EPJ Web of Conferences **307**, 04047 (2024) https://doi.org/10.1051/epjconf/202430704047
*EUROPHOTON 2024*

# Generation of 22-mJ, 2.0-ps Pulses from a 1-kHz Ho:YLF Regenerative Chirped Pulse Amplifier

**Martin Bock, Lorenz von Grafenstein, Mark Mero, Tamas Nagy, and Uwe Griebner***
*Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, 12489 Berlin, Germany*
**griebner@mbi-berlin.de*

**Abstract:** We report a CW-pumped Ho:YLF regenerative amplifier (RA) delivering pulses with 22.5-mJ energy and 2.0-ps duration at 1 kHz. The RA emitting at 2051 nm is broadband-seeded and implemented in a chirped pulse amplification system. © 2024 The Author(s)

## 1. Introduction

Intense ultrashort pulses around 2 µm wavelength have experienced great attention triggered by a number of applications in this field, such as generating high-harmonics, XUV frequency combs, or hard X-rays [1]. Direct amplification of ultrashort pulses, usually based on Chirped Pulse Amplification (CPA) is typically based on the optical transition of Cr-, Tm- or Ho-ions in the 2-µm spectral range. Compared to Cr- and Tm-doping, the bandwidth of Ho-doped gain media is typically narrower but they feature a longer upper-state lifetime connected with a high stimulated emission cross-section and a smaller quantum defect for resonant pumping [2]. Among the many singly Ho-doped host media, YAG and YLF are the most widespread and have proven their suitability for obtaining high-repetition rate, high-energy pulses whereby few-ps pulse energies >10 mJ have been achieved exclusively for 2-µm systems containing Ho:YLF [3,4]. For the amplification of high-energy ultrashort pulses, Ho:YLF is advantageous compared to Ho:YAG because of its lower nonlinear refractive index (~5 times) and its negative dn/dT coefficient [2]. Scaling of the few-picosecond pulse energy of kHz driver systems at 2-µm for strong-field physics application is desirable. Here we focus on the regenerative amplifier (RA), which is the core component of multi-10 mJ class Ho:YLF CPA systems [3,4]. Millijoule RAs around 2-µm wavelength with kilohertz repetition rate have been reported for Ho:YAG, Ho:YLF and Cr:ZnSe [5-7]. The highest pulse energy of 13 mJ was demonstrated for a 1 kHz Ho:YLF RA with 2.4-ps pulse duration [6].

Materials with long fluorescence lifetime are ideal for RAs, as they support the accumulation of population inversion when pumped in the continuous-wave (CW) regime. However, such RAs demonstrate unusual pulse amplification dynamics when the gain relaxation time is in the range or longer than the inverse repetition rate and the accumulated pulse energy is sufficient to cause substantial depletion of the inverted medium [8]. Understanding these bifurcation phenomena is a prerequisite for the design of high-performance ultrashort pulse RAs operating at repetition rates in the vicinity of the inverse fluorescence lifetime of the gain medium [9].

Here we report on pulse energy scaling of ps Ho:YLF regenerative amplifiers above 15 mJ operating at few-kHz repetition rates which is based on careful analysis of the bifurcation dynamics.

## 2. Experimental setup and results

A broadband 2-µm source based on an optical parametric amplifier operating at 25 kHz is implemented as seed. It provides 4-µJ pulse energy within the Ho:YLF amplification band. After passing a chirped-volume Bragg grating, pulses with 1-ns duration are injected into the RA. The RA is constructed as a ring cavity, similarly to our proven design [4,6] which features high stability against changes of the pump power and resulting alterations of the thermal lens. An antireflection-coated, 0.5% Ho-doped YLF rod is used as gain medium. It is end-pumped by an unpolarized 100-W CW Tm:fiber laser and water cooled to 7°C. The required Pockels cell (RTP) operates in the $\lambda/2$ regime and is combined with a $\lambda/2$ plate to realize, in addition to setting the number of round-trips, pulse picking for the aimed repetition rate of a few kHz

The key parameters governing the amplification dynamics are the repetition rate, pump power, number of pumped ions, seed energy and number of round trips. If the repetition rate is given, in our case a few kHz, a viable path to reduce bifurcation dynamics in the RA is to decrease the total gain by increasing the seed energy. All calculations are conducted with the simulation model in [9]. Simulated bifurcation diagrams for 1 and 2 kHz RA repetition rates are presented in Fig. 1a. The impact of the round-trip number in our RA for a fixed seed pulse energy has been analyzed in detail in [9]. For the available 100-W pump power our, simulations predict pulse energies in the saturated regime after only 13 round-trips in the RA of 23 mJ and 15 mJ for the 1-kHz and 2-kHz repetition rate, respectively.

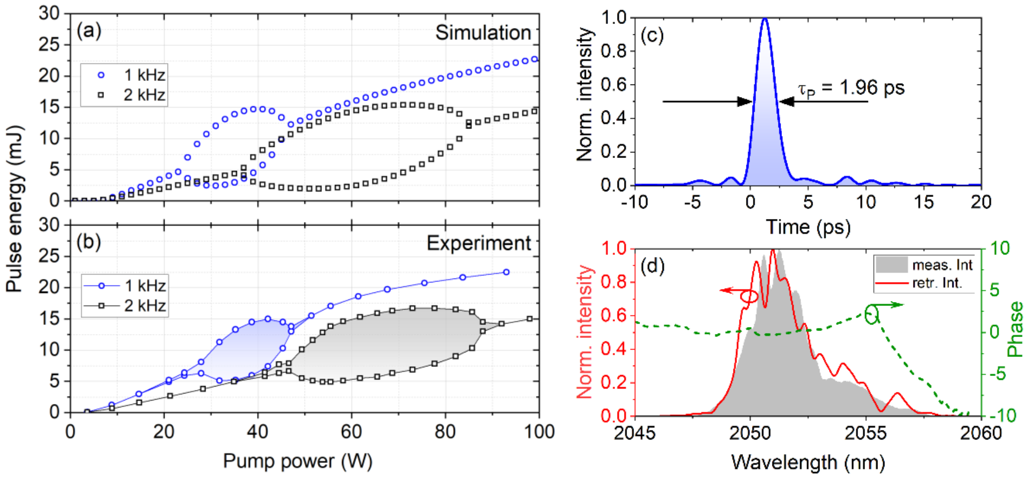


**Fig. 1** Ho:YLF regenerative amplifier performance. Simulated (a) and measured (b) bifurcation diagrams as a function of the incident pump power for 1 and 2 kHz repetition rate. SH-FROG characterization of the re-compressed pulses (1 kHz), (c) retrieved pulse shape, (d) measured (gray) and retrieved (red) spectra together with the retrieved spectral phase (green).

The validity of our simulations is impressively confirmed by the experimental implementation of the RA. We examine the bifurcation diagram of the RA at 1-kHz and 2-kHz repetition rate as shown in Fig. 1b. The emitted pulse energy amounts to 22.5 and 15 mJ for the 1 and 2 kHz RA, respectively, and reveals an excellent long-term pulse stability of <0.11% rms. The beam quality is analyzed at low and maximum pulse energy of 3.4 mJ and 22.5 mJ, respectively. It exhibits $TEM_{00}$ features with $M^2$ <1.1. Due to the high seed energy of 4 µJ, the maximum pulse energy is reached after just 13 round-trips in the RA. Compared to the RA described in [6], this reduces the gain narrowing. The RA spectrum centered at 2051 nm has a bandwidth of 6.9 nm at $1/e^2$-level (Fig. 1d) and the pulse duration amounts to 320 ps. The RA pulses are sent to a Treacy-type compressor consisting of two dielectrically-coated gratings. The latter de-chirp the amplified pulses connected with a very low loss of ~1%. The compressed pulses are characterized by second harmonic frequency resolved optical gating (SH-FROG). The results are presented in Fig. 1c,d, exhibiting pulses with a duration of 1.96 ps (FWHM) which is close to the Fourier-transform limit of 1.8 ps.

## 3. Conclusion

To conclude, we have demonstrated high-energy few-ps 2.05-µm RAs operating at 1-kHz and 2-kHz repetition rate. Pulse energies as high as 22.5 mJ and 15 mJ were generated at 1 kHz and 2 kHz, respectively. The highest peak and average power for any 2-µm few-ps RAs are achieved with 10 GW and 30 W, respectively.

## 4. References

[1] K.-H. Hong, C.-J. Lai, J. P. Siqueira, P. Krogen, J. Moses, C.-L. Chang, G. J. Stein, L. E. Zapata, and F. X. Kärtner, "Multi-mj, kHz, 2.1 µm optical parametric chirped-pulse amplifier and high-flux soft x-ray high-harmonic generation," Opt. Lett. **39**, 3145 (2014).

[2] M. Schellhorn, "A comparison of resonantly pumped Ho:YLF and Ho:LLF lasers in CW and Q-switched operation under identical pump conditions," Appl. Phys. B **103**, 777 (2011).

[3] U. Elu, T. Steinle, D. Sánchez, L. Maidment, K. Zawilski, P. Schunemann, U. D. Zeitner, C. Simon-Boisson, and J. Biegert, "Table-top high-energy 7 µm OPCPA and 260 mJ Ho:YLF pump laser," Opt. Lett. **44**, 3194 (2019).

[4] L. von Grafenstein, M. Bock, D. Ueberschaer, A. Koc, U. Griebner, and T. Elsaesser, "2.05 µm chirped pulse amplification system at a 1 kHz repetition rate - 2.4 ps pulses with 17 GW peak power," Opt. Lett. **45**, 3836 (2020).

[5] P. Malevich, G. Andriukaitis, T. Flöry, A. J. Verhoef, A. Fernandez, S. Ališauskas, A. Pugžlys, A. Baltuška, L. H. Tan, C. F. Chua, and P. B. Phua, "High energy and average power femtosecond laser for driving mid-infrared optical parametric amplifiers," Opt. Lett. **38**, 2746 (2013).

[6] P. Fuertjes, L. von Grafenstein, D. Ueberschaer, C. Mei, U. Griebner, and T. Elsaesser, "Compact OPCPA system seeded by a Cr:ZnS laser for generating tunable femtosecond pulses in the MWIR," Opt. Lett. **46**, 1704 (2021).

[7] S. Vasilyev, J. Peppers, I. Moskalev, V. Smolski, M. Mirov, E. Slobodchikov, A. Dergachev, S. Mirov, and V. Gapontsev, "1.5-mJ Cr:ZnSe Chirped Pulse Amplifier Seeded by a Kerr-Lens Mode-Locked Cr:ZnS oscillator," *Laser Congress 2019 (ASSL, LAC, LS&C), OSA Technical Digest* (Optical Society of America, 2019), paper ATu4A.4.

[8] M. Grishin, V. Gulbinas, and A. Michailovas, "Dynamics of high repetition rate regenerative amplifiers," Opt. Express **15**, 9434 (2007).

[9] L. von Grafenstein, M. Bock, and U. Griebner, "Bifurcation analysis in high repetition rate regenerative amplifiers," IEEE J. Sel. Topics Quantum Electron., **24**, 3000213 (2018).