1 kHz, multi-mJ Yb:KYW bulk regenerative amplifier

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Abstract: We report on a high-energy Yb:KYW dual-crystal regenerative amplifier, delivering 6 mJ at 1 kHz. The pulses centered at 1030 nm, stretched with chirped fiber Bragg gratings, can sustain a sub-ps duration after recompression.

OCIS codes: (140.3280) Laser amplifiers; (140.3538) Lasers pulsed; (140.3615) Lasers, ytterbium

1. Introduction

High energy lasers are sought for pumping optical parametric chirped pulse amplifiers (OPCPA), generating ultrashort pulses suitable for the creation of single attosecond pulses via high harmonic generation (HHG).

Ytterbium doped laser media are attractive for high energy pulses due to low quantum defect, lack of parasitic effects such as excited-state absorption, cross relaxation and up-conversion, leading to high efficiency and low heat load operation. In addition, most Ytterbium-doped materials provide emission linewidths that allow for fs-pulse generation. Among the well-developed, hence reliable materials, Yb:KYW has a thermal conductivity of 3.6 W/m/K, a lifetime of 300 µs [1] and its emission spectrum supports pulses a few hundreds of femtosecond long. Our pump line for OPCPAs is constituted of a regenerative amplifier followed by a booster amplifier based on cryogenically cooled Yb:YAG. Yb:KYW is suitable gain medium for the first amplification stage in the pump chain because the peak wavelength corresponds to Yb:YAG emission peak and it provides enough bandwidth supporting sub-ps pulse duration to pump the first OPA stages.

Previously, high energy Yb:KYW based regenerative amplifiers were demonstrated as thin-disc, as in Ref [2]. In 2007, a cryogenic Yb:KYW laser was reported with 5.5 mJ energy and 3.4 nm wide spectrum, enhanced by shaping the seed spectrum [3]. In addition, the multi-pass Yb:KYW amplifier scheme delivering 27 mJ at 100 Hz was demonstrated [4] in 2011. In this work, we describe and demonstrate a Yb:KYW bulk regenerative amplifier reaching to 6.5 mJ at room temperature, with 70 decades gain.

2. Experimental

The experimental set-up, shown in Figure 1, was constituted of a seeder, a stretcher and a regenerative amplifier followed by a grating compressor. The commercial, 42 MHz Yb:KYW oscillator delivered transform limited 210 fs pulses centered at 1030 nm wavelength. The stretcher consisted of four chirped-fiber Bragg gratings (CFBG1-4), whose dispersion is matched to the grating compressor. The stretching ratio was chosen considering the complete amplification chain, inclusive a future booster after the regenerative amplifier. To avoid non-linearities in the fibers, the seed output was attenuated to the mW level, but needed to be amplified in between the CFBG's to also compensate for the losses introduced by the circulators (C1-3). At the output of the stretcher including the fiber amplifiers (FA1-2), pulses with 0.6 nJ energy and 3.2 ns duration were send into the regenerative amplifier. The latter relied on a two-ytterbium doped KYW crystal resonator with a similar configuration to the one described in [5]. The short cavity, symmetric on S, middle point between both crystals, and containing both crystals and mirrors M1, M2 and DC, was extended with a 4-f telescope to integrate the switching elements (Pockels cell, thin-film polarizer and quarter-waveplate). In order to minimize the non-linearities, hence the aberrations on the beam, the spot sizes were increased up to 400 µm in the crystals and 1 mm in the switching elements. The compressor is based on two multi-dielectric gratings with 1760 lines/mm at 60° angle of incidence.

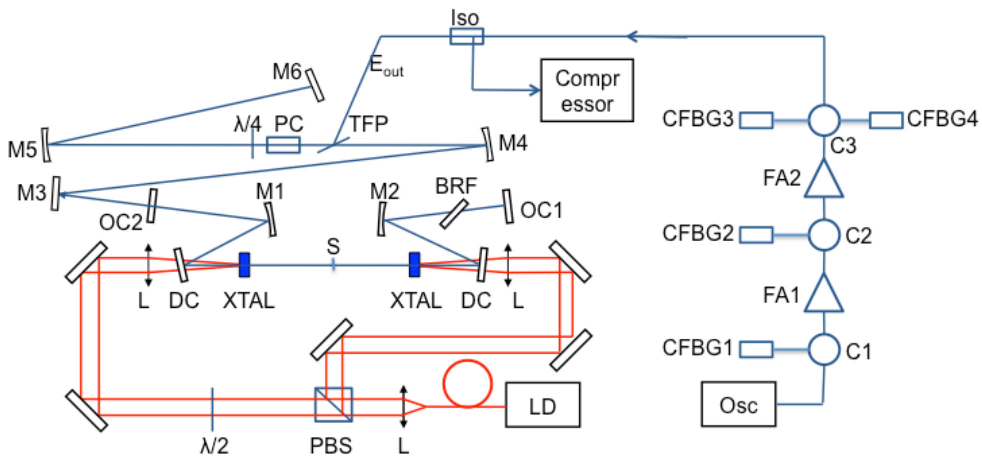

Fig. 1. Layout of the regenerative amplifier with seeder and stretcher. The input in the regenerative amplifier consisted of oscillator (Osc), chirped fiber Bragg gratings (CFBG1-4), 3-port circulators (C1,C2), 4-port circulator (C3), fiber amplifiers (FA1-2), a Faraday isolator (Iso). The cavity of the regenerative amplifier included both crystals (XTAL's), dichroic mirrors (DC's), Pockels cell (PC), thin film polarizer (TFP), quarter-waveplate (λ/4), high reflective mirrors (M1-M6), where M1 and M2 are curved mirrors with 500 mm radius of curvature, and M4 and M5 have 1000 mm radius of curvature. To acquire the tuning curve, a birefringent filter (BRF) was inserted in the cavity. For testing the laser head in CW operation, the output couplers OC1 and OC2 were inserted; OC1 was replaced with a high-reflector for operation as a regenerative amplifier.

The 2% doped, 3 mm long crystals cut along the n_g axis were pumped with a fiber-coupled laser diode, delivering a maximum of 120 W at a wavelength of 981 nm, corresponding to the peak absorption of the material. The horizontal polarization of the amplified field corresponded to the n_m axis of the crystal in order to match later on the wavelength of the following amplifier, centered at 1030 nm. It also consequently allowed cooling along the n_p axis of the crystal, which is of advantage for its higher thermal conductivity coefficient.

3. Results

The laser-head was first characterized as a continuous-wave oscillator. Without switching elements but inserting a 15% output coupler, the slope efficiency was measured to be 40%. The maximum output power extractable with a beam quality factor better than 1.1 was 19.4 W. The tuning curve, measured by inserting a birefringent filter in the cavity and for 15 % output coupling, illustrates the tunability between 1021 nm and 1033 nm, with a peak output power at 1031 nm, as displayed on Fig. 2 (left). The beam quality, measured with the 4-sigma algorithm, was equally good ($M^2 < 1.1$) when operating as regenerative amplifier, as shown on Fig. 2 (right).

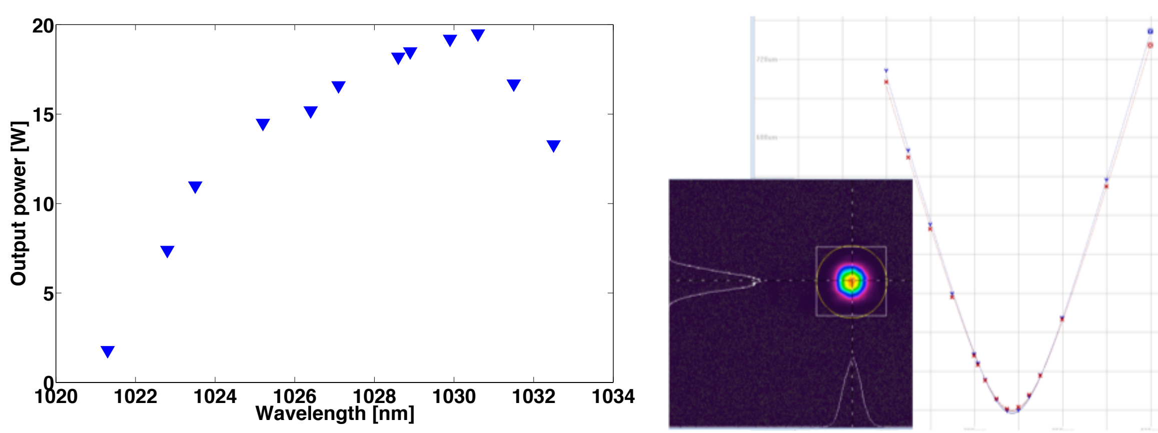

Fig. 2. Characterization of the laser-head: left, tuning curve taken in cw operation, and right, measurement of the beam quality in regenerative operation.

Figure 3 (left) shows the efficiency curve during the cavity-dumped operation of the laser. In this operation regime, the output energy was 5.5 mJ for 130 W pump power, 825 ns extraction time and 500 µs pumping duration at 1 kHz. Figure 3 (right) compares the spectra from the seeder and at the output of the amplifier, operating first in cavity-dumping and second as regenerative amplifier. The seed spectrum was centered around nm and 4.9 nm wide.

The structures on it were due to self-phase modulation in the fiber amplifiers and the sharp edges to the filtering in the CFBGs. The lower part overlapped with the 5.7 nm wide spectrum of the resonator in cavity-dumped operation. As a result, the seed spectra was reshaped and narrowed to 3.6 nm, which supports Fourier-transform limited pulse duration below 400 fs. Due to the gain narrowing, the pulses were shortened to 2.35 ns at the output.

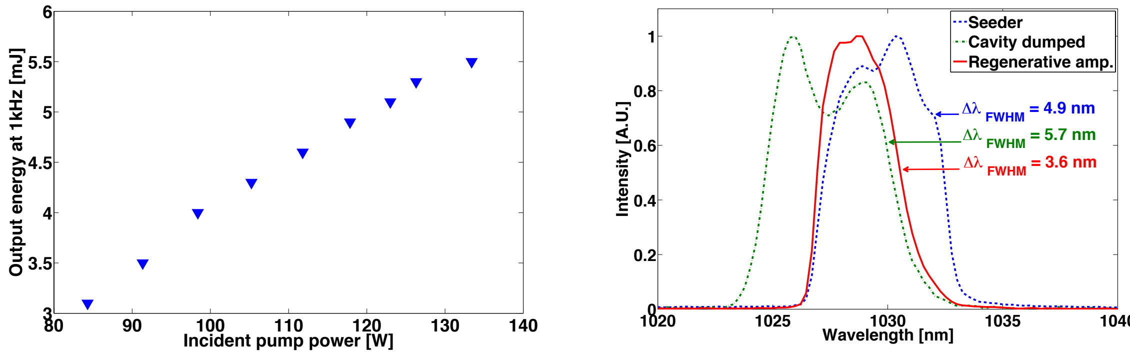

Fig. 3. Spectra of the seeder (blue, dashed curve), the laser-head in cavity-dumped (green, dot-dashed curve) and regenerative amplifier (red, plain curve) operation.

As a regenerative amplifier, 6.5 mJ were extracted after 600 ns extraction time, corresponding to 30 round-trips, for 500 µs pumping time at full pump power. A measurement of the pulse energy over 60 h, recording every pulse, showed a standard deviation of less than 100 µJ. The pre- and post-pulses were measured to be smaller than 1% and 1.5%, respectively.

This is to date, to our knowledge, the highest energy demonstrated with a bulk Yb:KYW regenerative amplifier.

4. Conclusion

In summary, we demonstrated a dual-slab Yb:KYW regenerative amplifier, delivering 6 mJ at 1 kHz. Even after gain narrowing, the spectrum supports sub-ps long pulses. This will later be further amplified to reach higher energy.

5. References

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