Addressing Spectral Narrowing in Cryogenic Yb:YAG: a 10 mJ Cryogenic Yb:YLF Regenerative Amplifier

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Abstract: We report a Yb:YLF based 10 mJ-class cryogenically-cooled regenerative amplifier with 2.1 nm FWHM spectral bandwidth. This system demonstrates the feasibility of high energy, sub-ps cryogenic lasers as an alternative to room temperature Yb:YAG.
OCIS codes: (140.3280) Laser amplifiers; (140.3538) Lasers, pulsed; (140.3480) Lasers, diode-pumped.

1. Introduction

The generation of high-energy pulses at high average power with sub-ps duration at 1-µm wavelength from diode pumped solid-state lasers is a critical area of laser development as it affects numerous applications. Indeed, lasers featuring such parameters find applications in fields as diverse as X-ray generation, material processing, nonlinear optical devices such as optical parametric chirped pulse amplifiers (OPCPAs) pumping and THz radiation generation and amplification. A number of architectures have been investigated toward the generation of simultaneous high average power and high energy, sub-ps duration optical pulses – mostly based on Yb:YAG gain medium – including room temperature thin-disk lasers [1] or room temperature crystal fiber [2]. Rod-type [3], slab [4] or composite thin-disk geometries [5] have also been investigated at cryogenic temperature and have resulted in the generation of kW average power at Joule level optical pulses [6]. The use of Yb:YAG at cryogenic temperature alleviates a number of shortcomings of the room temperature operation yet suffers from reduced emission bandwidth and therefore struggles to deliver sub-ps duration pulses.

Here, we follow up on previous work [7] to investigate the potential of cryogenic Yb:YLF as an alternative to Yb:YAG to deliver sub-ps duration pulses at high energy. We present a regenerative amplifier delivering up to 11 mJ energy with a spectral bandwidth supporting sub-750 fs duration optical pulses seeded by a homebuilt fiber frontend.

2. Experimental layout

The regenerative amplifier consists of a 4-mirror ring cavity arranged in bowtie geometry (Fig. 1). The seed pulses are provided by a home-built fiber laser frontend that delivers up to ~100 nJ energy pulses at 38 MHz repetition rate. The spectro-temporal properties of this frontend system were tailored to ideally seed a high energy amplifier chain: the pulses are temporally stretched to 1 ns duration and carry up to 2.4 nm of spectral bandwidth (FWHM) corresponding to a transform-limited duration of ~500 fs (for a $sech^2$ temporal profile). The gain medium employed in the regenerative amplifier is a 1.75 mm thick, 25%-doped Yb:YLF crystal with a 6x8 mm^2 clear aperture featuring two undoped caps. The crystallographic orientation of the gain medium is arranged to ensure amplification along the E//a axis. The crystal is mounted onto a copper heat sink attached to a liquid-nitrogen Dewar. The seed pulses are injected into and ejected from the regenerative amplifier cavity via a combination of a thin-film polarizer, a half-wave plate and a Pockels cell. The Pockels cell employed in our setup is operated in half-wave voltage and consists of a 1 cm diameter KD*P crystal. In this experiment, the high voltage switch of the Pockels cell limits the repetition rate of the amplifier system to 10 Hz. The pump power is provided by a fiber coupled diode bar array emitting at 960 nm wavelength and providing up to 280 W continuous wave average power. The unpolarized output of the delivery fiber is split into two equal arms via a polarizing beam splitter and relay imaged to a flat-top 1.5 mm diameter spot via a three-lens imaging telescope onto the gain medium. The spectral output of the amplifier was recorded using a 0.1 nm spectral resolution spectrum analyzer and the spatial properties measured using a CCD camera.

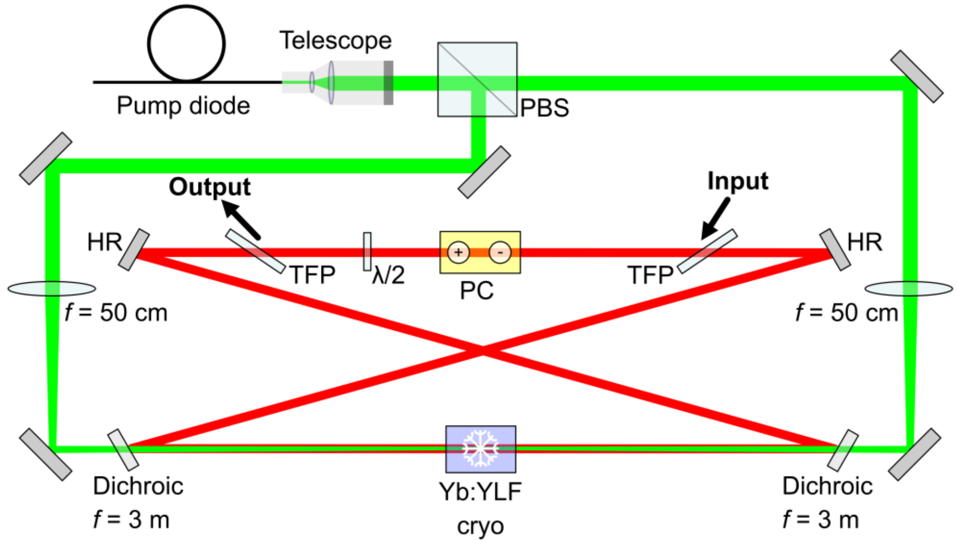

Fig. 1. Layout of the cryogenically-cooled Yb:YLF regenerative amplifier. HR: high reflectivity mirror, TFP: thin film polarizer, PC: Pockels cell, PBS: polarizing beam splitter.

3. Laser performances

The regenerative amplifier is operated in the unsaturated regime owing to the relatively low emission cross section of Yb:YLF (σ_σ = 1.2x10^{-20} cm² at 77 K [8]) – compared to σ_e = 10x10^{-20} cm² for Yb:YAG at 77 K – that place the saturation fluence above the damage fluence. An energy of 11 mJ is obtained at the output of the amplifier after 64 passes in the cavity for a seed energy of 3.5 nJ. The diode pump source was set to operate gated at 280 W with a gate duration of 2 ms. Increasing the seed energy to 21 nJ results in a reduction of the number of passes to yield the same 11 mJ output energy after 56 passes (Fig. 2 – left). We observe only limited spectral narrowing from 2.4 nm to 2.1 nm during the amplification process despite the net gain of ~10^6 (Fig. 2 – right), in good agreement with our numerical simulations. Notice that a comparable amplifier featuring a cryogenically cooled Yb:YAG gain medium showed a reduction of the seed spectrum down to 0.24 nm spectral width, supporting a ~6.5 ps duration (assuming a Gaussian temporal profile) [9]. The spatial profile of the amplified beam was recorded and shows a Gaussian distribution in the near field (Fig. 2 – left, inset).

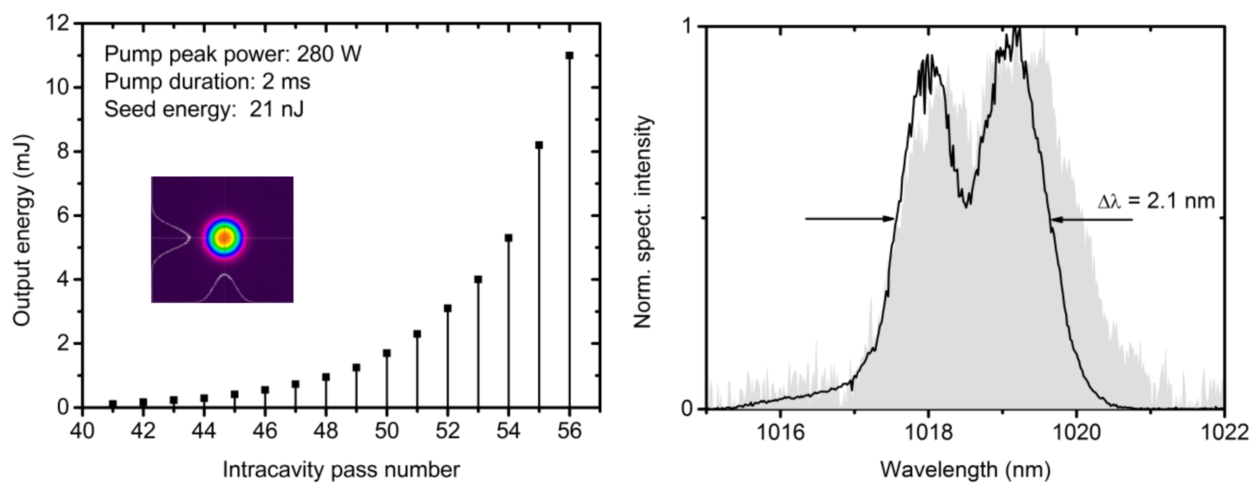

Fig. 2. (Left) Measured output energy versus number of passes in the regenerative amplifier cavity for a set pump peak power of 280 W and a set pump duration of 2 ms – inset: measured amplified output spatial profile in the near field; (right) measured output spectrum at 10 mJ energy (black line) and measured seed spectrum at the input of the regenerative amplifier (grey shadow).

4. Conclusion & future work

We demonstrated a cryogenically cooled, diode pumped regenerative amplifier delivering up to 11 mJ energy and maintaining a spectral width supporting sub-ps duration with excellent spatial profile. Future work includes

increasing the repetition rate to the 100 Hz regime, add a subsequent amplifier to boost the energy to the 100 mJ level and demonstrate temporal compression. This laser system is dedicated to drive nonlinear parametric devices.

5. References

[1] C. Teisset, M. Schultze, R. Bessing, M. Haefner, S. Prinz, D. Sutter, and T. Metzger, “300 W picosecond thin-disk regenrative amplifier at 10 kHz repetition rate,” in *Advanced Solid State Lasers (ASSL)*, 2013, p. paper JTh5A.1.

[2] X. Délen, Y. Zaouter, I. Martial, N. Aubry, J. Didierjean, C. Hönninger, E. Mottay, F. Balembois, and P. Georges, “Yb:YAG single crystal fiber power amplifier for femtosecond sources,” *Opt. Lett.*, vol. 38, no. 2, pp. 109–111, 2013.

[3] M. Hemmer, F. Reichert, K. Zapata, M. Smrz, A.-L. Calendron, H. Cankaya, K.-H. Hong, F. X. Kaertner, and L. E. Zapata, “Picosecond, 115 mJ energy, 200 Hz repetition rate cryogenic Yb:YAG bulk-amplifier,” in *Conference on Laser and Electro-Optics (CLEO)*, 2015, p. paper STu4O.3.

[4] S. Banerjee, K. Ertel, P. D. Mason, P. J. Phillips, M. De Vido, J. M. Smith, T. J. Butcher, C. Hernandez-Gomez, R. J. Greenhalgh, and J. L. Collier, “DiPOLE: a 10 J, 10 Hz cryogenic gas cooled multi-slab nanosecond Yb:YAG laser.,” *Opt. Express*, vol. 23, no. 15, pp. 19542–51, 2015.

[5] L. E. Zapata, H. Lin, A.-L. Calendron, H. Cankaya, M. Hemmer, F. Reichert, W. R. Huang, E. Granados, K.-H. Hong, and F. X. Kärtner, “Cryogenic Yb:YAG composite-thin-disk for high energy and average power amplifiers,” *Opt. Lett.*, vol. 40, no. 11, pp. 2610–2613, 2015.

[6] C. M. Baumgarten, B. A. Reagan, M. Pedicone, H. Bravo, L. Yin, H. Wang, M. Woolston, B. Carr, C. Menoni, and J. Rocca, “Demonstration of a Compact 500 Hz Repetition Rate Joule-Level Chirped Pulse Amplification Laser,” in *Conference on Laser and Electro-Optics*, 2016, p. paper STu3M.3.

[7] D. E. Miller, L. E. Zapata, D. J. Ripin, and Tso Yee Fan " Sub-picosecond pulses at 100 W average power from a Yb:YLF chirped-pulse amplification system," Optics Lett., vol. 37, no. 13, pp.2700-2702, 2012.

[8] T. Y. Fan, D. J. Rippin, R. L. Aggarwal, J. R. Ochoa, B. Chann, M. Tilleman, and J. Spitzberg, “Cryogenic Yb3+- doped Solid State Lasers,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 13, no. 3, 2007.

[9] K. Hong, J. Gopinath, D. Rand, A. M. Siddiqui, S. Huang, E. Li, B. J. Eggleton, J. D. Hybl, T. Y. Fan, and F. X. Kärtner, “High-energy, kHz-repetition-rate, ps cryogenic Yb:YAG chirped pulse amplifier,” *Opt. Lett.*, vol. 35, no. 11, pp. 1752–1754, 2010.