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30-fs 1.6 mJ Pulses at a kHz Repetition Rate from a Single Stage DPSS Yb Amplifier

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Abstract: 200-fs 2.5-mJ pulses from a cw-diode-pumped Yb:CaF_2 MOPA are spectrally broadened in Ar and recompressed to 30 fs at 980 nm using a prism pair. Multi-millijoule 12-fs pulses are feasible upon higher-order spectral phase correction.

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For over 15 years Ti:sapphire pulse amplifiers emitting 25–150-fs pulses at kHz repetition rates have dominated the field of ultrafast applications and ultrashort-pulse laser technology, ultimately leading to the generation of near-single-cycle pulses around the wavelength of 800 nm via external compression. Self-phase modulation (SPM) induced spectral broadening in a gas-filled hollow fiber and laser beam filamentation in gases are well developed techniques for routine production of few-optical-cycle pulses at a sub-mJ energy [1-5]. In this contribution we show encouraging results for millijoule-level pulse broadening and recompression obtained with a novel broadband diode-pumped single-stage regenerative 1030-nm Yb:CaF_2 amplifier [6], which holds potential for a robust, compact and cheap (no additional pump lasers for the seeder and the amplifier) alternative to kHz Ti:sapphire amplifiers.

The layout of the system is presented in Fig. 1. In comparison with the performance of our cw-pumped Yb laser reported earlier [6], the output energy before the grating compressor was improved to reach 5.5 mJ at 1 kHz by using a Brewster-cut Yb crystal. To reduce the system complexity, the deformable mirror in the stretcher was not used this time at the expense of worsening the compressed pulse duration form 170 fs to about 200 fs. Because of the high-loss diffraction gratings in the compressor, the energy of the compressed pulse is currently limited to 2.5 mJ at 1030 nm.

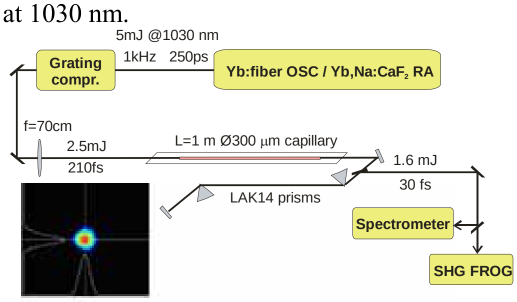

Fig.1: Layout of experimental setup and far-field profile of the hollow fiber output at the Ar pressure of 2.2 bar.

The output beam of a diffraction-limited quality was coupled into a 300-μm diameter, 1-m-long fused silica hollow-core fiber mounted on a V-groove aluminum holder inside of a vacuum tube with 1-mm-thick Brewster windows. Prior to filling it with gas, the tube is evacuated below 10^{-2} mbar. In addition to working with the hollow-fiber SPM, we also characterized the pulses broadened and mildly self-compressed in a static gas cell when the beam bypasses the capillary inside the gas tube. The spectra recorded at different gas pressures and the corresponding phases, retrieved from SHG FROG measurements are presented in Fig.2a and 2b for the cases of a filament in a static gas cell and the 300-μm capillary, respectively. The inset to Fig.2a shows an up to ×2 self-compression of the output pulse occurring at higher Ar pressures, which represents an attractive and easily implementable low-loss pulse shortening add-on for the regenerative amplifier.

Owing in part to the outstanding input beam quality, the throughput of the hollow fiber was 65% (~1.6 mJ) and remained nearly constant with gas pressure. Starting with the Ar pressure of 2.4 bar, white light generation from the walls of the glass capillary was observed, which prevented us from operating at higher pressures. Spectra supporting a 12-fs transform-limited pulse duration were recorded at 2.2 bar. The corresponding chirped pulse carries a reasonably-behaved phase, as revealed by the corresponding FROG measurements (Fig. 2b-d). The pulses were partially recompressed to 30 fs FWHM using a low-loss prism compressor (a pair of 60° LAK14 prisms). The corresponding results of SHG FROG characterization are given in Fig. 3. Note that in order to avoid phase excursions in the spectral wings, where the prism compressor runs into higher-order phase correction problems, the pulse spectrum was deliberately narrowed by lowering the Ar pressure to 2.0 bar. Therefore, despite a significantly narrower gain bandwidth than that of Ti:sapphire, the Yb laser is capable of delivering similar energy and pulse duration specifications as broadband Ti:sapphire amplifiers.

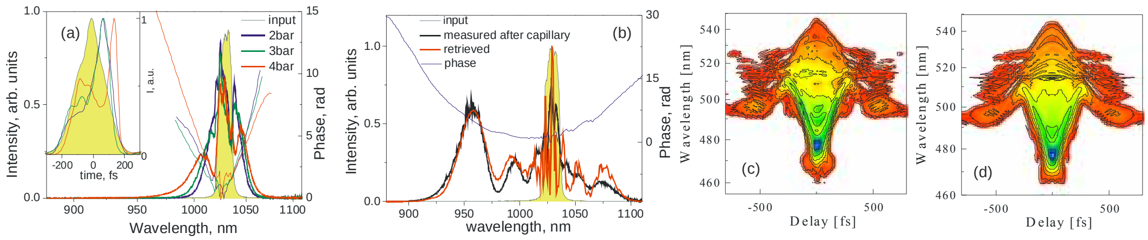

Fig. 2: SHG FROG characterization of chirped pulses. Spectral intensity and phase after a filament in an (a) Ar-filled cell and (b) hollow fiber at 2.2 bar of Ar. (c) measured and (d) reconstructed SHG FROG traces after a 2.2-bar hollow fiber.

The developed system has large potential for scaling up the energy of the compressed pulses. This potential originates from a substantially longer wavelength, in comparison with widely used Ti:Sapphire-based femtosecond laser systems. The intensity of a laser pulse which can be successfully transported and spectrally broadened in a gas-filled hollow fiber is limited by ionization of the gas. In spite of attempts to use the ionization nonlinearity for spectral broadening of pulses at a multi-mJ energy level [7,8], SPM in gases is still the most controllable and reliable technique for ultrashort pulse production. The inner diameter of a hollow-core waveguide is limited by coupling and maintaining of the fundamental mode of the waveguide when a laser pulse propagates through. Thus, the maximum energy in a laser pulse which can be realistically transmitted and spectrally broadened for the Ti:Sapphire wavelength of 800 nm is ≤ 1 mJ for a 250-300 μm capillary filed by Ne. In our system we can use capillaries with a diameter up to 400-450 μm which, with using Ne, will allow an increase in energy of compressed pulses of a factor of 4-5 at least.

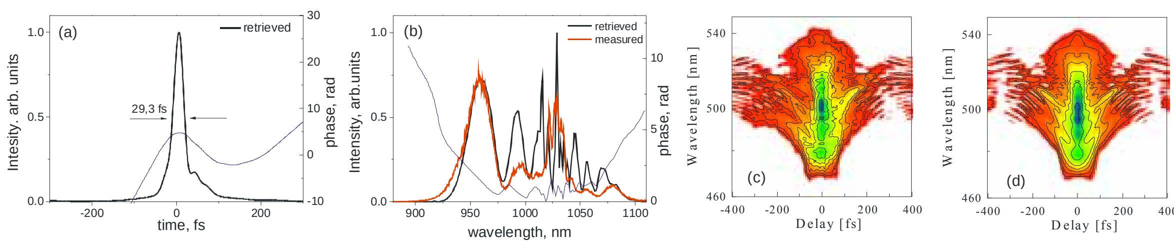

Fig. 3: Partial recompression to 30 fs with a LAK14 prism pair of the pulse transmitted through the hollow fiber at 2.0 bar of Ar. (a) reconstructed temporal intensity and phase. (b) spectral intensity and phase. (c) measured and (d) reconstructed SHG FROG traces.

In conclusion, we demonstrated for the first time efficient pulse compression at millijoule energy level of the output of the 200 fs, 1 kHz, cw-diode-pumped Yb:CaF_2 MOPA, using spectral broadening in a gas-filled hollow-core fiber and the simplest prism compressor. This system has large potential for further energy scaling of the compressed pulses and can compete with similar energy level Ti:sapphire laser amplifiers over which, owing to direct diode pumping, it holds the edge in terms of robustness, dependability, and simplicity.

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