A 250 W average power, 100 kHz repetition rate cryogenic Yb:YAG amplifier for OPCPA pumping

L. E. Zapata[1], F. Reichert[2], M. Hemmer[1], F. X. Kärtner[1,2,3]

[1]Center for Free-Electron Laser Science, Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany
[2]Department of Physics & The Hamburg Center for Ultrafast Imaging (CUI), Universität Hamburg, Hamburg, Germany
[3]Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, USA
*Corresponding author: michael.hemmer@cfel.de

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A cryogenically-cooled, bulk-Yb:YAG, 4-pass amplifier delivering up to 250 W average power at 100 kHz repetition rate is reported. The 2.5 mJ amplified optical pulses show a sub-20 ps duration before temporal compression and a spectrum supporting a transform-limited duration of 3.6 ps. The power instabilities were measured to be <0.5% rms over 30 min at full power and the spatial intensity profile showed a flat-top distribution and near diffraction-limited beam quality. This compact amplifier is an ideal source for pumping either near-IR or mid-IR optical parametric chirped pulse amplifiers (OPCPA).

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The amplification of few-cycle pulses to the few tens of microJoule level – with peak intensities in the 10^{14} W/cm^2 range – at repetition rates up to 100 kHz is relevant for numerous strong-field physics applications investigating small cross-section processes [1].

Over the past decade, optical parametric chirped pulse amplification (OPCPA) has proven to be a method of choice for the amplification of few-cycle optical pulses at simultaneously high average power and high repetition rate at wavelengths ranging from near-IR to mid-IR [2]–[4]. Several studies have shown that thermal effects in optical parametric amplifiers (OPA) become noticeable at several hundreds of Watts of pump power [5], [6] yet only little has been done so far to mitigate these effects [7] and power scaling is still currently limited by the availability of high average power pump lasers. As the OPCPA technique matured over the past ten years, Yb:YAG has simultaneously emerged as an excellent gain medium for the generation and amplification of picosecond pulses at simultaneously high energy and high repetition rate – i.e., high average power – making it an ideal gain medium for OPCPA pump lasers. Several methods have shown the most promising results in obtaining mJ-level pulses at the highest average powers including the slab-amplifier approach [8], the crystal fiber approach [9], the room temperature thin disk approach [10] or, the cryogenic approach, either in bulk gain media [11] or in composite thin-disk (CTD) geometries [12]. The cryogenic approach draws from the favorable scaling of both spectroscopic and thermo-mechanical properties of Yb:YAG at cryogenic temperature as discussed in detail in [13]. The room temperature thin-disk approach has enabled the generation of 2 mJ energy at 100 kHz repetition rate (200 W average power) in a regenerative amplifier configuration. However the higher gain that can be obtained at cryogenic temperatures makes further scaling possible in simpler architectures and impacts favorably on the cost and complexity of these systems.

In this Letter, we report on a compact and rugged 4-pass amplifier relying on cryogenically cooled bulk Yb:YAG delivering over 250 W average power at 100 kHz repetition rate. The amplified 2.5 mJ energy pulses exhibited a sub-20 ps stretched duration and a 3.6 ps transform-limited duration. The spatial intensity profile, pointing stability and power stability were all compliant with the tight requirements imposed by OPCPA pumping applications.

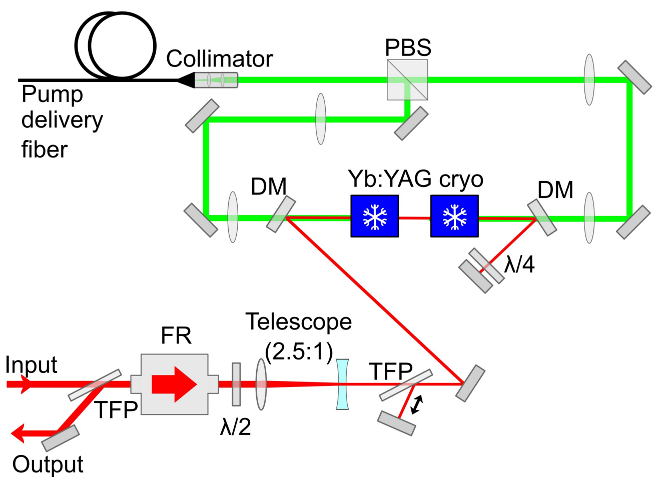

Fig. 1. Layout of the 4-pass, polarization switched amplifier featuring two cryogenically cooled Yb:YAG rods and a 2 kW continuous wave pump laser. The overall footprint of the system is ~0.7x1 m^2. TFP, thin-film polarizer; FR, Faraday rotator; DM, dichroic mirror; PBS, polarizing beam splitter.

The cryogenically cooled amplifier is seeded by a commercial front-end consisting of a modelocked oscillator, a folded transmission grating-based Martinez-type stretcher and a low energy regenerative amplifier (Amplitude Systèmes) operating at 100 kHz repetition rate. This system was tuned to ensure optimum spectral overlap between the seed pulses and the narrow gain bandwidth of the cryogenically cooled Yb:YAG amplifier. As a result, the seed pulses showed ~40 µJ energy in a spectral width as narrow as 0.65 nm FWHM centered at 1029.5 nm wavelength and exhibited a measured pulse duration of 27 ps. We evaluated the seed beam quality via focusing the seed beam with a 30 cm focal length lens and measured a beam diameter 1.05 times larger than the diffraction limit in the focus confirming the good beam quality of the seed. The pointing stability of the seed beam was also characterized and instabilities less than 40 µrad were measured. Upon exiting the regenerative amplifier, the seed pulses were directed toward the injection line of our 4-pass, polarization switched amplifier (Fig. 1). This injection line consists, in successive order, of a thin-film polarizer (TFP), an 8 mm aperture Faraday rotator – rated for operation up till 300 W – combined with a half-wave plate, a downsizing telescope with a 2.5:1 demagnification factor and a second TFP. The seed pulses were then passed four times via polarization switching through two 0.5 x 1.5 x 2.3 cm^3 1%-doped Yb:YAG crystals placed in series. Both crystals were attached to a common cold finger placed under vacuum and maintained at liquid nitrogen temperature (77 K). The pump power was provided by a 2 kW continuous-wave laser diode module emitting at ~940 nm wavelength coupled into a 600 µm core delivery fiber (NA = 0.2). At the exit of the fiber, the pump light was collimated using a lens doublet, split into two arms using a polarizing beam splitter and the tip of the fiber was relay imaged onto each Yb:YAG rod with ~1:3 magnification, yielding a 1.7 mm diameter flat-top pump profile in each rod (Fig. 1). The output power performance was characterized using a pyro-detector rated for 500 W average power, the temporal characteristics were gathered using a commercial intensity autocorrelator operated in non-collinear geometry, spatial characterization was performed using a commercial CCD detector with 4.4 µm pixel size and spectral information was collected using an optical spectrum analyzer with 50 pm resolution.

The single-pass small-signal gain of the amplifier was characterized using 50 nJ energy seed pulses with 0.8 nm FWHM spectral width. The pump laser was operated in pulsed mode at 0.3% duty cycle (3 ms pumping at 1 Hz repetition rate) to limit thermal loading. A small signal gain of 4700 was measured at 1 kW pump power resulting in up to 235 µJ output energy in a single-pass configuration and 1% of the saturation energy.

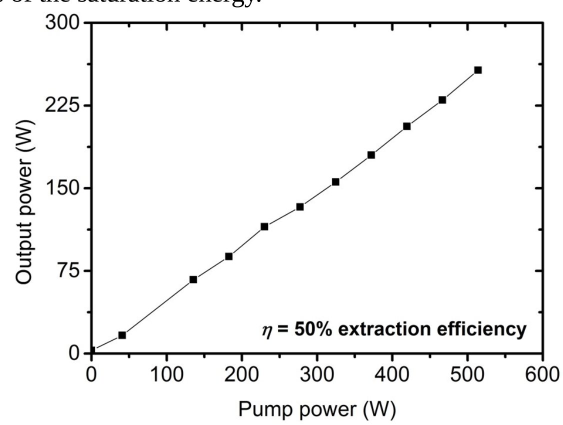

Fig. 2. Measured output power versus pump power characteristics at 100 kHz repetition rate with a seed power of 4 W (40 µJ). The extraction efficiency could be further improved by improving mode matching and providing additional seed power.

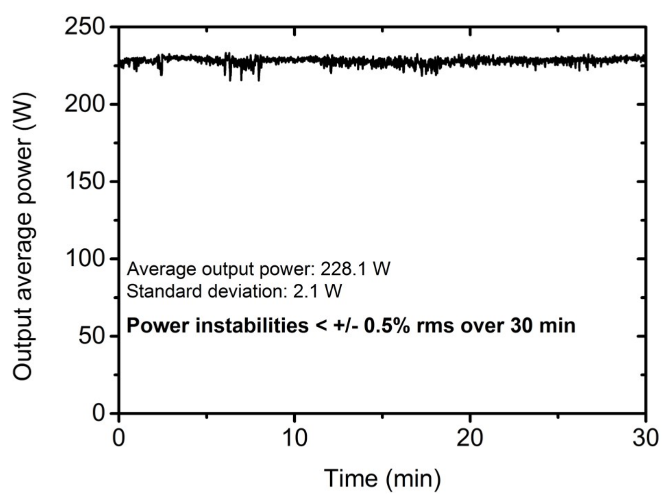

Fig. 3. Measured output power over 30 min at 230 W average output power (2.3 mJ energy). Power instabilities were computed to be < ±0.5% rms over 30 min. The measurement was performed at a sampling rate of 1 Hz.

Amplification with the full 4 W seed at 100 kHz repetition rate in 4-pass configuration resulted in up to 257

W average output power at ~515 W continuous wave pump power, yielding an extraction efficiency of ~50% (Fig. 2). Owing to the relatively efficient energy extraction, the temperature increase of the crystal was measured to be less than 20 K. The extraction efficiency could nonetheless be further improved to approach the theoretical limit of 90% by e.g. increasing the seed power and ensuring close mode-matching between pump and seed over the four passes. Despite the linear increase of output power with pump power, we limited the pump power to 515 W as we started to observe the onset of spatial profile distortions at the amplifier output. These distortions may be attributed to the heating up of the BK7 lenses composing the pump relay telescopes, which show residual absorption at 940 nm. The power stability was recorded over 30 minutes at 230 W and showed instabilities less than ±0.5% rms over 30 minutes (Fig. 3), a value compatible with OPCPA pumping applications.

The output of the amplifier was spatially characterized in both near and far-field to assess the suitability of this amplifier as an OPCPA pump. As a near-field measurement we chose to image the exit face of the Faraday rotator while the far-field spatial intensity profile was recorded at the focus of a 30 cm focal length lens. The near-field intensity profile shows a super-Gaussian distribution, confirming that the amplifier is operated in saturation. The amplified near-field spatial profile remains unchanged over tens of minutes after a few seconds of initial warm-up. The beam quality was evaluated by investigating the far-field behavior of the amplified beam: we find that the amplified beam focuses close to the diffraction-limit size and observe no difference between the far-field intensity profile of the seed and that of the amplified beam (Fig. 4). The pointing stability of the amplified beam was also investigated and showed fluctuations < 60 and 35 µrad in the horizontal and vertical direction respectively.

We finally investigated the spectro-temporal behavior of the amplifier. The spectral width of the seed was measured to be 0.65 nm FWHM and its pulse duration was measured to be 27 ps – assuming a Gaussian profile (Fig. 5). Owing to the close matching of the seed spectral width with the emission linewidth of cryogenically cooled Yb:YAG (~1 nm FWHM), we observe limited spectral narrowing and consequently little temporal narrowing upon amplification.

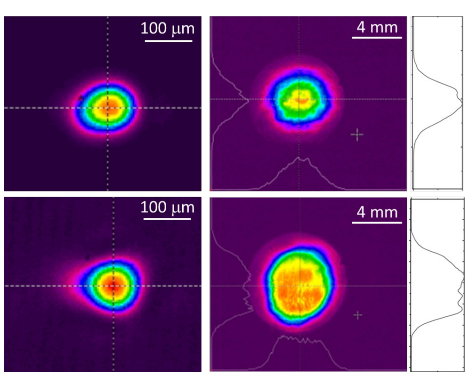

Fig. 4. Measured typical seed spatial intensity profile in the far-field (upper left) and near-field (upper right) and amplified far-field profile (lower left) and near-field profile (bottom right). The 1D-lineouts show typical cross-section of the near-field profiles. The near-field spatial profile was obtained by imaging the end-facet of the Faraday rotator. The far-field was obtained at the focus of a 30 cm focal length lens.

The amplified spectrum showed a spectral width of 0.55 nm FWHM at 230 W output power and the corresponding pulse duration was measured to be 19.4 ps – assuming a Gaussian temporal profile. Notice that seeding a wider spectrum still resulted in an amplified spectral width of 0.55 nm FWHM, resulting in sub-optimum seeding of the amplifier. The peak power on the end facet of the last crystal in the final pass is assessed to be ~5 GW/cm^2. The B-integral accumulated through the amplifier was computed to be ~1.2. This relatively low value of B-integral is experimentally corroborated by the absence of beam distortions, the cleanliness of the autocorrelation trace of the amplified pulses and the lack of evidence of self-phase modulation on the output spectrum. The output pulses show a transform-limit of 3.6 ps yet no attempt has been made at compression. Notice that the small chirp rate we employed could readily be increased, therefore reducing the – already low – B-integral and assuring compression to the transform-limit.

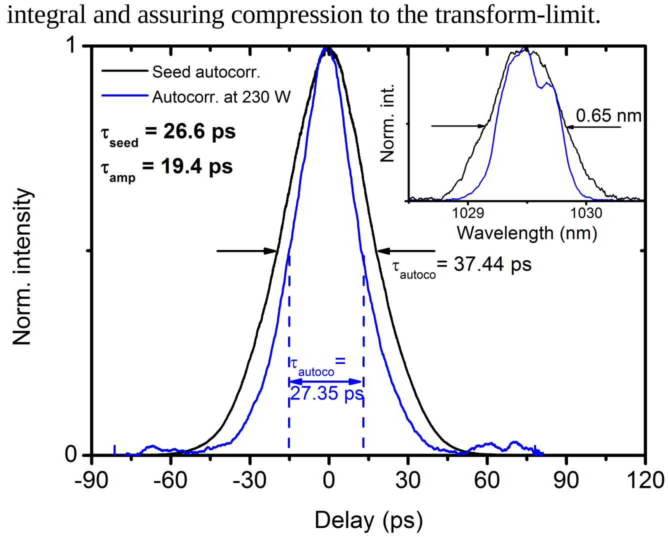

Fig. 5. Measured intensity autocorrelation of the seed (black line) and amplified (blue line) pulses. Upon decorrelation assuming Gaussian temporal intensity profile, the measured seed pulse was computed to be ~27 ps and the amplified pulse duration to be ~19 ps. Inset: seed (black line) and amplified (blue line) spectra.

In conclusion, we have demonstrated a compact and rugged 4-pass amplifier relying on cryogenic Yb:YAG technology. The amplifier readily provides up to 250 W output power at 100 kHz repetition rate in a super-Gaussian spatial intensity profile. The 2.5 mJ amplified pulses show a 0.55 nm FWHM spectral width and a sub-20 ps stretched pulse duration. The high-gain 4-pass geometry limits the accumulated B-integral throughout the amplification making future temporal compression to the transform-limited duration of 3.6 ps achievable. The beam quality, pointing stability and power stability of this amplifier makes it an ideal source for pumping near-IR or mid-IR OPCPAs. Further power scaling could be achieved by better mode-matching while modestly increasing the seed energy – which would yield a higher extraction efficiency –, further, replacing the BK7 pump telescope lenses for Infrasil lenses would limit thermal distortions of the pump optics and scaling the aperture of the Faraday rotator would enable higher average power handling.

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