Diode-pumped ytterbium-based chirped-pulse amplifier

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ABSTRACT

This paper will describe a comparative study on four different Yb-doped laser materials in a diode-pumped femtosecond chirped-pulse amplifier. Broadband multi-pass amplification using single crystalline Yb:CaF_2, Yb:KGW, and Yb:YAG as well as Yb-doped fluoride phosphate glass was demonstrated. The seed pulses as short as 85 fs were generated in a Ti:Sapphire oscillator tuned to a center-wavelength of 1030 nm and then boosted to the 100 μJ-level in a diode-pumped Yb:glass regenerative amplifier. Furthermore, the amplifier performance at nanosecond and microsecond time-scales was analyzed. With regard to the 10-nm line-width of the emission cross section the gain narrowing in Yb:YAG was investigated in particular. The pulse spectrum was narrowed to 1.9 nm at a total gain of 10^3 in an Yb:YAG multi-pass amplifier. This corresponds to a compressed pulse duration of 0.85 ps. When seeding with nanosecond pulses of a Q-switched oscillator a maximum pulse energy of 220 mJ at a repetition rate of 10 Hz has been achieved.

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

1. INTRODUCTION

After the invention of the technique of chirped pulse amplification (CPA)[1] we have witnessed tremendous progress in the field of high-intensity laser physics. Nowadays, pulses with highest peak-powers at up to the Petawatt level are generated with either high-energy, low-repetition rate, sub-picosecond glass lasers or femtosecond laboratory scale Titanium-sapphire systems. The optical parametric chirped pulse amplification (OPCPA) scheme[2–5] seems to be a promising alternative for pushing the peak intensities to even higher levels at shortest pulse durations down to a few cycles of the electromagnetic field. However, the lasing performance of the next generation peak power lasers based on the OPCPA technique directly depends on the pulse parameters of the pump laser system. Therefore, compact high-energy picosecond lasers with high repetition rates are required preferably based on diode-pumped solid-state gain media.[6–8]

The Max-Planck-Institute for Quantum Optics in Garching, Germany follows the OPCPA concept with the construction of the Petawatt Field Synthesizer (PFS) which is designed for multijoule few-cycle pulses. A high energy, ytterbium-based, diode-pumped, high repetition rate laser amplifier (HYDRA) as a picosecond pump source is presently under development in cooperation with the Institute of Optics and Quantum Electronics in Jena, Germany for this ambitious project. With regard to the planned output pulse energy of 50 J and a repetition rate of 10 Hz of the final amplifiers the considered pump laser will rank at the top of highest energy per pulse diode pumped lasers together with MERCURY,[9] LUCIA,[10] HALNA,[11] or POLARIS.[12]

Recently, the lasing performance of the laser system described generating nanosecond pulses containing an energy of 220 mJ at a repetition rate of 10 Hz[13] as well as a subsequent booster with an output pulse energy of 2.9 J at 1 Hz repetition rate[14] has been reported. The overall outline of the PFS system[15] and its pump laser HYDRA[16] with Yb:YAG as amplifying medium has also been presented recently. In general, owed to the quasi-three level scheme of ytterbium-doped gain media a minimum pump intensity is required to bleach out the absorption at

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XVII International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, edited by Rui Vilar, Olinda Conde, Marta Fajardo, Luís O. Silva, Margarida Pires, Andrei Utkin, Proc. of SPIE Vol. 7131, 713110 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.816705

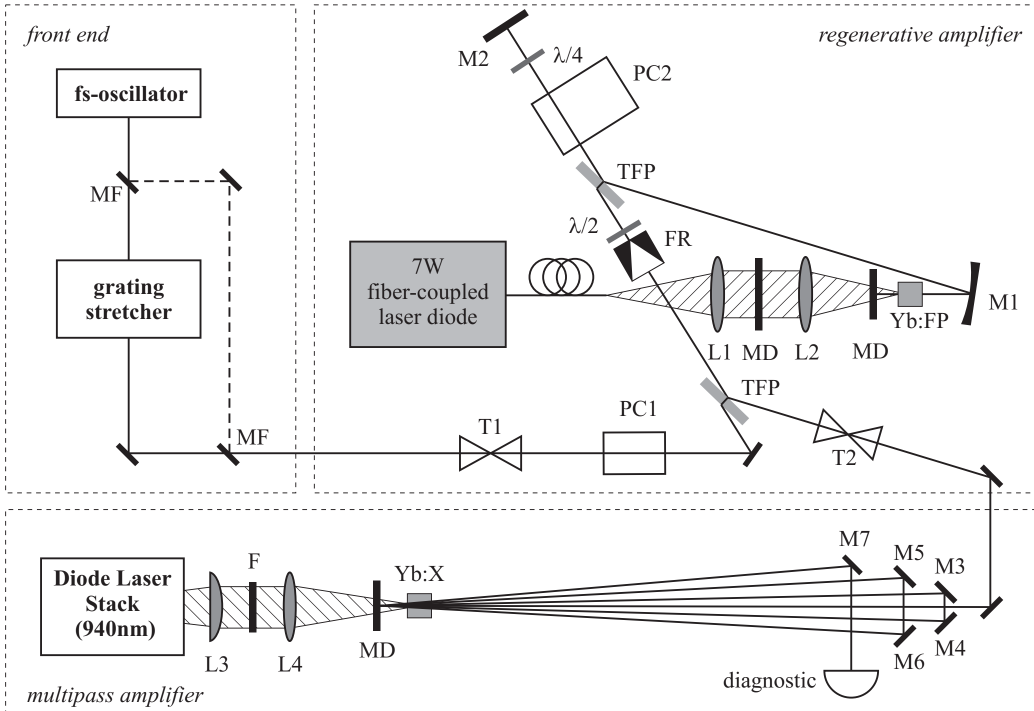

Figure 1. Layout of the two-stage CPA system: regenerative amplifier based on Yb-doped fluoride phosphate glass (Yb:FP), seeded either by a femtosecond or chirped pulses; multi-pass amplifier based on Yb-doped laser materials (Yb:X); MF, flip mirror; MD and F dichroic flat mirrors (HR 1020-1060 nm, AR 930-980 nm); M1, concave reflecting mirror (radius of curvature: 200 mm, HR 0° 1020-1060 nm); M2, plane reflecting mirror (HR 0° 1020-1060 nm); M3–M7, dielectric plane deflecting mirrors (HR 45° 1010-1060 nm); TFP, thin film polarizer; $\lambda/4$, quarter-wave plate; $\lambda/2$, half-wave plate; PC1, pulse picking Pockels cell; PC2, pulse coupling Pockels cell; FR, Faraday rotator; T1, spherical lens telescope (magnification: 1) for divergence control; T2, spherical lens telescope (total magnification: 3); L1 and L2, spherical lenses ($f = 75$ mm); L3, cylindrical lens ($f = 115$ mm); L4, spherical lens ($f = 250$ mm).

the laser wavelength. Due to this major drawback the extraction efficiency of amplifiers generating nanosecond pulses with energies in the multi-100 mJ-range and beyond is limited by laser-induced damage.[17]

Here we present the laser performance of four different laser materials such as Yb:YAG, Yb-doped fluoride phosphate glass, Yb:CaF_2, and Yb:KGW suitable for the power amplifiers of the considered pump laser system. Single crystalline and ceramic Ytterbium-doped Yttrium Aluminum Garnet (Yb:YAG) with superior thermal properties for high average power operation has been extensively developed in the past.[18,19] Recently, ytterbium-doped alkaline-earth fluorides (Yb:CaF_2, Yb:SrF_2, Yb:BaF_2) have attracted considerable interest for diode-pumped femtosecond-lasers and amplifiers.[20–23] Yb-doped fluoride phosphate glass (Yb:FP)[24] showing a broadband, smooth emission cross section is superior for high gain femtosecond pulse amplification but is reserved for lower average power lasers due to its moderate thermal properties. Another appropriate laser material for broadband high average-power multi-pass amplification is Yb:KGW with which diode-pumped femtosecond oscillators and regenerative amplifier have been already demonstrated.[25,26] In this paper we will show the results of our comparative survey of suitable laser materials to achieve high energy diode-pumped, chirped-pulse amplification. The given parameters allow us to scale the concept described towards higher pulse energies and peak powers.

2. EXPERIMENTAL SETUP

Figure 1 shows the layout of the two-stage diode-pumped chirped pulse amplifier. The seed pulses are generated in a commercial Ti:Sa oscillator (Mira 900, Coherent Inc., USA) with an average output power of 300 mW at a center-wavelength of 1030 nm and a repetition rate of 85 MHz. A pulse duration of 85 fs and a pulse bandwidth of 18.5 nm at a center-wavelength of 1030 nm was measured. Later, a broadband Ti:Sa oscillator serves as common

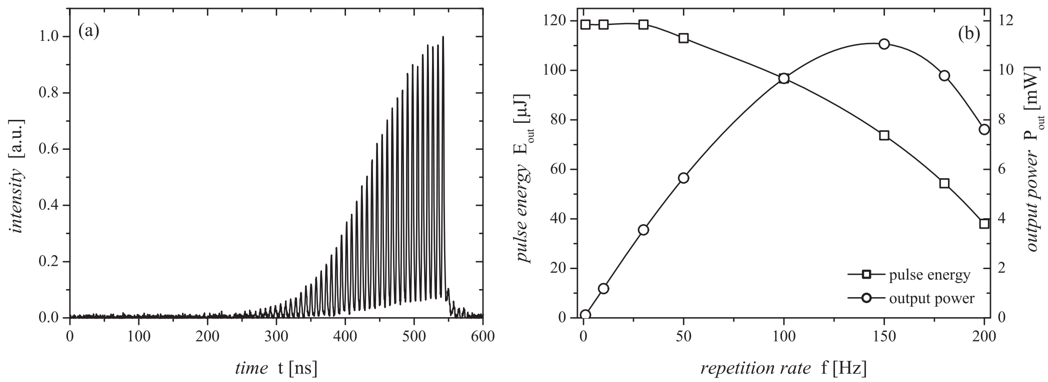

Figure 2. Dynamic of the regenerative Yb:glass amplifier; (a) intra-cavity pulse train at chirped-pulse amplification, pedestal signal due to limited temporal resolution of the photo-diode, (b) output pulse energy and output power vs. repetition rate.

front-end for both the OPCPA chain and the pump laser system, in order to synchronize the pump and signal pulses. With an 8-pass grating stretcher[27,28] the fs-pulses are stretched to 2 ns, whereas picosecond pulses can be stretched to a similar pulse duration by extending the grating separation distance.

The regenerative amplifier employing Yb:FP glass is pumped at a wavelength of 976 nm by a 7 W fiber-coupled laser diode (Lumics GmbH, Germany). The diode was driven in pulsed mode with a pulse length of 3 ms. A plane dichroic mirror (MD) acting as a wavelength coupler, a concave mirror (M1, radius of curvature R = 200 mm), and a plane end mirror (M2) form a folded hemispherical resonator. Two achromatic lenses (f = 75 mm) are used to image the output of the 200 μm-fiber into the Yb:FP glass.

Both drivers of the pulse picking (PC1) and the intra-cavity (PC2) switching DKDP Pockels cell provide adjustable voltage pulses with rise and fall times of less than 4 ns (BME KG, Germany) at a repetition rate of up to 10 kHz. A Faraday-rotator, a thin film polarizer (TFP), and a half-wave plate separate the in- and output gate of the amplifier.

In Tab. 1 the properties and the geometry of the anti-reflection coated laser materials are summarized. The

Table 1. Material and sample parameters.

	Yb:FP[24]	Yb:YAG[29]	Yb:CaF_2[20]	Yb:KGW[25]
peak emission cross section [10^{-20}cm^2]	0.42	1.9	0.2	2.8
fluorescence lifetime [ms]	1.4	0.95	2.2	0.6
Yb-concentration	$8 \cdot 10^{20}$ cm^{-3}	3 mol%	2 mol%	5 mol%
rod length [mm]	6	8	20	4
rod diameter [mm]	12	6	28	12

gain medium of the subsequent multi-pass amplifier was pumped by a stack of 25 fast axis collimated diode-laser bars (Jenoptik Laserdiode GmbH, Germany) with a peak output power of 4 kW at a wavelength of 940 nm. A pump duration of 1.5 times the fluorescence lifetime for each gain medium was chosen. In order to re-collimate the pump light along the slow axis and focus it into the gain medium each diode-stack was followed by a toric (fast axis: f = 800 mm; slow axis: f = 115 mm) and a spherical lens (f = 250 mm). The plane dichroic mirror (MD) directly behind the gain medium is also utilized as folding mirror for the multi-pass setup with high reflection (HR) coated turning mirrors (M3–M7). As an example a 6-pass arrangement is shown in Fig. 1. In order to protect the diode-stack from optical damage due to transmitted nanosecond pulses a further dichroic mirror (F) was added between L3 and L4 as a filter.

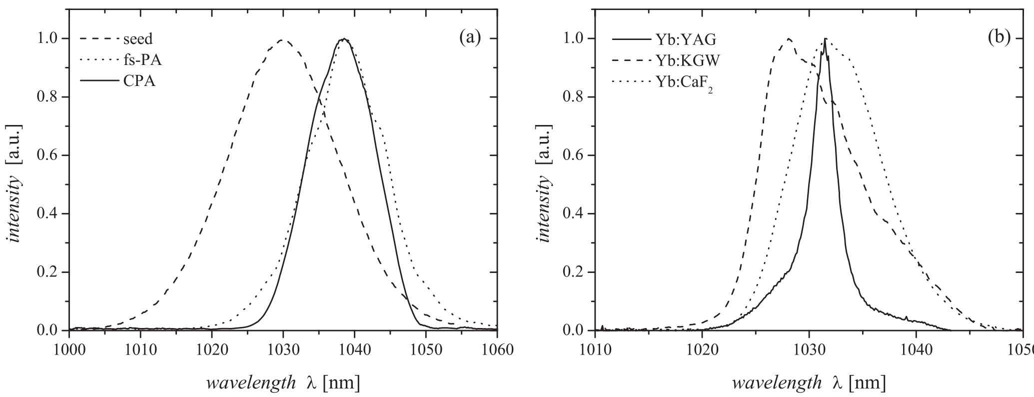

Figure 3. Spectra of the regenerative and the multi-pass amplifier: (a) pulses of the fs-oscillator (seed), fs-pulse amplification (fs-PA) $\Delta\lambda$=12.9 nm (FWHM), pulse energy: 20 μJ, and chirped pulse amplification (CPA): $\Delta\lambda$=11.6 nm (FWHM), pulse energy: 118 μJ, (b) chirped-pulse amplification employing Yb:YAG, Yb:KGW (E || a-axis), or $Yb:CaF_2$ seeded with the output of the regenerative amplifier; total gain adjusted for each laser material: G=10.

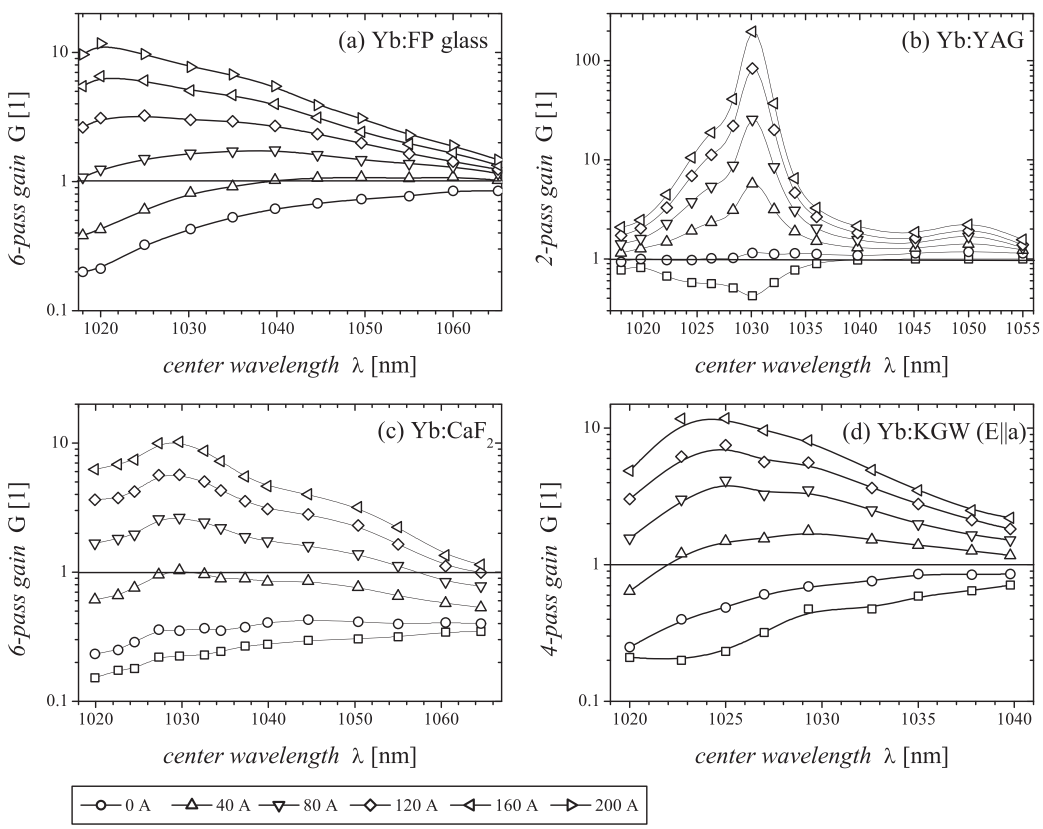

Figure 4. Small signal gain at multi-pass (2-, 4-, and 6-pass configuration depending on the desired maximum gain G) amplification using several Ytterbium-doped gain media, tunable seed with a pulse duration of 100 μs. The peak-current of the pumping diode-stack has been varied, whereas the output power linearly depend on the driver current: P = 4 kW at I = 200 A, lasing threshold of the laser-diodes: I_{thr} = 18 A. Pump pulse duration: 1.5 times the fluorescence lifetime for each laser material; spot size of the pump profile: 0.2 cm^2.

3. EXPERIMENTAL RESULTS

3.1 Regenerative Yb:FP glass amplifier

An output power of 170 mW was measured in continuous-wave (cw) operation. In Q-switched mode a maximum pulse energy of 150 μJ at a pulse duration of 6 ns and a repetition rate of 10 Hz was achieved. The intra-cavity pulse train detected with a GaAs photo-diode behind M2 is shown in Fig. 2(a). After 540 ns a pulse energy of 118 μJ at repetition rates below 30 Hz was obtained. The number of round trips for maximum output pulse energy and therefore the internal losses increase at higher repetition rates. Due to gain saturation a high pulse-to-pulse stability was observed. In the case of chirped-pulse amplification and Q-switched mode saturation of the gain could be achieved.

Figure 2(b) illustrates the influence of the repetition-rate on the output average power and the pulse energy. Both, the fluorescence lifetime and the photon lifetime which is related to the intra-cavity losses determine the characteristic repetition-rate where the maximum average output power occurs. In this case a maximum average power of 14.7 mW at a repetition rate of 150 Hz was obtained. When seeding with femtosecond pulses the pulse energy was limited to 20 μJ in order to prevent laser induced damage of the gain medium. Both input and output spectra at femtosecond as well as at chirped-pulse amplification was determined shown in Fig. 3(a). The center wavelength is red-shifted from 1030 nm to 1038.5 nm, which is owed to spectral filtering of both the effective gain spectrum of the laser glass (see 2) and the coatings of the intra-cavity optics used. Furthermore, the bandwidth of the output pulse spectra was narrowed to 11.6 nm and 12.9 nm at full width half maximum (FWHM), respectively.

3.2 Multi-pass Yb-based amplifier

The lasing performance of the four laser materials Yb:YAG, Yb:FP glass, Yb:CaF_2, and Yb:KGW under investigation was analyzed in a multi-pass amplifier. Except for Yb:FP glass which is pumped at 1 Hz the presented amplifier operates at a maximum repetition rate of 10 Hz. At a total gain of 10 the output spectra of the multi-pass chirped-pulse amplifier employing different Yb-doped laser crystals are shown in Fig. 3(b). In addition, the tuning range of the small signal gain was measured using microsecond pulses (pulse duration: 100 μs). In order to achieve a tuning range of 1020 nm − 1070 nm a Liot-filter was placed inside the the regenerative amplifier operating in quasi-cw mode. In fact, the data gathered (see Fig. 4)

$$\ln G = \sigma_g \, N_{dop} \, L \tag{1}$$

represent the effective gain cross section[30]

$$\sigma_g(\lambda) = \beta \cdot \sigma_e(\lambda) - (1 - \beta) \cdot \sigma_a(\lambda) \tag{2}$$

depending on the emission cross section σ_e, the absorption cross section σ_a and the saturation parameter $\beta = N/N_{dop}$, whereas L is the length of the gain medium, N the density of excited and N_{dop} the density of the doped Yb-ions.

In comparison to the broad-band gain media introduced Yb:YAG provides the highest gain at a given pump density, which supports a high extraction efficiency, but gain narrowing becomes an issue in the case of picosecond pulse amplification even at a spectral width of 10 nm of its emission cross section. Moreover, amplified spontaneous emission (ASE) and parasitic lasing[31] was observed at high pump intensities and a high doping level. Figure 5 illustrates the influence of the small signal gain on the pulse spectrum when using Yb:YAG as laser material. Therefore, the output pulse energy of the Yb:glass amplifier has been reduced to 10 μJ in order to avoid gain saturation during the experiment resulting in an output pulse energy of 20 mJ. A simple estimation of the output pulse bandwidth $\Delta\lambda_{out}$ depending on the small signal gain G, the gain spectrum, and the seed pulse bandwidth $\Delta\lambda_{in}$ is given by:[32]

$$\frac{1}{(\Delta\lambda_{out})^2} = \frac{\ln G_0}{(\Delta\lambda_g)^2} + \frac{1}{(\Delta\lambda_{in})^2}. \tag{3}$$

In this case, the effective gain bandwidth $\Delta\lambda_g$ determined by curve fitting is 5 nm. The pulse spectrum was narrowed to 1.9 nm at a total gain of 10^3 in an Yb:YAG multi-pass amplifier. This corresponds to a compressed

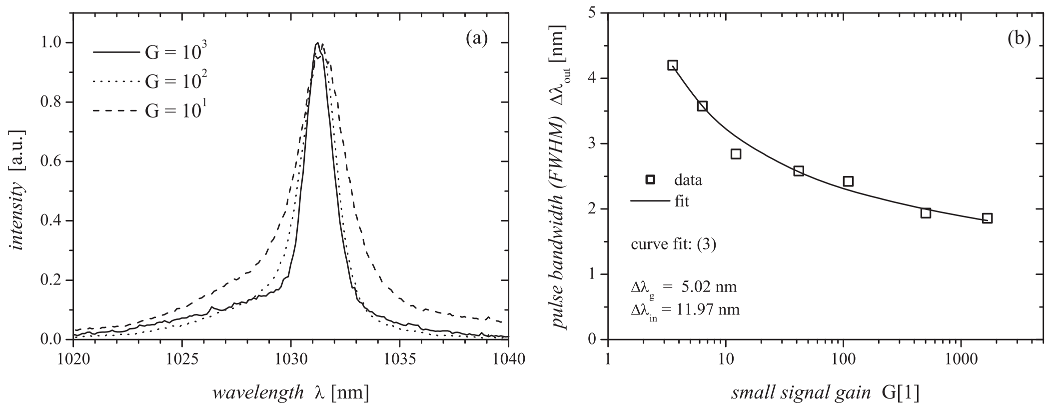

Figure 5. Influence of gain narrowing in Yb:YAG; (a) output pulse spectra at a small signal gain of 10, 10^2, and 10^3, (b) output bandwidth (FWHM) vs. small signal gain of the Yb:YAG multi-pass amplifier.

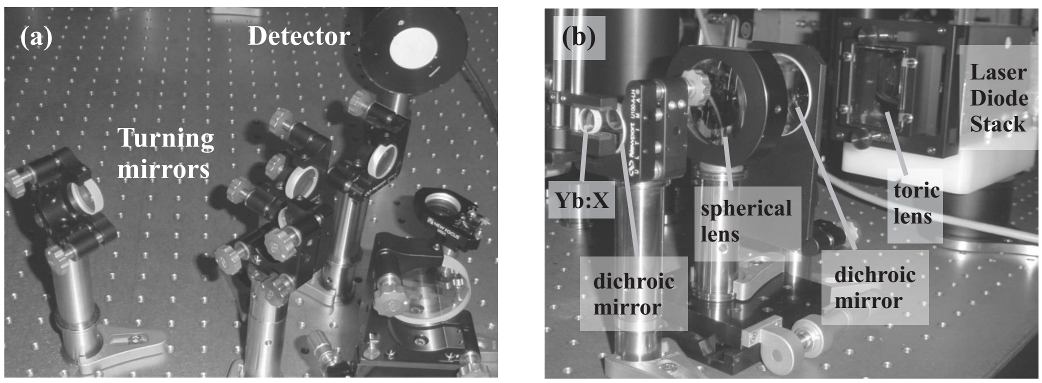

Figure 6. Experimental setup of the Yb-based diode-pumped multi-pass amplifier.

pulse duration of 0.85 ps and to an uncompressed pulse duration of 200 ps due to temporal pulse shortening.
In order to avoid laser induced damage due to temporal pulse shortening the amplifier performance up to gain saturation was tested with nanosecond pulses of the Q-switched seed laser. An output pulse energy of 220 mJ without optical damage at a pulse duration of 6 ns, an optical-to-optical efficiency of 9.4%, and a repetition rate of 10 Hz was achieved using a 6-pass Yb:YAG amplifier.[13] The experimental setup of the diode-pumped chirped-pulse multi-pass amplifier is shown in Fig. 6.

4. OUTLOOK AND CONCLUSION

In summary, we have comparatively investigated diode-pumped femtosecond chirped-pulse amplification (CPA) employing four different Yb-doped laser materials. Although the extraction efficiency of ytterbium-based nanosecond lasers is limited due to their quasi-three level scheme a significant progress towards efficient diode pumped nanosecond lasers generating pulses containing energies up to the 200 mJ-level was achieved.
Focussing on the spectral properties of the presented multi-pass amplifier the relationship between gain and pulse spectrum using different Yb-doped laser materials was analyzed. Both tunable microsecond and chirped pulse multi-pass amplification using Yb:YAG, Yb:CaF_2, Yb:KGW, and Yb-doped fluoride phosphate was investigated. The experiments described allow an accurate estimation of the short-pulse amplification properties of a certain gain medium without the influence of a resonator compared to an intra-cavity tunable laser. In this case, Yb:YAG provides the highest gain at a given pump fluence on the expense of the pulse bandwidth. However, using broad-band laser materials such as Yb:KGW or Yb:CaF_2 comparable gain and extraction efficiency can be achieved by increasing the number of amplifier passes.
Future work is now in progress to boost the output pulse energy and to re-compress the pulses. In the case of

Yb:YAG it becomes necessary to reduce the seed pulse bandwidth to 3–4 nm in order to avoid temporal pulse shorting at chirped pulse amplification. In conclusion, we believe that the data and experience gathered will allow a further scaling of the pulse energy in order to increase the peak power capability of the diode pumped lasers.

ACKNOWLEDGMENTS

We would like to thank M. Hellwing, F. Kronhamn (Institute of Optics and Quantum Electronics Jena, Germany), M. Rabe, R. Bertram (Institute for crystal growth Berlin, Germany), and T. Bergmann (BME KG, Murnau, Germany) for their technical contribution. Furthermore, we thank R. Uecker (Institute for crystal growth Berlin, Germany), L. Su (Shanghai Institute of Optics and Fine Mechanics), R. Moncorgé (CEA-CNRS-ENSICAEN, Université de Caen, France), D. Ehrt (Otto-Schott-Institute Jena, Germany), and D. Wulff-Molder (Korth Kristalle GmbH, Germany) for laser material supply. The authors acknowledge the funding of this work by the German Max-Planck-Society and the German Federal Ministry of Education and Research (BMBF).

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