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Abstract: We report on the development of a 50-mJ-class ~10-ps chirped-pulse amplifier at kHz repetition rates using cryogenic Yb:YAG regenerative and multi-pass amplifiers. The system is well suited as pump laser for kHz high-average-power ultra-broadband OPCPAs.

OCIS codes: (140.3280) Laser amplifiers, (140.3615) Lasers, ytterbium, (320.7090) Ultrafast lasers

1. Introduction

Ultrabroadband optical parametric chirped pulse amplification (OPCPA) [1] shows several distinctive advantages over conventional laser amplifiers, such as the possibility for few-cycle-pulse amplification without the need for external compression, wavelength selectivity coverage from near-infrared (NIR) to mid-IR, and direct amplification of passively carrier-envelope-phase stabilized mid-IR pulses after difference-frequency generation (DFG). For these reasons, high-power ultrabroadband OPCPA is now considered one of the most promising techniques for a driving source in attosecond science. Although high-energy high-contrast OPCPA systems with a relatively narrow bandwidth can be pumped by conventional nanosecond lasers, the ultrabroadband few-cycle OPCPA technique benefits from picosecond pump lasers because a low stretching factor results in good compressibility, and high-peak-power pumping required to achieve broad phase-matching bandwidth in short nonlinear media is also feasible. However, the availability of high-average-power and high-energy picosecond pump sources is still the main challenge for scaling the average-power and energy of ultrabroadband OPCPA systems. Recently, multi-mJ picosecond Nd:YLF amplifier chains have been developed and used for several OPCPA systems at 1-kHz pulse repetition frequency (PRF) [2,3], but further scaling of energy at kHz PRF is difficult because of thermal beam distortions [4] and optical damage issues with Nd:YLF amplifiers.

Among several laser gain media for ultrashort pulse amplification, Yb:YAG is very attractive for scaling both average power and energy due to broad emission bandwidth. Recently thin-disk Yb:YAG technology has been successfully used and 25-mJ pulses at 3-kHz PRF was demonstrated directly from a thin-disk picosecond CPA Yb:YAG regenerative amplifier (RGA) [5]. Meanwhile, cryogenic Yb:YAG laser technology has been developed for both high-energy and high-average-power amplification with laser heads of much reduced complexity. Based on this technology, a 7.5-mJ picosecond RGA at 10 Hz [6] and a 287-W picosecond double-pass amplifier at 78 MHz [7] were demonstrated. High-energy picosecond pulse sources at kHz PRF are important for energy and power scaling of existing few-cycle OPCPA systems for phase-matched high-harmonic generation with high-photon energies [8,9]. In this paper, we describe the development of a 50-mJ-class picosecond pulse source at kHz PRF using a cryogenic Yb:YAG RGA and a multipass amplifier. The CPA scheme uses a chirp fiber Bragg grating (CFBG) stretcher and a high-efficiency high-damage-threshold compressor with multi-layer dielectric (MLD) gratings.

2. Experimental setup

The optical layout of the high-power CPA picosecond cryogenic Yb:YAG laser system operating at kHz PRF is illustrated in Fig. 1. The CPA chain consists of 4 sub-systems: (a) picosecond fiber seed source with a CFBG-stretcher, (b) kHz cryogenic Yb:YAG RGA, (c) 4-pass cryogenic Yb:YAG amplifier, and (d) pulse compressor based on a MLD grating pair. The front-end oscillator is a mode-locked femtosecond Yb-fiber laser at 78-MHz PRF with a spectral bandwidth of ~50 nm centered at 1030 nm. The output pulses from the Yb-fiber laser are stretched to ~400 ps by a CFBG with a ~0.9-nm bandwidth centered at 1029 nm. The Yb-fiber pre-amplifier in Fig. 1(a) compensates for the power loss in the CFBG caused by bandwidth filtering (~50 nm to 1.5 nm) and optical losses. An average power of ~10 mW (0.12 nJ) is available for seeding the cryogenic Yb:YAG RGA. The cw-diode-pumped

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RGA is designed for amplification to >10 W at 1–2-kHz PRF with 45 W of pump power. A 10-mm-long Yb:YAG crystal with 2-at.% doping is pumped by a fiber-coupled laser diode at 940 nm and cooled down to 77 K in an evacuated liquid nitrogen dewar. The pump beam size at the crystal is 1.3 mm in diameter. The RGA is switched by a BBO PC with a quarter-wave voltage synchronized to the mode-locked pulse train. The fluence for operation at 5-mJ output pulse energy is <0.5 J/cm^2 for the Yb:YAG crystal and dielectric mirrors and <0.1 J/cm^2 for the PC. These values are low enough to avoid surface damage. The accumulated B-integral in the RGA is calculated to be <1 rad for 400-ps stretching. In the initial experiment, we obtained stable 5.5-mJ output pulses at 1 kHz PRF with ~70 W of pump power after 30-32 roundtrips in the cavity. Further cavity and switching optimization will allow the same output energy at a lower pump power, and increasing the PRF to 2 kHz will increase the average power.

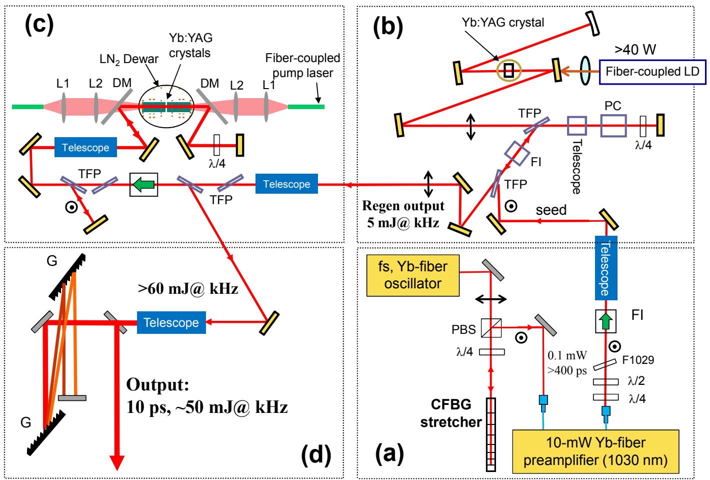

Fig. 1 Optical layout of a 50-mJ-class picosecond laser system at kHz PRF: (a) fiber seed source composed of a Yb-fiber laser, CFBG stretcher, and Yb-fiber pre-amplifier, (b) 5-mJ kHz cryogenic Yb:YAG regenerative amplifier, (c) >60-mJ 4-pass cryogenic Yb:YAG amplifier, and (d) high-energy high-average-power pulse compressor based on MLD gratings. PBS, polarization beamsplitter; λ/4, quarter waveplate; λ/2, half waveplate; F1029, band-pass filter at 1029 nm; FI, Faraday isolator; CFBG, chirped fiber Bragg grating; TFP, thin-film polarizer; PC, Pockels cell; L1-L3, lens; CM, concave mirror; DM, dichroic mirror; G, diffraction grating.

The >5-mJ pulses from the RGA will be subsequently amplified in the 4-pass amplifier and compressed in the MLD grating compressor. In the amplifier design, the number of passes through the two Yb:YAG crystals in this amplifier is limited to 4 with a Faraday isolator, as shown in Fig. 1(c), because a collinear geometry between the seed and pump beams is much easier to implement in our cryogenic system. The optimized beam size at the Yb:YAG crystals is ~2.3 mm in diameter for saturated operation at 4 pass with ~100 W of pump power at 1-kHz operation (~200 W at 2 kHz), but it is set to ~3.2 mm to mitigate optical damage. These restrictions require a pump power of ~330 W for the generation of unsaturated ~60-mJ output energy at 1 kHz (~660-W pump power for 2-kHz operation). The MLD gratings in the compressor have a groove density of 1752 lines/mm with a diffraction efficiency of >95% at 1030 nm over a bandwidth of 10 nm. A separate test on the MLD grating compressor with ~6-nm-bandwidth pulses has shown a total throughput efficiency of >80% and good compressibility of sub-ps pulses. Finally, we expect to obtain output pulses with ~50-mJ energy and ~10-ps duration at 1–2-kHz PRF without any spatial distortion after the MLD grating compressor. Multipass amplification and compression experiments are underway. Detailed characterization and repetition-rate dependence will be reported. This laser is a promising pump source for multi-mJ few-cycle OPCPA systems at both 2.2 μm [3] and 800 nm via frequency doubling.

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