversally cooled gain medium, pump peak-power: 26 kW, pump duration: 1.5 ms, repetition rate: 10 Hz, assumed thermal load: 10% of the absorbed pump power, crystal edge temperature: 20°C, peak temperature difference between crystal center and edge at steady state: 17 K, thermal conductivity[23] of Yb:YAG at an Yb^{3+}-concentration of 1.4%: $10\,Wm^{-1}K^{-1}$, thermal optical coefficient: $dn/dT = 9{\cdot}10^{-6}\,K^{-1}$.

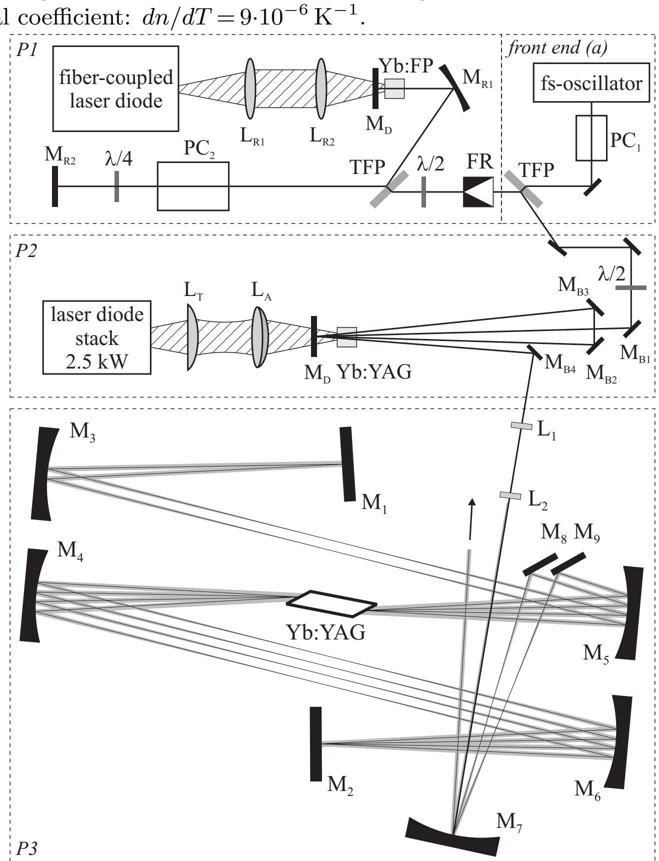

Figure 3. Setup of the CPA system with the amplifier stages P1–P3: front end followed by a pulse picker Pockels cell (PC1), a thin-film polarizer (TPF), a Faraday rotator (FR), and a half-wave plate ($\lambda/2$); regenerative amplifier P1 with Yb-doped Fluoride-Phosphate glass (Yb:FP) pumped by a 7 W fiber-coupled laser diode at a center-wavelength of 976 nm, fiber output imaged to the gain medium by a spherical lens telescope (LR1 and LR2), stable cavity formed by a dichroic mirror (MD), a concave mirror (MR1) and a plane end mirror (MR2), Pockels cell (PC2), thin-film polarizer (TFP), and quarter-wave plate ($\lambda/4$) for switching input and output pulses; booster amplifier P2 with Yb:YAG pumped by a stack of 25 fast-axis collimated laser-diodes at a center-wavelength of 940 nm, diode stack followed by a toric lens (LT) for beam symmetrization and an achromatic focussing lens (LA), multi-pass amplifier with turning mirrors (MB1–MB4) and dichroic mirror (MD); 4-pass Yb:YAG amplifier P3 with relay imaging, Yb:YAG crystal with Brewster cut, plane end mirrors (M1, M2), concave mirrors (M3–M7, radius of curvature: 750 mm), plane turning mirrors (M8, M9), and a cylindrical lens telescope (L1 and L2) for adjustment of the beam aspect ratio.

Up to now, chirped pulse amplification to the 100 mJ-level has been demonstrated using the amplifier stages P1 and P2, whereas the feasibility of high-energy pulse amplification employing the Yb:YAG-based amplifier stage P3 has been tested with nanosecond pulses which have been generated in a Q-switched oscillator.

3. DESIGN AND MODELLING

The generation of laser pulses containing high pulse energies of more than several joules is reserved for laser systems in a bulk design due to energy storage and scalable beam aperture, in contrast to fiber lasers or thin-disk lasers being suitable for high average power. Considering high optical energy densities stored within the bulk amplifier medium, thermal aspects as well as problems with respect to amplified spontaneous emission (ASE) depending on the geometric dimensions and the emission cross section of the laser material have to be taken into account.

By means of the amplifier stage P3 the simulation models considering the temperature profile inside the gain medium as well as the short-pulse amplification is described. The gain medium is designed for a maximum fluence of 10 Jcm^{-2} which is the saturation fluence of Yb:YAG. In the case of the presented amplifier, a slab design[25] of the gain medium (3.3 mm width, 16 mm height, and 16 mm length) with Brewster cut has been preferred (see Fig. 2). In general, the thermal behavior of a high-average-power slab laser is superior to a gain medium with circular cross section due to an increase of the heat sink surface. The Yb:YAG crystal (grown by FEE, Germany) comprises an Yb^{3+}-concentration of 1.4%. With an absorption efficiency of 74% the gain medium is transversally pumped by two laser diode modules (provided by Jenoptik Laserdiode GmbH[26,27]) each having a peak output power of 13 kW. The transversally-cooled crystal (see Fig. 2) is thermally-coupled to two micro-channel heat sinks. Figure 2 also shows the evolution of the temperature profile inside the Yb:YAG crystal from power-on to steady-state. A peak temperature difference of 17 K between crystal center and edge at steady-state has been calculated resulting in a thermally-induced (cylindrical) lens with a focal length of 1.2 m.

Figure 3 shows the setup of the amplifier stages P1–P3. A detailed description of the amplifier design of P1 and P2 is given in.[8] In the case of the amplifier stage P3 the gain medium is placed into a double 4-f, relay imaging optical configuration, where the plane mirrors M1 and M2 receive images of the beam profile at the Brewster-cut gain medium. In order to prevent the ionization of air and subsequent optical breakdown, vacuum tubes are placed at the focal regions. By tilting of mirror M1 the cavity between the mirrors M1–M6 acts as semi-stable cavity allowing an arbitrarily adjustable number of amplifier passes.

In order to estimate the chirped ns-pulse amplification in Yb:YAG especially in terms of possible gain narrowing, a rate equation model including the absorption and emission cross section of the gain medium has been employed. The simulation of the expected output-pulse parameters is based on numerical integration of the rate equation system[28,29] including the quasi-three-level scheme of the Yb^{3+}-ion:

$$d\left(\frac{\partial N}{\partial t}\right) = -c\,\sigma_g(\lambda, N)\,\varphi(\lambda)\,N\,d\lambda \quad \text{and} \quad \frac{\partial \varphi(\lambda)}{\partial t} = c\,\sigma_g(\lambda, N)\,N\,\varphi(\lambda), \tag{1}$$

with

$$\sigma_g(\lambda, N) = \beta\,\sigma_e(\lambda) + (1-\beta)\sigma_a(\lambda),\ \beta = N/N_{dop}. \tag{2}$$

Here, φ denotes the photon density per volume and wavelength interval, σ_a and σ_e the absorption and emission cross section, λ the wavelength, N the density of excited Yb^{3+}-ions in the $^2F_{5/2}$-level, N_{dop} the total density of Yb^{3+}-ions, and c the velocity of light, respectively. Initially, a spatially homogeneous inversion $N(x, y, z)$ as well as a Gaussian-shaped pulse spectrum and intensity profile of the input pulse has been defined. Here, for the simulation of the pulse amplification at nanosecond timescale a homogeneously broadened gain spectrum has been assumed.

Figure 4(a) illustrates the gain narrowing at Gaussian-shaped input spectra with a bandwidth of 5 nm dropping to 2 nm while amplification by a factor of 100. In addition, the emission spectrum of Yb:YAG is also given in 4(a). When seeding with pulses at a center-wavelength below or above 1030 nm the gain narrowing is reduced while the output pulse spectrum is shifted towards peak-emission wavelength of Yb:YAG. Furthermore, spectral shaping of the input pulses might be considered in order to counteract the gain narrowing. Figures 4(b–d) show the

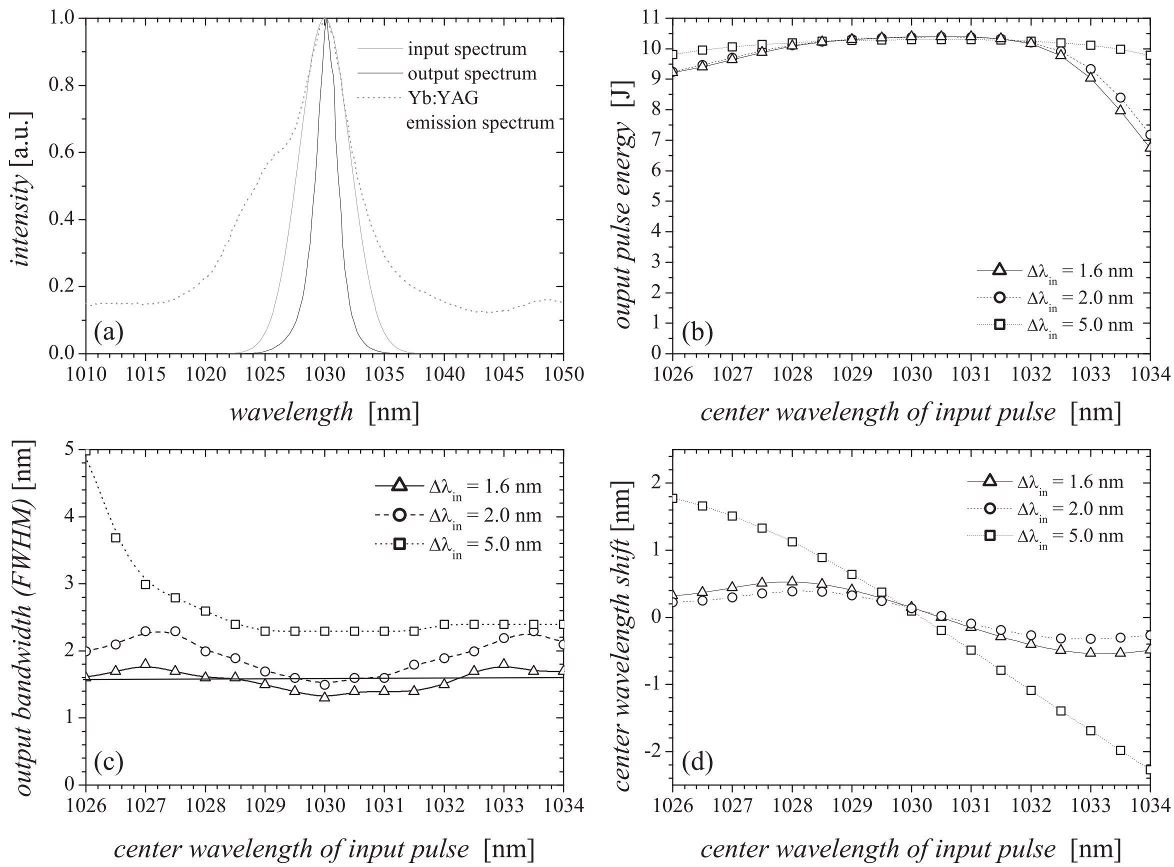

Figure 4. Simulation results concerning the pulse parameters of the Yb:YAG slab multi-pass amplifier, pump power: 26 kW, pump duration: 1.5 ms, numbers of amplifier passes: 4, input pulse energy: 100 mJ; (a) output pulse spectrum at Gaussian-shaped input pulse with a center-wavelength of 1030 nm and a spectral width of 5 nm (FWHM), emission spectrum of Yb:YAG. (b) output pulse energy, (c) spectral width of the output pulse (FWHM), and (d) center-wavelength shift of the output pulse vs. center-wavelength of the input pulse.

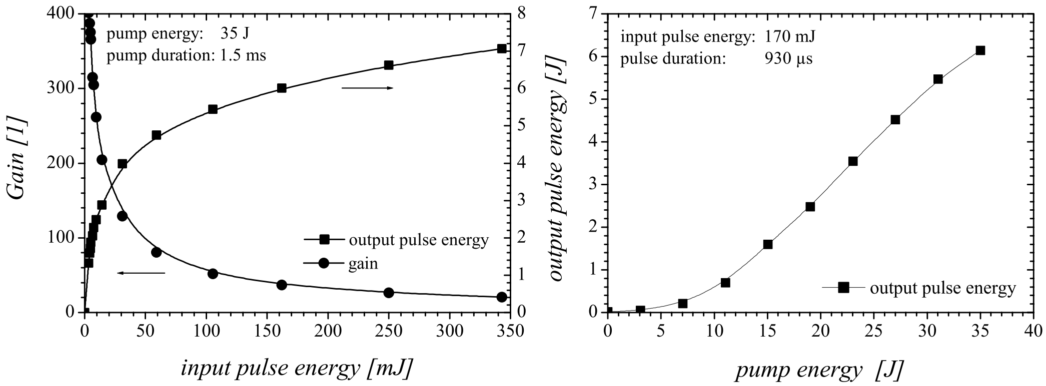

Figure 5. Millisecond pulse amplification, pulse duration: 930 μs, numbers of passes: 4; (a) Output pulse energy and total gain vs. input pulse energy at a pump energy of 35 J, (b) Output pulse energy vs. pump pulse energy, input pulse energy: 170 mJ.

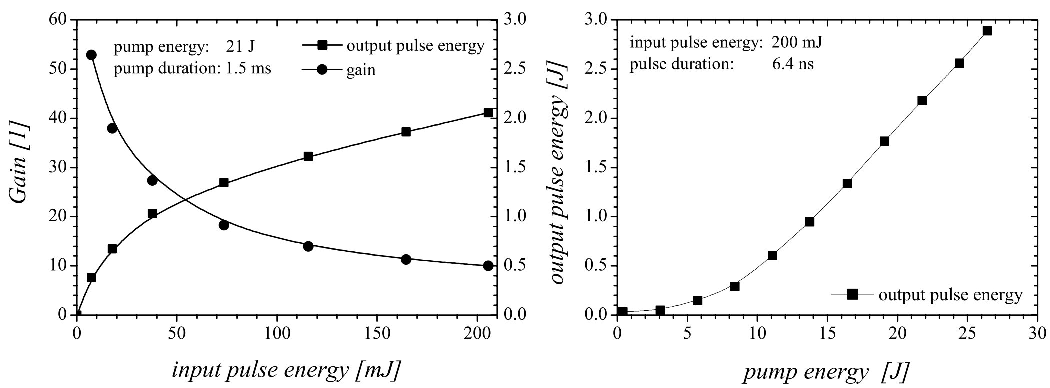

Figure 6. Nanosecond pulse amplification, pulse duration: 6.4 ns, numbers of passes: 4; (a) Output pulse energy and total gain vs. input pulse energy at a pump energy of 21 J, (b) Output pulse energy vs. pump pulse energy, input pulse energy: 200 mJ.

simulation results of the output pulse energy, the spectral width of the output pulse, and the center-wavelength shift depending on the center-wavelength of the input pulse. Here, a perfect spatial overlap between seed pulse and inversion profile has been assumed and losses such as ASE have also been neglected in the model.

4. EXPERIMENTAL RESULTS

First verification of the single pass gain revealed a significant parasitic lasing within the Yb:YAG crystal at increasing pump power. These parasitic oscillations have been suppressed by AR-coating the pump entrance faces and a thin absorbing coating between crystal and heat sink. Although a moderate dopant concentration of the gain medium has been chosen the small-signal gain is limited to a maximum value of 1.6 cm^{-1} due to the ASE which reduces the energy storage capability of the crystal.

The laser dynamics of the amplifier stage (P3) at both nanosecond and millisecond time-scale have been analyzed.

When operating in quasi-cw mode (millisecond pulses) the amplification can be verified without the risk of laser induced damage. In the millisecond regime a maximum output pulse energy of 7.1 J (7.6 kW peak-power) at maximum pump-power and at a pump duration of 1.5 ms has been achieved (see Fig. 5). The maximum small-signal gain left for short pulse amplification at the end of the pump pulse is expected to be reduced due to fluorescence losses as well as ASE. Finally, a tuning range of 5 nm (FWHM) in the quasi-cw mode has been measured, which suggests that a necessary condition for picosecond pulse amplification has been fulfilled.

In order to approximate the PFS-conditions before the front-end has been installed completely, the amplifier was seeded by pulses generated in a Q-switched oscillator (output pulse energy: 5 mJ, repetition rate: 10 Hz, pulse duration: 6 ns) and a subsequent Yb:YAG booster (output pulse energy: 200 mJ, max. repetition rate: 10 Hz, beam quality: TEM_{00}). The amplifier dynamics analyzed at nanosecond pulses are shown in Fig. 6. A maximum output pulse energy of 2.9 J could be achieved, before laser induced damage on the crystal surface occurred. As a consequence of the result shown in Fig. 6(b) the optical-to-optical efficiency (currently 10%) is mainly limited by the damage threshold compared to the threshold pump energy. A slight improvement of extraction efficiency can be yielded either by an increase of the input pulse energy or by adding further amplifier passes.

At nanosecond pulses the damage threshold fluence scales with the inverse square-root of the pulse duration resulting in 44% reduction of the maximum possible pulse energy in the case of a pulse duration of 2 ns instead of 6 ns. Thus, twice the necessary fluence has been applied when seeding with pulses of the Q-switched laser. Taking into account the above damage scaling, this result translates to more than 1.5 J at 2 ns. A slope efficiency of 15% and an optical-to-optical efficiency of 10% has been achieved, which meets the designed specification in terms of the number of required pumping diodes. Since the stored energy in the crystal by far exceeds the energy converted into one beam, later multiplexing of four beams is straightforward and each beam can extract the same energy from the crystal. The result mentioned above is a proof of principle for further scaling of the output pulse energy at a similar amplifier concept.

In addition, for supporting ps-pulses in a CPA system, the amplification bandwidth has to be sufficiently large. Recently, employing the Yb:YAG booster amplifier (P2) and chirped-broadband seed pulses a bandwidth of 3 nm at a gain G=10 has been measured, dropping to 2.3 nm at G=100 and 1.5 nm at G=1000. This indicates that at least the last two Yb:YAG stages of the full system (P3 and P4) will not suffer too badly from gain narrowing. Substituting Yb:YAG by another gain material (Yb:Glass, Yb:CaF_2) in the booster (P2) will keep the bandwidth high up to the input of these stages. At present a minimum bandwidth of 1.5 nm can be safely assumed, which represents a bandwidth limited pulse duration of 1.1 ps after re-compression.

Alternatively, the qualification of Yb:CaF_2 as a promising new gain instead of Yb:YAG has been intensified. Yb:CaF_2 comprises a high gain bandwidth (>40nm) which allows pulse durations of 100-150 fs of direct diode-pumped laser systems. A maximum output pulse energy of 750 mJ (at a pulse duration of 6 ns) has been demonstrated within the presented laser amplifier (P3), whereas at regenerative amplification of fs-pulses (total gain: 10^4) a bandwidth of 13 nm has been obtained.[30]

With reference to the simulation presented in section 3 the expected gain narrowing has been measured, whereas the maximum pulse energy which could be extracted in quasi-cw mode without laser induced damage is reduced to both fluorescence losses (ASE) and limited overlap between laser beam and gain profile. When operating at 10 Hz repetition rate no significant focussing of the laser beam due to thermal lensing has been observed.

5. CONCLUSION

In summary, we have demonstrated nanosecond pulse amplification up to the 3 J-level within a 4-pass Yb:YAG amplifier. In the case of nanosecond pulses an optical-to-optical efficiency of 10% at a pump duration of 1.5 ms has been obtained. When seeded with millisecond pulses a maximum output pulse energy of 7.1 J has been achieved. With regard to chirped pulse amplification in Yb:YAG the seed bandwidth was not dramatically reduced by gain narrowing at maximum small signal gain of 1000. Future work is now in progress to accommodate and operate the presented Yb:YAG amplifier in a CPA system with expected pulse duration of 1 ps and peak power in excess of 1 TW after re-compression. In conclusion, we believe that the research invested into the pump laser has demonstrated the feasibility and scalability of our approach. Up to now, no fundamental flaws in the concept were identified, and the data and experience gathered will allow the construction of the full-scale pump laser for PFS.

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