Long-term-stable 120-W, 220-µJ, 120-fs Thulium-based fiber-CPA for materials processing

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We demonstrate a thulium-based fiber amplifier delivering pulses tunable between <120fs and 2ps duration at up to 228 µJ of pulse energy at a center wavelength of 1940 nm and 500-kHz repetition rate. Due to the excellent long-term stability, this system proves the ability of this technology to be integrated into ultra-fast material processing machines.

1. Introduction

Ultrafast ytterbium-based fiber-laser systems operating around 1 µm wavelength have become an interesting platform particularly for demanding applications that simultaneously require high average powers and peak powers (e.g. high-harmonic generation) [1]. Their rapid development over the last two decades was built upon an efficient mitigation of detrimental nonlinear effects through the use of advanced single-mode, large-core fiber designs [2] and chirped-pulse-amplification (CPA) [3]. However, the most recent milestones in power-scaling were achieved by the simultaneous mitigation of thermal and nonlinear effects through the coherent combination of ultrafast pulses [4,5]. This technique is based on splitting the light into several spatially separated amplification channels that are subsequently coherently recombined into a single beam.

Besides the performance scaling aspect, the laser wavelength is an important parameter as it can be beneficial for many applications, e.g. for high-field physics due to the quadratic wavelength dependence of the ponderomotive potential [6]. Tm-doped fiber lasers have proven to be promising and relatively straightforward candidates for the realization of efficient, high-average- and peak-power, ultrafast lasers in the 2 µm-wavelength region [7–9]. Here we demonstrate the coherent combination of four thulium-based fiber amplifiers (TDFA). The fiber-CPA delivers pulses with <120 fs full width at half-maximum duration with up to 228 µJ of pulse energy at a center wavelength of 1940 nm. These output characteristics together with the excellent long-term stability (<0.5% over 48h at >120 W average output power) make it a unique laser system, which is ideally suited as a driving source for very demanding scientific and industrial applications.

2. Laser-system design

The laser system follows a typical fiber-CPA concept similar to references [7–9] with all thulium-based fiber amplifiers being cladding-pumped at 793 nm wavelength by low-brightness diode-lasers. The all-fiber frontend of the system is seeded by a commercial ultrafast fiber-oscillator emitting <100 fs pulses at a center wavelength of 1940 nm and a pulse-repetition frequency of 25 MHz. The ultrafast pulses are stretched with chirped-fiber-Bragg gratings to a duration of around 800 ps and are amplified in two polarization-maintaining TDFA. A fiber-coupled acousto-optic modulator allows for the tuning of the pulse-repetition frequency between 25 kHz and 25 MHz. These pulses are free-space-coupled to the final pre-amplifier consisting of a thulium-doped polarization-maintaining photonic-crystal fiber (TmPCF) similar to the one used in reference [8].

The output beam is then split into four channels using a cascaded setup of thin-film polarizers (TFPs) followed by appropriate delay lines to ensure temporal overlapping for efficient recombination after the main amplifiers. The individual delay lines are equipped with piezo-driven mirrors for fine-adjustment of the path length and stabilization of the path-length differences. After every combination step of two beams, a small fraction of the combined beam is directed toward a Hänsch-Couillaud detector to determine the polarization state. This information is processed with a PID regulator that controls the corresponding delay line to optimize the beam for linear polarization and therewith maximum transmission through the subsequent TFP.

In order to avoid the detrimental impact of molecular water-vapor absorption on the beam and pulse quality [10], the high-power free-space sections of the system, i.e. the high-power coherent combining and the chirped-pulse compressor, have been placed in vacuum.

3. Laser characterization

The main amplifiers are TmPCF with a length of 2.6 m that are each seeded with ≈100 nJ pulse energy. At a pulse repetition rate of 500 kHz each channel delivers 67 µJ pulse energy corresponding to an average power of 33.5 W at a pump-power level of about 120 W. With a total combining efficiency of 95% and a compression efficiency of 90% the laser system delivers 228 µJ pulse energy with a compressed pulse duration of <120 fs. A typical autocorrelation trace at this pulse energy is

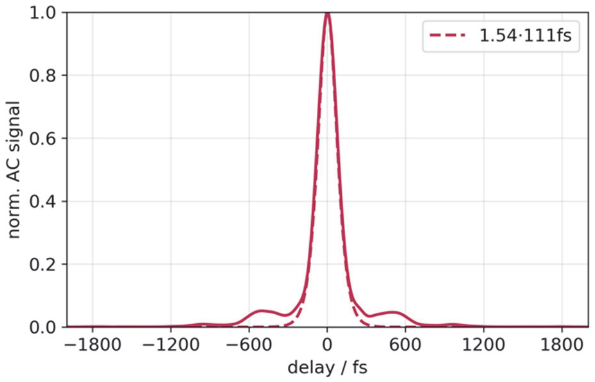

Figure 1: Second-harmonic autocorrelation function of the output pulse corresponding to a pulse-duration of <120fs (111fs, assuming $sech^2$-shape) at 228 µJ pulse energy.

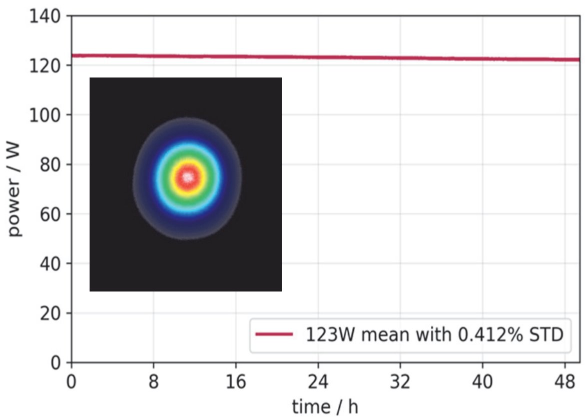

Figure 2: Average-power measurement over >48h operation time. The inset shows the output beam at the highest power level.

depicted in Fig. 1 indicating good pulse quality. A further increase of the output-pulse energy is possible but increases the accumulated nonlinearity to B≥3 rad, which reduces the pulse quality. With the conservative assumption that >70% of the pulse energy are contained in the main feature, the peak power of the laser system is >1.3 GW. The laser system has been continuously operated and characterized over several days at 1 MHz pulse repetition rate and an average output power of 123 W. Excellent long-term stability has been achieved with an average power fluctuation of <0.5% RMS over 48 hours of operation as is shown in Fig. 2. The TmPCF delivers near diffraction-limited output (M^2<1.2), which has been verified by earlier work [8]. As a result of operating the high-power sections in vacuum together with the utilization of suitable optics, the excellent beam quality is maintained in the system. The inset in Fig. 2 shows the Gaussian-like beam after pulse compression at the highest average-power.

4. Summary

We have presented the first high-power coherently combined thulium-based fiber-CPA. The laser system incorporates four amplifier channels and delivers pulses with >228 µJ energy at <120 fs pulse duration and a repetition frequency of 500 kHz. Excellent long-term stability is achieved with an averaged power fluctuation of <0.5% RMS over >48 hours of operation at an average power >120 W. Given the presented parameters, this is the first commercial system simultaneously delivering >100 W average power and >1 GW peak power in the 2 µm wavelength regime. Besides its excellent suitability for driving high-harmonic generation to the water-window aiming at coherent diffractive imaging, the system can be used for exploring ultrafast laser-materials processing in the 2µm wavelength region [11].

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