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Broadband regenerative amplifier based on Ho:CALGO at 2.1 µm

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Abstract
We present a broadband Ho:CALGO regenerative amplifier operating at 2.1 µm, delivering a pulse energy of 342 µJ at 1 kHz with a spectral bandwidth of 5 nm, supporting sub-ps pulse duration.

1. Introduction

High-energy ultrafast 2.1 µm lasers are attractive sources for material processing as well as driving lasers for nonlinear wavelength conversion to the mid-infrared and terahertz, and the high-photon energy XUV region. Ho^{3+}-doped gain crystals are promising for high-energy power amplifiers due to their large emission cross sections at 2.1 µm wavelength and long upper-level lifetimes of several ms, enabling large energy storage. In-band pumping by 1.9-µm Tm-fiber lasers enables laser operation with a small quantum defect, i.e., small thermal load and high efficiency. This makes Regenerative Amplifiers (RA) based on Ho-doped materials an excellent choice for reaching mJ-class pulses with large amplification factors. However, the most commonly used Ho^{3+}-doped materials (YAG and YLF) exhibit strongly structured and narrow gain profiles, thus amplification of broadband seed pulses is severely limited by gain narrowing. This makes reaching femtosecond pulses challenging, particularly in regimes of high extraction. To mitigate the gain narrowing effect, amplitude and/or phase pre-shaping of the seed pulse and intracavity gain shaping by an etalon were utilized so far using Ho:YAG and Ho:YLF, and thereby 1-ps, 3.8-mJ pulses [1], and 2.4-ps, 2.2-mJ pulses [2] were achieved, respectively. However, these techniques introduce additional losses to the entire system, limiting the available seed energy or total amount of gain. In addition, conventional Ho-based RAs are mostly seeded by large and complex laser systems such as supercontinuum sources based on Yb-based OPA [3] or Er-based fiber lasers [4], and Tm,Ho fiber lasers including multiple pre-amplifiers [1]. That makes the overall systems inefficient and costly. In this context, novel Ho-doped materials with an appropriate combination of large bandwidth and gain cross section would enable us to make significant advances in high-energy fs sources at 2.1 µm. In this regard, Ho:CALGO offers a desirable gain profile [5], as well as high thermal conductivity which is comparable to YAG [6], making it an attractive alternative for amplifiers with a sub-ps pulse duration.

In this study, we present the first demonstration of a Ho:CALGO-based RA. The system is directly seeded by a diode-pumped 2.1-µm mode-locked oscillator without preamplifiers, realizing a simple and compact configuration. We demonstrate the ultrashort pulse amplification using 2 different polarization geometries of Ho:CALGO crystals. A maximum pulse energy of 342 µJ was obtained at a repetition rate of 1 kHz with a π-polarization geometry, which exhibits higher emission / gain cross sections than a σ-polarization. A broadband amplified pulse spectrum was observed that supports a Fourier Transform-Limited (FTL) pulse duration of 850 fs.

2. Experimental results

The developed RA is based on a conventional Chirped Pulse Amplifier (CPA) system and composed of a seed oscillator, a stretcher, and an amplifier stage, as shown in Fig. 1a. The seed laser is a diode-pumped SESAM mode-locked Tm,Ho:CLNGG laser operating at 2097 nm, described in more detail in [7]. It delivers a pulse energy of 1.7 nJ at a repetition rate of 70.3 MHz with a nearly FTL pulse duration of 120 fs. The seed pulses were negatively stretched by a Treacy stretcher, resulting in ≈180 ps pulse duration with a reduced pulse energy of 1 nJ. The seed pulse had a spectral bandwidth of 30 nm at a center wavelength of 2097 nm after the stretcher (Fig.1b). The RA stage is composed of a linear cavity, including an RTP-based Pockels cell and a quarter wave plate that acts as an optical switch. As a gain medium, we prepared two Brewster-cut, 3.1-at.%-doped Ho^{3+}:CALGO crystals, one has a length of 14.48 mm with π-polarization geometry (E//c), and the other one is 12.83-mm long with σ-polarization geometry (E⊥c). The gain crystal was pumped by a continuous-wave single-mode Tm-fiber laser at 1908 nm. The pump absorption amounted to ~70% and ~80% for π-polarization and σ-polarization crystals, respectively.

Using the π-polarization crystal, a maximum amplified pulse energy of 342 µJ was obtained at a repetition rate of 1 kHz under 25 W pumping. The number of Round Trips (RT) was 41, determined experimentally by the balance between the gain saturation and the bifurcation threshold [7]. Figure 1b shows the amplified spectrum. The center wavelength was blue-shifted to 2077 nm, and the spectral bandwidth was 5 nm. Although the spectrum suffered from gain narrowing, the bandwidth still supported the FTL pulse duration of 850 fs. For the σ-polarization crystal, an increased number of RTs of 88 was required because of higher saturation fluence as the saturation fluence is inversely proportional to the cross sections (see Fig. 1b dashed lines). We obtained a maximum pulse energy of 265 µJ at a repetition rate of 1 kHz under 18.3 W pumping. In this case, the energy scaling was limited at an earlier point than the π-polarization case by the accumulated B-integral due to the increased number of RTs. The amplified spectrum shown in Fig. 1b had a center wavelength of 2088 nm with a spectral bandwidth of 8 nm corresponding to 750 fs FTL pulse duration, indicating less gain narrowing influence than the π-polarization case. This is due to the flatter gain profile for σ-polarization mitigating the gain narrowing during amplification, resulting in a broader amplified pulse spectrum.

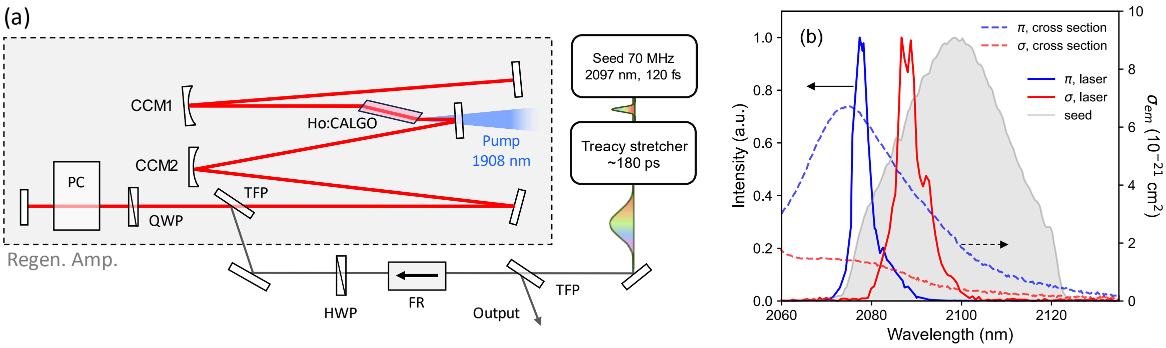

Fig. 1(a) Experimental setup of the Ho:CALGO regenerative amplifier (TFP: Thin Film Polarizer, FR: Faraday Rotator, HWP: Half Wave Plate, QWP: Quarter Wave Plate, PC: Pockels Cell, CCM1&CCM2: Concave Mirror with R=500 mm). (b) Spectra of seed and amplified pulses (solid lines) and the emission cross-section spectra (dashed lines) for both polarizations.

For further power and energy scaling, the optimization of the seed laser will be straightforward to realize, in particular a slightly shifted center wavelength, a higher seed power and/or a larger stretching ratio will result in significant improvements. Currently, the spectral filtering due to the gain narrowing works as temporal filtering to the chirped pulse, resulting in pulse shortening after the amplification by the same factor of spectral narrowing. The higher peak power inside the RA cavity leads to a larger B-integral and damage to the crystal. Therefore, a wavelength-optimized high-power seed laser would help to reduce the B-integral, increase amplification efficiency, and increase the bifurcation threshold [8]. In addition, better thermal handling of the gain crystal should allow for higher average output powers.

In summary, we demonstrate the first 2.1-µm Ho:CALGO RA directly seeded by a simple diode-pumped mode-locked oscillator. A maximum output energy of 342 µJ was achieved at a repetition rate of 1 kHz using the π-polarization geometry, seeded by nJ-level pulses. Although the amplified spectrum was affected by gain narrowing, a spectral bandwidth of 5 nm supporting sub-ps pulse duration was achieved. This result is comparable to previous reports of Ho:YAG or Ho:YLF RAs without the need for any spectral shaping. Optimized cavity engineering and seed source will lead to a robust and efficient mJ-level broadband amplifier at 2.1 µm in the near future.

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