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High repetition rate, µJ-level, CPA-free ultrashort pulse multipass amplifier based on Ho:YLF

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Abstract: We report on CPA-free multipass amplification of ps-pulses in Holmium-doped yttrium lithium fluoride (Ho:YLF) crystals up to µJ pulse-energy-covering repetition rates from 10 kHz up to 500 kHz. The seed pulses at a wavelength of 2.05 µm are provided by a Ho-based all-fiber system consisting of a soliton oscillator and a subsequent pre-amplifier followed by a free-space AOM as pulse-picker. Considering the achieved pulse peak power at MW-level, this system is a powerful tool for efficient pumping of parametric conversion stages addressing the highly demanded mid-IR spectral region.

OCIS codes: (140.7090) Ultrafast lasers; (140.3580) Lasers, solid-state; (140.3280) Laser amplifiers; (140.3070) Infrared and far-infrared lasers.

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1. Introduction

Within the last decade, there has been increased research in the field of ultrafast high-energy lasers operating in the 2 µm wavelength range as efficient pump sources for the generation of mid-infrared (mid-IR) radiation in optical parametric conversion stages [1, 2]. Additionally, they exploit a broad field of direct applications in medicine, communication, metrology, and micromachining of polymers [3]. Laser amplifiers based on Holmium-doped YLF crystals have proven to be efficient candidates due to their comparably high gain, low quantum defect, broad spectral bandwidth to support ultrashort pulse amplification [3], and a low negative coefficient of thermal expansion [4]. With respect to the widely used Ho-doped $Y_3Al_5O_{12}$ (YAG), Ho:YLF has a lower nonlinear refractive index and a longer upper laser level lifetime [4]. Common amplification schemes in Ho:YLF rely on chirped pulse amplification (CPA) in regenerative amplifiers (RA) [5, 6] or cryogenically cooled high-power linear amplifiers [2, 7]. These systems generate multi-mJ pulse energies, but at the expense of a low repetition rate in the range of 1 kHz and a complex, table-top size setup. Furthermore, temporal recompression after amplification requires highly efficient compression stages that are usually based on diffraction gratings or chirped volume Bragg gratings. In addition to losses that are ranging from few [2, 6, 8, 9] up to tens of percent [2, 10–12], these compression stages can be bulky and expensive. There are only few Holmium-doped crystal amplifier systems operating in the pulse repetition regime above 1 kHz published so far. In 2013, Dergachev presented amplification of ps-pulses at 10 kHz in a RA with subsequent single-pass amplifier based on longitudinally pumped Ho(0.5 at.%):YLF crystals [4]. The pulse duration of about 300 ps in combination with a pulse energy of 1.16 mJ corresponds to a pulse peak power of 3.6 MW. In 2015, Grafenstein et al. achieved about 70 dB gain in a Ho:YLF RA with a pulse energy of up to 1.1 mJ at 10 kHz [13]. Recompression of the RA output pulses has not been studied, thus, the stretched pulse duration remains at 50 ps corresponding to a pulse peak power of 20.7 MW. However, ultrashort pulse duration of less than 10 ps is beneficial for the mentioned applications. An alternative approach for the generation of ultrashort pulses with high energies is a CPA-free multipass amplification working at room temperatures. In order to scale the pulse energy from fiber-based seed sources at nJ-level to the µJ-level, multiple passes through the gain medium, long crystals, high doping concentrations, small beam diameter, or a combination of these parameters will be required for proper amplification.

Here, we present a CPA-free multipass amplification of ultrashort 5 ps pulses in Ho:YLF crystals up to µJ pulse energy covering repetition rates ranging from 10 kHz up to 500 kHz. To the best of our knowledge, this is the first ultrashort pulse amplifier based on Ho-doped crystals at 2 µm exceeding 100 kHz pulse repetition rate and maintaining MW-level pulse peak power. This MW-level amplifier system can be used as front-end for subsequent booster stages or to generate mid-IR radiation in ZGP-based tandem configurations of OPG and OPA. Additionally, this turn-key laser system benefits from very small footprint and its simplicity compared to complex table-top size CPA RA configurations or cryogenically cooled high-power linear amplifiers in the 2 µm spectral region.

2. Experimental setup

The setup of the laser system is shown in Fig. 1 and consists of three main parts: an all-fiber seed source based on Ho-doped fiber, a free-space acousto-optic modulator (AOM, AA Opto-Electronic, MT80-A0.4-2000) for pulse-picking, and a multipass amplification stage based on a Ho:YLF crystal. The seed source provides ultrashort pulses with a duration of 5 ps and a pulse energy of 21 nJ at 24 MHz repetition rate. It is comparable to the one described in [14] and exhibits a spectral bandwidth of 1.7 nm at a central wavelength of 2051 nm. A set of two quarter-wave and one half-wave plate adapts the output polarization state in order to achieve highest diffraction efficiency in the consecutive AOM pulse-picker. By focussing the laser beam into the AOM crystal to a spot diameter of about 200 µm, a proper rise and fall time similar to the pulse-to-pulse temporal distance of 42 ns has been achieved. The resulting efficiency in the first diffraction order is about 50 % corresponding to an injected pulse energy into the amplifier stage of 10 nJ. An optical isolator (Thorlabs, IO-4-2050-HP) with about 90 % transmission at 2050 nm separates the amplified output pulses of the amplifier and the seed pulses.

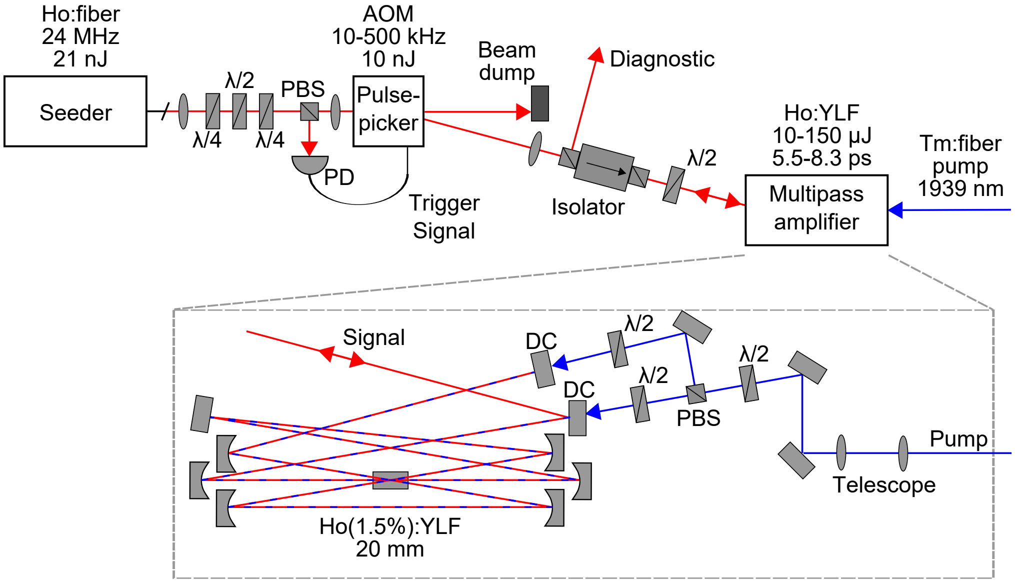

Fig. 1. Schematic setup of the amplifier. PD: photo diode, PBS: polarization beam splitter, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, DC: dichroic mirror.

The multipass amplification stage consists of a 20 mm long Ho:YLF crystal with rather high 1.5 at.% Ho^{3+} doping concentration. It is wrapped in Indium foil and mounted on a TEC cooled copper mount which is set to a temperature of 280 K. Both end facets with an aperture of 5x5 mm^2 provide anti reflection coatings for the signal and pump wavelength at 2050 nm and 1940 nm, respectively. The amplification stage is working in ambient air.

Signal and pump radiation are combined via dichroic mirrors and folded three times through the gain medium. Spherical mirrors, which exhibit high reflection for both the signal and the pump wavelength, focus the beam to a diameter of 250 µm at each pass inside the gain medium. The signal beam is intrinsically back reflected such that an overall number of 6 passes contribute to the amplification process. In order to mitigate an inhomogeneous distribution of the inversion level due to strong pump absorption in the highly doped Ho:YLF crystal, the amplifier is dual end-pumped.

An in-house built polarization maintaining Tm:fiber laser amplifier provides up to 17.7 W continuous pump power centered at a wavelength of 1939 nm. Pump and signal polarization can be tuned by means of half-wave plates in order to hit the c-axis of the Ho:YLF uniaxial crystal for highest amplification efficiency. A telescope is used for mode-matching of the pump and signal beam. This lab-based setup including seeder and pump source is able to fit a 60 cm by 90 cm breadboard, which results in a rather compact package.

3. Experimental results

The output power of the amplifier stage was measured at different pump powers with a seed pulse energy of 9 nJ behind the optical isolator and a pulse duration of 5 ps. The results are shown in Fig. 2(a) for pulse repetition rates between 10 kHz and 500 kHz. The pump splitting ratio for the dual end-pumping is set to about 90 % launched into the first folded path through the gain medium, whereas 10 % of the pump power is fed in through the last folded beam path in the Ho:YLF crystal. We have to mention that for repetition rates of less than about 40 kHz unstable self-lasing of the amplifier stage limited the available pulse energies. The aforementioned splitting ratio has been chosen such that the self-lasing threshold highest for low repetition rates and, at the same time, it is optimized for the largest optical-to-optical efficiency at higher pulse repetition rates. On the other hand, at pulse repetition rates of more than 40 kHz the achievable pulse energies are pump power limited. In Fig. 2(b) the corresponding pulse energies are depicted. We achieved pulse energies of 145 µJ at 10 kHz and 11.2 µJ at 500 kHz. Due to the dual end-pumping scheme it was not possible to measure the unabsorbed pump power. However, since the doping concentration is as high as 1.5 at.% and the propagation length is 60 mm considering the threefold beam pass through the gain medium, we estimate the absorption to be close to 90 %. This has been calculated based on a numerical simulation similar to the one described in [15].

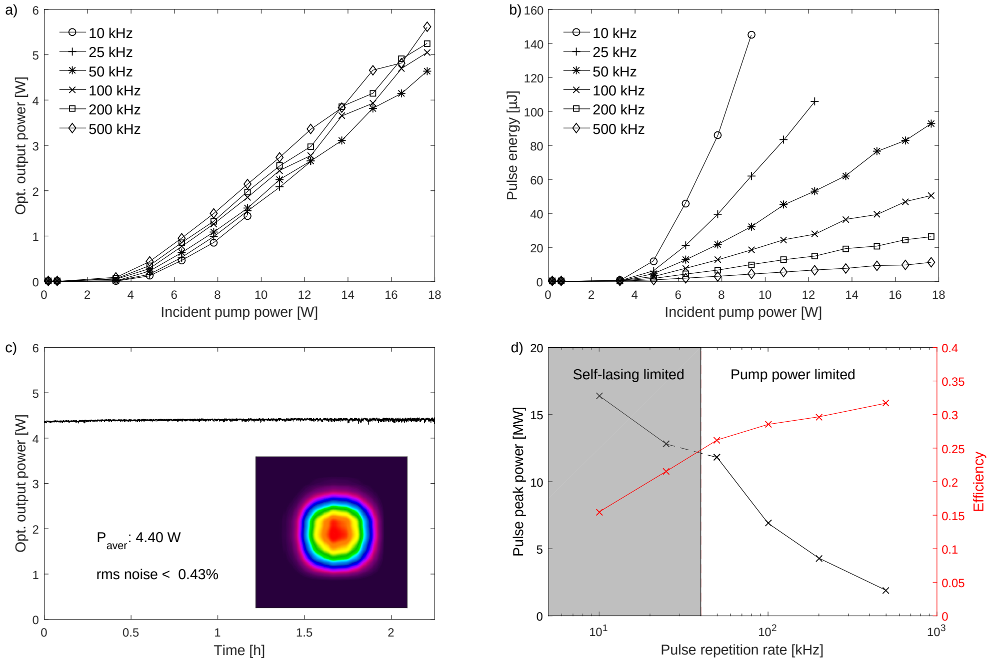

Fig. 2. Experimental results showing (a) average optical output power with increasing pump power for different pulse repetition rates, (b) the corresponding pulse energies, (c) a long-term power measurement for 44 µJ at 100 kHz (inset: far-field beam profile for 5.2 W at 200 kHz measured with an Ophir NanoScan beam profiler) and (d) the pulse peak power for the different repetition rates (black) as well as the optical-to-optical efficiency (red).

The MW-level pulse peak power is maintained up to the highest pulse repetition rate. The maximum achieved peak power is 16.4 MW at 10 kHz, as can be seen in Fig. 2(d). However, 1.9 MW peak power for a 500 kHz pulse train is suitable for efficient nonlinear parametric conversion as well. We believe that further power scaling is feasible, since no saturation effects occur regarding the average optical output power. Increasing the available pump power is straight forward and allows to benefit from the linear increase of the pulse energy.

The optical-to-optical efficiency of our laser amplifier is as high as 15.5 % in the case of the lowest pulse repetition rate of 10 kHz, but increasing towards 32 % at highest repetition rate of 500 kHz, as shown in Fig. 2(d). This is a remarkably high value compared to other publications on Ho:YLF ps-pulse amplifiers with efficiencies of about 20 % [6] or less [2, 4, 12]. Even a higher efficiency seems to be possible by cooling the Ho:YLF to a temperature far below room temperature or by scaling the focal beam size of the amplifier for each individual repetition rate. However, one has to be careful with the extreme peak intensities in the focal area inside the Ho:YLF which potentially damage the material. Wienke et al. mentioned damage of the bulk Ho:YAG material for pulse energies of more than 700 μJ at a stretched pulse duration of 90 ps considering a beam diameter of 320 μm in the focus of the last pass through the gain medium, which corresponds to 9.1 GW/cm^2 pulse peak intensity [11]. Here, 145 μJ pulse energy at ultrashort pulse duration of 8.3 ps already results in 33.5 GW/cm^2 considering a spot diameter of 250 μm. This potential limitation can be overcome by using a dual stage amplifier with increasing beam size.

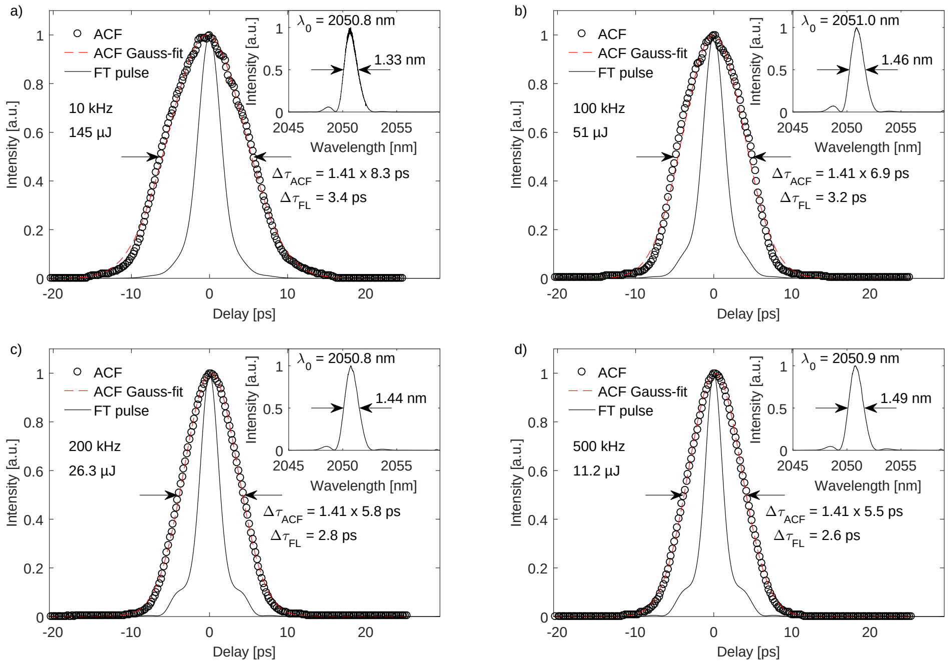

Fig. 3. Autocorrelation traces for different pulse repetition rates at maximum achieved pulse energy and Fourier-limited pulses based on the corresponding optical spectrum, respectively. Inset: Optical spectrum measured with an optical spectrum analyzer (YOKOGAWA AQ6375) at a resolution of 0.05 nm.

In order to investigate the stability of our laser system, we measured the output power at an average output power of 4.4 W and a repetition rate of 100 kHz corresponding to a pulse energy of 44 μJ. The results are shown in Fig. 2(c) and the root mean square noise amounts to less than 0.5 % within a period of more than two hours confirming a stable output. This result proves, additionally, a good pointing stability, since a spatial instability would significantly affect the signal to pump beam overlap. Furthermore, this turn-key laser system has been running in our laboratory environment with a daily power-up routine without any need of alignment within several weeks. A far-field beam profile at an average output power of more than 5.2 W and a repetition rate of 200 kHz is depicted in the inset of Fig. 2(c). Due to the low quantum defect and the aforementioned beneficial thermo-mechanical properties of Ho:YLF, we did not observe any thermal lensing in the Ho:YLF when increasing the amount of incident pump power.

The autocorrelation traces in Fig. 3 show some amount of temporal broadening from 5.5 ps at 500 kHz (assuming a Gaussian-shaped pulse) up to 8.3 ps at 10 kHz in each case at maximum pulse energy. We attribute this effect to the higher pulse energies generated at lower repetition rates and, therefore, higher gain that results in stronger gain narrowing. The latter is confirmed by a Fourier analysis of each corresponding spectrum (insets of Fig. 3), which reveals a loss of more than 20 % of the spectral bandwidth compared to the injected spectral pulse full width at half maximum of 1.7 nm at 10 kHz repetition rate. It should be noted that there is a minor change in the pulse shape at the generation of higher pulse energies. Nevertheless, we believe that the autocorrelation traces at lower pulse repetition rates do not severely deviate from the actual pulse in the temporal domain. We did not observe any pre- or post-pulses within an autocorrelator temporal scan range of 150 ps. We calculated an upper limit of the accumulated B-integral for the last pass in our amplifier stage to less than 0.35 rad. The calculations are based on the highest pulse energies of 145 µJ, a propagation length of 20 mm, and a spot diameter of 250 µm in the Ho:YLF crystal. This proves that further CPA-free energy scaling is feasible.

4. Conclusion

In conclusion, we demonstrated amplification of ultrashort laser pulses in the 2 µm wavelength region up to the MW-level peak power in a wide range of repetition rates in a simplified and compact CPA-free multipass amplifier based on highly doped Ho:YLF. In particular, we achieved 145 µJ pulse energy at lowest repetition rate of 10 kHz corresponding to more than 42 dB gain or 11.2 µJ at the highest pulse repetition rate of 500 kHz maintaining ultrashort pulse durations of 8.3 ps and 5.5 ps, respectively. This stable and efficient laser system is a powerful tool for pumping of subsequent parametric conversion stages based on an OPG/OPA tandem configuration to address the highly demanded mid-IR spectral region.

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