Fiber Based Ultrashort Pulse System with Kilowatt Level Average Power

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Abstract. We report on the generation of 830 W of compressed average power at 78 MHz pulse repetition frequency and 640 fs pulse duration. We discuss further power scaling including the issue of transversal spatial hole burning.

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1. Introduction

Ultrashort pulse laser systems combining simultaneously high peak and average power are desirable in many applications. Especially the high pulse repetition rate results in a reduced measurement time in fundamental science and in an increased processing speed for industrial applications. Extreme parameters, i.e. mJ-level pulses at average powers beyond one kilowatt and diffraction limited beam quality, is still a huge challenge for every existing laser architecture. So far, a serious step towards the kilowatt average power ultrashort pulse laser system was only demonstrated with slab [1] and fiber technology [2]. In continuous wave operation, fiber lasers with multi kilowatt average power and fundamental mode beam quality are state-of-the-art. They profit from their enormous advantages in thermal management due to their large ratio of surface to active volume and the confinement of the beam in a waveguide structure, keeping the beam unaffected from thermal lens problems. Otherwise, this confinement in small cores could deny further power scaling in ultrashort pulse operation due to the onset of nonlinear effects.

To overcome this drawback, the application of the chirped pulse amplification (CPA) technology in combination with photonic crystal fibers (PCFs) was extremely fruitful during the last decade, since PCFs offer the combination of a short fiber length and a large core. Consequent technological improvements have led to fiber CPA systems capable of producing ultrashort pulses with mJ-level pulse energies [3].

In this contribution we present a three-stage fiber CPA system showing the ability of femtosecond fiber amplifiers to approach average powers at the kilowatt level with fundamental mode beam quality. To the best of our knowledge, the achieved average power of 830 W for compressed pulses is the highest ever reported for an ultrashort-pulse solid-state laser system.

2. Experimental setup and results

A schematic setup of the laser system presented herein is shown in Fig. 1. It consists of a passively mode-locked femtosecond oscillator, a dielectric grating stretcher, three single-pass amplifier stages and a dielectric grating compressor. The oscillator emits 200 fs pulses at 1042 nm signal wavelength with 78 MHz pulse repetition frequency and 150 mW average power.

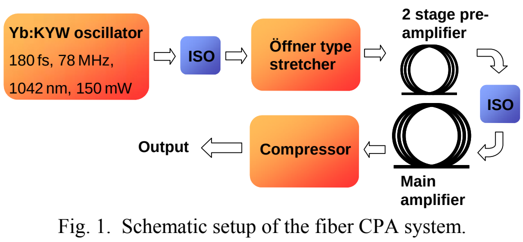

Fig. 1. Schematic setup of the fiber CPA system.

These pulses are stretched to 800 ps duration with an Öffner type stretcher using a 1740 lines/mm dielectric reflection grating. The spectral cut inside the stretcher due to the finite width of the grating has been chosen to be twice the spectral bandwidth (FWHM). This is advantageous in nonlinear CPA systems (B-integral > π rad), since an appreciable amount of the acquired non-compressable phase is generated by the wings of the stretched pulse. Thus, through this spectral clipping the detrimental influence of this part is effectively removed [4].

Afterwards, the stretched oscillator signal (120 mW) is amplified in two single-pass amplifier stages that comprise a 1.2 m and a 1.5 m long double-clad PCF respectively, both with 30 µm mode field diameter and 170 µm pump cladding diameter. The maximum output power of the pre-amplifier stages is >100 W, but we limited the main amplifier seed to about 50 W in order to avoid thermal lensing in the optical Faraday isolator. The main amplifier fiber is a water-cooled 8 m long double clad fiber with 27 µm mode field diameter and 500 µm air-clad. Pump light at 976 nm wavelength is launched into the main amplifier with 85 % coupling efficiency. Compared to the pre-amplifier fibers this fiber has no PCF structure, although the core is nano-structured in order to produce a low numerical aperture. The choice of this fiber might seem surprising since large-core fiber designs like e.g. the Rod-type fiber would allow for higher pulse energies thanks to the reduced signal core intensity and, therefore, reduced nonlinear phase. However, these large mode area fibers are limited to some hundred watts of average power due to the threshold-like onset of mode instabilities in high-power operation. At these power levels the signal strongly depletes the inversion only in the inner region of the doped area. Now, the remaining inversion at the edge of the core preferably amplifies higher order modes (HOMs) due to their bigger mode overlap. This effect is known as transversal spatial hole burning (TSHB) [5], but commonly only implicated in a degradation of beam quality. HOMs can be found in every large mode area fiber that is not strictly single mode. The losses of these HOMs often exceed by far that of the fundamental mode and, up to moderate power levels, the fundamental mode can be easily excited by mode-matching leading to the expression "effectively single-mode". Thus, the reason behind the choice of this relative small core fiber is to reduce the HOM content and, in this way, to raise the threshold for these instabilities close to the kilowatt level. The resulting amplifying slope is depicted in Fig. 2.

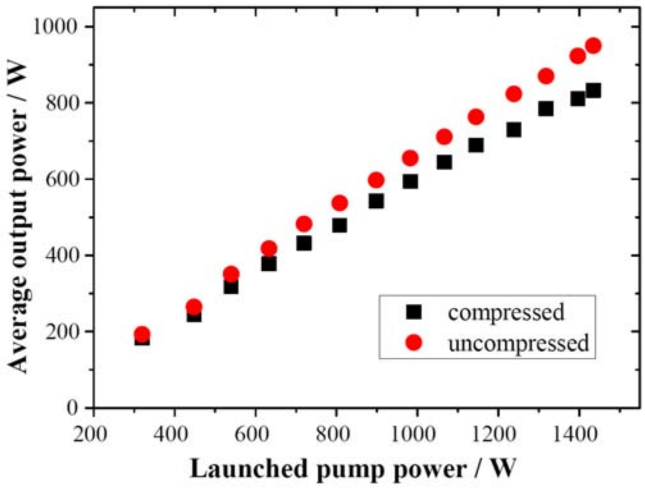

Fig.2. Output power of the fiber CPA system vs. launched pump power before and after compression.

At a maximum launched pump power of 1450 W the signal output power is 950 W corresponding to 12.2 µJ pulse energy. Finally, the pulses are compressed using two high-efficiency 1740 lines/mm dielectric reflection gratings [6]. Both gratings possess about 99 % diffraction efficiency resulting in a total 95 % compressor throughput. These gratings were designed for 1040 nm central wavelength and a Littrow angle of 64.8°. They were fabricated using electron-beam direct writing and reactive ion-beam etching into the top layer of a highly reflective dielectric multilayer stack. The compression efficiency drops slightly from 95 % to 88 % at maximum signal power due to depolarisation taking place inside of the fiber. Thus, the resulting maximum compressed signal power is 830 W with 10.6 µJ pulse energy. The beam quality of the main amplifier was measured to be $M^2 < 1.3$ at this power level (Fig. 3 right).

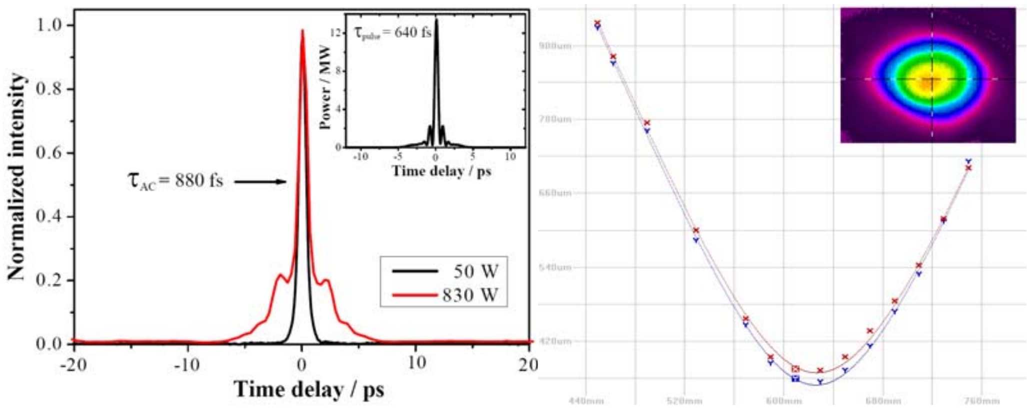

Fig.3. Output power of the fiber CPA system vs. launched pump power before and after compression.

The measured autocorrelation of the compressed pulses is shown in Fig. 3 (left) for low and maximum output power. Due to the acquired nonlinear phase (mainly in the main amplifier) with a calculated B-integral of 11 rad, the autocorrelation width increases from initially 750 fs to 880 fs and a wing structure appears. We calculated the corresponding pulse shape (inset Fig. 3, left) using a split-step Fourier algorithm. The results are in good agreement with the measured autocorrelation and spectra. Assuming a calculated deconvolution factor of 0.73 and that according to the simulation 70 % of the total pulse energy is in the central peak, the resulting peak power is 12 MW. Pulse quality improvements are feasible, e.g. by increasing the stretched pulse duration using larger gratings or by increasing the oscillator pulse repetition frequency. Further average power scaling beyond the kilowatt level and the realisation of higher pulse energies will be possible by using appropriate fiber designs with larger cores and reduced higher order mode content. This includes gain and/or loss management [7], e.g. doping only the central region of the core and/or increasing HOM losses. Finally, using these high average power large mode area fibers will enable ultrashort pulse fiber systems combining output powers beyond 1 kW and pulse energies in the mJ range.

In conclusion we demonstrated a fiber CPA system with 950 W of average power at 78 MHz pulse repetition frequency with fundamental mode beam quality. The pulses are efficiently compressed to 640 fs pulse duration and 830 W of average power. Beside these record parameters we discuss possibilities to overcome limitations of current large mode area fiber amplifiers imposed by transversal spatial hole burning enabling fiber CPA systems with kW average power and GW peak power.

Acknowledgements

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4. References

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