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Generation of three-cycle multi-millijoule laser pulses at 318 W average power

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The generation of three-cycle multi-millijoule pulses at 318 W power is reported by compressing pulses of a Yb-fiber chirped pulse amplifier in a 6 m long stretched flexible hollow fiber. This technique brings high-power lasers to the few-cycle regime.

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One of the main quests of contemporary laser research is the energy and power scaling of ultrashort light pulses, especially in the few-cycle regime. Besides applications in attosecond science or time-resolved studies [1], few-cycle pulses at high power also open up new possibilities in industrial applications such as manufacturing of three-dimensional (3D) integrated photonic circuits [2].

There are two approaches to reach the few-cycle regime (<10 fs) with multi-millijoule pulses. One is optical parametric chirped pulse amplification (OPCPA) [3]; the other is postcompression of multi-cycle laser pulses in gas-filled hollow-core fibers (HCFs) [4]. State-of-the-art high-power lasers can produce multi-millijoule pulses of several 100 fs to picosecond durations, e.g., via a coherent combination of several fiber amplifiers [5]. However, the combination of high pulse energy and high average power together with the need for large spectral broadening (>30) in order to reach the few-cycle regime represents an enormous challenge for which no solution has yet been found. For the compression of such pulses, radical up-scaling of the HCF dimensions is necessary, which has recently become possible by using the stretched flexible hollow-fiber (SF-HCF) technology [6], enabling free length scalability without sacrificing waveguide quality. This technology has already shown the required large compression factors, e.g., 33-fold compression [7] and the capability of handling high pulse energies [8], but the average power has not yet exceeded 15 W [9].

Here we demonstrate 30-fold compression of high-energy 5.8 mJ, ~300 fs pulses at 100 kHz repetition rate to 10 fs duration containing only three optical cycles at 318 W average power level in a single 6 m long SF-HCF compressor. This result marks the highest average power of a few-cycle laser system ever achieved [10], representing more than a 20-times increase compared to existing SF-HCF technology [9] and a sixfold increase relative to the highest power of multi-millijoule systems reported to date [3].

Figure 1 illustrates the full experimental arrangement, showing the current status of the HR2 laser system that was developed by Active Fiber Systems (AFS) for the ELI-ALPS research facility. The light source is an Yb-fiber chirped pulse amplifier (CPA) system operating at 100 kHz repetition rate with up to 16 coherently combined channels producing >1 kW, 10 mJ, ~300 fs output with about 0.3% rms stability (over >9 h). For the experiments presented here, eight parallel rod-type amplifier channels are used with a power of 580 W. After pointing stabilization, a variable attenuator is placed directly in front of the HCF compressor. The beam is then focused into the waveguide by a reflective telescope consisting of $R = -2$ m focusing and $R = 3$ m defocusing mirrors. Behind the telescope, a steering mirror directs the converging beam onto the entrance of the HCF. In the experiments, we use a 6 m long SF-HCF of 400 μm inner diameter, which is sealed at both ends by AR-coated 1 mm thick fused silica windows. Behind the fiber assembly, the diverging beam first passes a wedge pair for fine chirp tuning and then is reflected off six pairs of matched chirped mirrors of -67 fs^2, introducing a total group-delay dispersion of -402 fs^2. The leakage of the first mirror is directed onto a CCD camera for monitoring the output beam. The throughput of the chirped mirror compressor is measured to be 93%. The beam is then recollimated by a focusing mirror

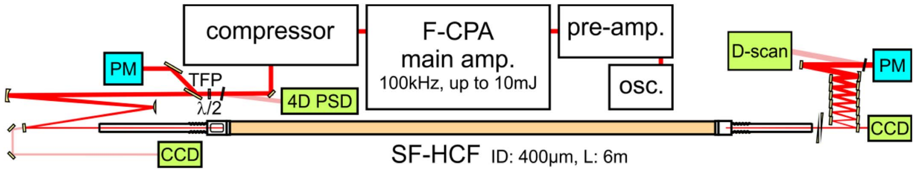

Fig. 1. Experimental layout. F-CPA, fiber chirped pulse amplifier; HCF, stretched flexible hollow-core fiber; d-scan, dispersion scan device; PM, water-cooled power meter; 4D PSD, position-sensitive detectors for near and far field; TFP, thin-film polarizer; $\lambda/2$, half-wave plate; CCD, camera.

of 10 m radius of curvature and subsequently hits a water-cooled power meter. One percent of the beam is sampled to a second-harmonic generation dispersion scan device (d-scan) for pulse characterization [11]. By aligning the HCF at 1 W, we achieved a transmission of 56%, close to the theoretical value of 69.5%. In order to dissipate more than 250 W of power deposited in the fiber assembly, we apply active liquid cooling along the full length of the capillary. By ramping up the input power, no change in the fiber transmission is observed. We apply argon (Ar) gas with a pressure gradient between the two ends [12]. In order to maximize spectral broadening, we optimize for the first time the gas pressures at both sides of the capillary requiring two separate proportional-integral pressure regulators. We found stable operation with maximal spectral broadening at 0.8 bar at the input side and 1.9 bar of Ar at the output side of the capillary, giving an increase of the B-integral by ~27% compared to the common case of evacuated entrance. Beyond these values, unstable operation starts, caused by periodic energy transfer between the eigenmodes, and further increasing the pressure the transmission drops.

The d-scan measurement of the pulse with a retrieval error of 1.0% is shown in Fig. 2. An independently measured high-resolution spectrum and the output beam profile are shown in the insets of Figs. 2(c) and 2(d). The retrieved pulse is 10.0 fs long, and its peak intensity is 72% of that of the transform limit.

The average power measured after the compressor reached 318 W indicates an overall throughput of the HCF compressor of 54%. We also recorded the evolution of the output power set to 285 W for a 30 min period of time, showing a constant power level without drifts or modulations with a low rms value of 1.0%, clearly demonstrating that the HCF compressor operates in a stable way in spite of the large thermal load.

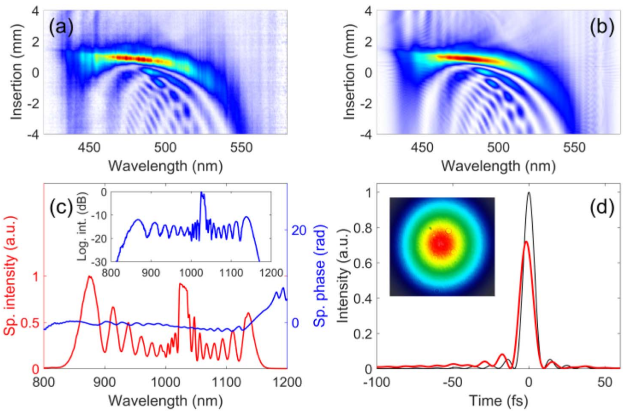

Fig. 2. D-scan measurement of the compressed pulses. (a) Measured and (b) retrieved traces; (c) spectrum with retrieved phase; inset, high-resolution spectrum in log scale; (d) retrieved pulse (red) and transform-limited shape (black) with 10.0 fs and 8.3 fs FWHM, respectively; inset, output beam profile.

In conclusion, 10 fs pulses containing three optical cycles are generated at 318 W average power by 30-fold compression of 5.8 mJ, ~300 fs pulses of a fiber CPA in a 6 m long SF-HCF. This marks a new milestone in the generation of few-cycle pulses in several aspects: This is the first time multi-millijoule few-cycle pulses beyond 100 W average power have been created. Furthermore, the achieved spectral broadening is by far the largest demonstrated in a single HCF above that power level. We exploit for the first time the full capability of pressure gradient operation of HCFs by optimizing both the input and output gas pressures. We demonstrate that SF-HCFs are capable of handling multi-millijoule pulses at 580 W average power without damage or thermal instabilities. Therefore, we are confident that the stretched flexible hollow fiber compressor technology will bring high-power industrial-grade lasers, such as the HR2, to the few-cycle regime.

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