Nonlinear compression in a rod-type fiber for high energy ultrashort pulse generation

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Abstract: We report the use of nonlinear compression in a very large mode-area rod-type photonic crystal fiber. This fiber allows the use of high energy pulses in the few microjoule range. We demonstrate the compression of 4 µJ, 338 fs pulses from a fiber chirped pulse amplification (FCPA) system down to 49 fs, 41 MW peak power pulses at a repetition rate of 200 kHz with an average power of 400 mW. The nonlinear compression setup is composed of a 5-cm-long rod-type fiber and a pair of SF10 prisms. The system was optimized to obtain good temporal quality, with a temporal Strehl ration of 86 % for the compressed 49 fs pulses.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (320.5520) Pulse compression.

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1. Introduction

The generation of high-average, high peak-power, ultra-short pulses is challenging for all laser architectures. Laser sources capable of generating such pulses will find numerous applications in medicine and fundamental science [1]. Towards this goal achievement, Yb-doped fiber chirped pulse amplification (FCPA) systems have been recently proven to be a very attractive alternative to the well established Ti:Sapphire based technology. Indeed, the geometry of fibers allows very good thermal properties, particularly suitable for high average power laser development: kW average power sources have been demonstrated in the CW regime. However, for femtosecond fiber systems, the nonlinear and gain narrowing effects limit the energy and pulsewidth that can be achieved. Current fiber technologies allow the generation of 1 mJ, 900 fs pulses in quasi-linear CPA regime [2], and the use of nonlinear CPA architectures allows the generation of 300 fs 100 µJ pulses [3], or 10 µJ 110 fs pulses [4]. The pulsewidth increases as higher energies are reached, because of gain narrowing and / or uncompensated higher-order spectral phase caused by nonlinearities. Stretcher-free setups allow the generation of shorter pulses by exploiting nonlinear effects in specific conditions such as the parabolic regime, leading to 1 µJ 60 fs pulses [5], but the pulse quality is limited by the very large amount of nonlinear phase accumulated.

A powerful technique to increase the peak power / reduce the pulsewidth of high energy subpicosecond FCPA-generated pulses is nonlinear post-compression in an optical fiber [6]. Subsequent propagation of the amplified pulses through a nonlinear waveguide leads to spectral broadening, imparted mostly by self-phase modulation (SPM). By removing the linear chirp with a compressor, a significant reduction of the pulse duration, by a factor of 5-10 compared to the initial pulsewidth, can be obtained. When the pulse energy available at the input of the compressor is large (typically greater than 100 µJ), the nonlinear guiding medium can be a gas-filled capillary, as recently demonstrated in reference [7]. Silica fibers can also be used as a nonlinear medium to provide the SPM when the input energy is lower. This technique has been used recently with a microstructured 40 µm-diameter LMA, and resulted in 0.73 µJ pulses of 20 MW peak power [8]. In this case, the output energy is limited by the mode area of the LMA fiber.

In this contribution we report, for the first time to our knowledge, the use of a rod-type photonic crystal fiber as the passive nonlinear element to provide the SPM induced spectral broadening at even higher energy level, due to the larger mode area exhibited by these fibers. Moreover, the uncompensated non-linear residual spectral phase, a crucial point for the compressed pulse quality [9-10], has been carefully optimized, resulting in the generation of high quality 49 fs pulses of 2 µJ energy exhibiting 41 MW peak power.

2. Experimental setup

The experimental setup of the FCPA system and the nonlinear compression is shown in Fig. 1. The FCPA laser consists in a passively mode-locked diode-pumped Yb:$CaGdAlO_4$ laser system, an acousto-optic modulator, a transmission grating stretcher, a double-clad ytterbium-doped fiber amplifier and a transmission grating compressor.

The oscillator, which is similar to that described in [11], produces 150 fs pulses at an output power of 650 mW and at 27 MHz repetition rate. Pulses have a 15 nm spectral bandwidth at 1040 nm central wavelength. The repetition rate is decreased to 200 kHz with an acousto-optic modulator. The stretcher is based on a 1600 lines/mm grating and is set to yield an output pulse duration of 150 ps. The amplification stage consists in a 2 m-long polarization-maintaining microstructured double-clad ytterbium-doped fiber with core/clad diameter of 40/200 µm, and both ends are angle-cleaved at 8° to suppress parasitic lasing. The fiber is pumped by a 25 W power laser diode at 978 nm. After amplification, the pulses could

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be recompressed by a grating pair with 1600 lines/mm and an overall 70 % efficiency. The polarization state of the beam is controlled through the whole system by half-wave plates in order to reach the best efficiency of stretcher, compressors and injection in the Yb-doped fiber.

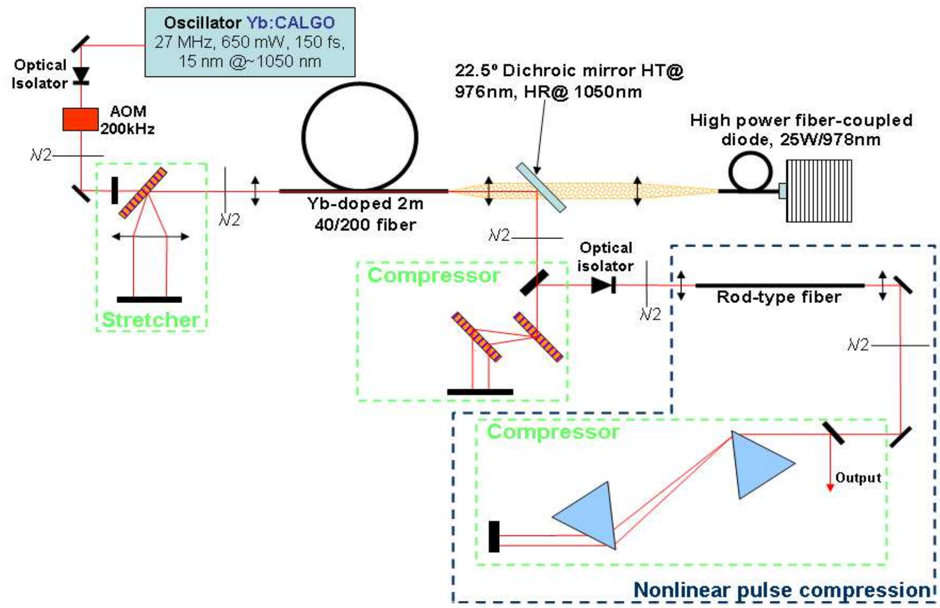

Fig. 1. Schematic drawing of the experimental setup.

The FCPA system could deliver pulses with energy up to 16 µJ after compression and a fairly constant spectral bandwidth of about 9 nm for the whole range of output energies and pulse duration varying between 183 fs for 1 µJ to 365 fs for the highest output energy. This is due to the specific choice of a moderate stretching ratio of 150 ps that aimed at the partial compensation of the gain narrowing effect by self phase modulation [5]. This resulted in some amount of non compensated higher-order phase for high energies, and therefore longer pulses for the same spectral width.

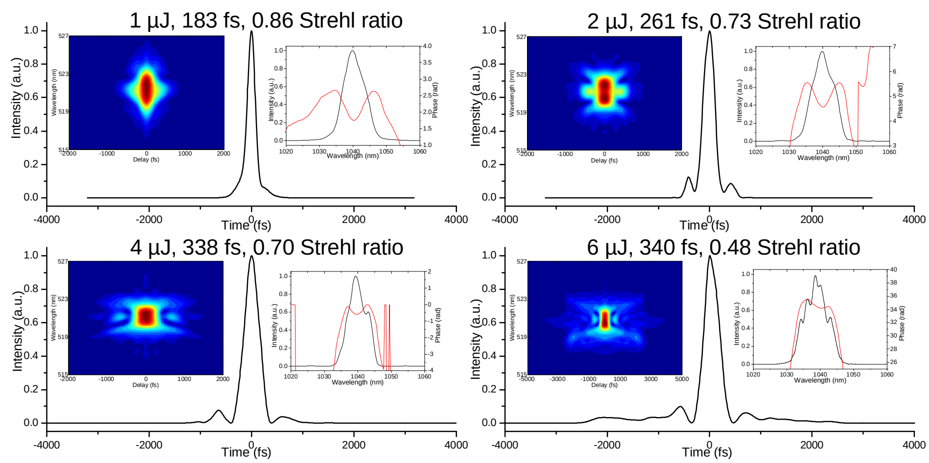

Fig. 2. FROG retrieved pulses at the YDFA output after compression for energies from 1 µJ to 6 µJ.

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In Fig. 2 are shown the compressed YDFA output pulses for energies in the range of 1 µJ to 6 µJ measured by a second-harmonic generation frequency-resolved optical gating (SHG-FROG) setup (corresponding FROG trace are shown as insets). The observed broadening of the pulse in time domain is mainly due to the increasing nonlinear effects in the YDFA that lead to high-order nonlinear phase which cannot be compensated by the grating compressor further indicated by the severe degradation of the pulses quality. The pulse quality characterization based on time-bandwidth product does not take into account the losses of energy in the satellite pulses and is strongly correlated to the shape of the pulses (Gaussian, sech, parabolic). It can even be misleading in the case of nontypical spectra,(for instance exhibiting multiple peaks). We therefore chose to use the equivalent of the Strehl ratio in the time domain, defined by the ratio between the measured peak power, and the peak power corresponding to the measured spectrum assuming a flat spectral phase (an ideally compressed pulse). The temporal Strehl ratio of the YDFA compressed pulses decreases from 0.86 down to 0.35 for the lowest to the highest pulse energy. This point is important to consider before compression since both the quality of the compressed FCPA pulse and compression will impact on the final compressed pulse quality.

3. Nonlinear compression

The concept of nonlinear pulse compression is based on the interplay between self-phase-modulation (SPM) and group velocity dispersion (GVD) during propagation of pulses in a waveguide and subsequent compensation of the imposed chirp. Clearly, only SPM causes the spectral broadening of a pulse and thus the possibility of temporal compression. But it has been shown that the influence of the GVD can lead to better pulse quality [12]. The reason for this is that without GVD the imposed frequency chirp is linear only in the central part of the pulse (except for parabolic pulses). By adding GVD, the pulse is reshaped in time and can develop an almost linear chirp across its entire width, which can be better compensated. If an input pulse with flat spectral phase is assumed, one can find an optimal fiber length with regards to achievable peak power and pulse duration [8]. When the nonlinear compressor is seeded by a CPA setup, the gratings compressor can also be adjusted to provide a non Fourier-transform limited pulse (and so a specific phase law) at the input of the nonlinear fiber to optimize output pulse quality.

By adjusting the output energy of the YDFA, we vary the strength of the nonlinear interaction in the rod-type fiber and therefore the induced spectral broadening. As the input energy to the rod-type fiber increases, the compressed pulse quality degrades due to higher-order nonlinear phase accumulated. Part of this effect could be minimized experimentally by adjusting the gratings compressor, in order to enhance the temporal quality of the output. This adjustment has two main effects. First, the peak power is reduced if the gratings compressor is not adjusted to minimize pulse duration, which subsequently decreases the nonlinear phase in the nonlinear fiber (e.g. the rod-type fiber in our case). Second, we systematically found optimum pulse compression by overcompensating the second order spectral phase in the amplifier, leading to negatively chirped pulses at the input of the nonlinear compressor of typically about 30-50% increased input pulse duration. This leads to some spectral compression in the nonlinear fiber, which makes the final compressed pulse longer, but with a better quality for a given input pulse energy. In our setup, the spectral broadening of pulses is realized by a 5 cm long rod-type fiber of 80 µm core diameter. Excitation of the fundamental fiber mode was a result of careful coupling of the input beam into the rod. The mode field diameter of this fiber has been measured to be 70 µm (corresponding to a nonlinear parameter γ=5.1×10-5 $W^{-}1.m^{-1}$) and considerably reduces the accumulation of nonlinearities compared to conventional LMA fibers, thereby allowing the nonlinear compression of higher energy pulses. The linearly polarized and almost linearly chirped pulses at the output of the fiber could be well compressed by an SF10 glass prism pair compressor. The overall nonlinear compression setup has an efficiency of 50%, as a result of a 75% coupling efficiency into the rod fundamental mode and 70% transmission through the reduced optical quality, low transmission prisms and rooftop mirror available at that time.

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The best compromise between compressed pulse quality and compression ratio was found for pulse energies in the range 2-4 μJ. As the input energy was increased, we could accordingly adjust the grating compressor so that we could achieve better quality pulses at the expense of an increased pulsewidth compared to the one we could ideally have setting the gratings compressor to minimum input duration. The optimization process was based on the real time monitoring of the output pulse autocorrelation trace each time additionally verified by FROG measurements. The FROG traces, retrieved pulse intensities, and spectrum for 2 μJ and 4 μJ incident pulse energy in the rodtype fiber are shown in fig. 3. The observed spectral asymmetry can be attributed to the input spectrum asymmetry, third-order dispersion in the rod as well as self-steepening. The spectral phase is quite flat in both cases, showing that the overall accumulated phase throughout the whole system (nonlinear CPA stage, grating compressor, rod-type fiber, prism compressor) has been well compensated. At the output of the prism compressor, 51 fs and 49 fs pulses are obtained with energies of 1 μJ and 2 μJ respectively. In the case of 1 μJ output energy, the obtained temporal Strehl ratio is approaching the ideal, with a value of 0.97, while for the highest output energy, the pulse quality is still very good, with a temporal Strehl ratio of 0.86. In the latter case the pulse peak power is 41 MW.

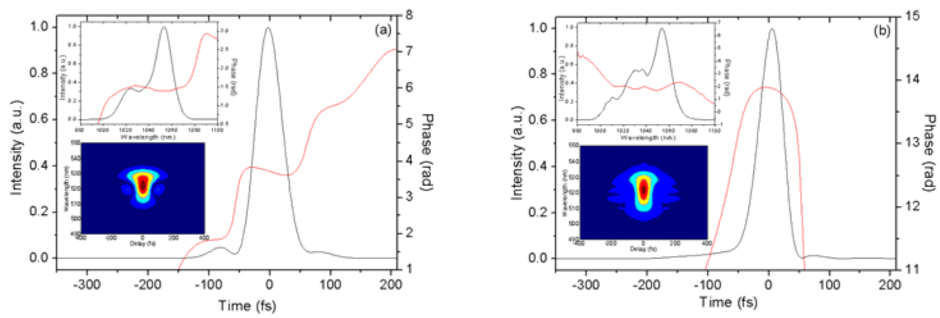

Fig. 3. FROG retrieved temporal and spectral (inset) intensities (black) and phase (red), at 2 μJ (left) and 4μJ (right) input energies.

To more concretely understand the impact of the intentionally induced negative chirp of the input pulses on the quality of the output compressed pulses, we run simulations of the nonlinear compression based on the split-step Fourier algorithm. As input pulses to the rod-type fiber we used the experimentally obtained FROG retrieved pulse intensities at the output of the YDFA. Then we varied the initial chirp of the pulses within a certain range, corresponding to few mm change of the distance between the compressor gratings around its optimal value (for optimized compression). Simulations verified that at the expense of some bandwidth loss (and therefore longer compressed pulses) an initial negative chirp of the order of -15000 fs^2 resulted indeed in the improvement of the output pulse quality. In fig.4 we show the result of such a simulation in the case of the 4 μJ pulse pulses from the YDFA (fig.2 down/left) for three values of initial chirp.

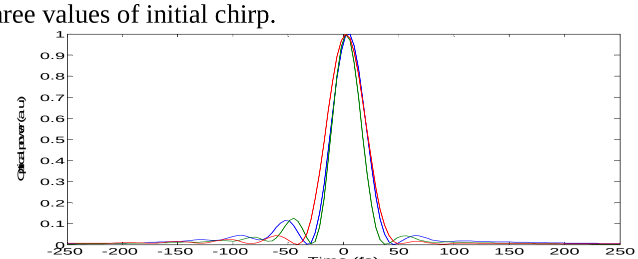

Fig. 4. Temporal profiles of the compressed pulses obtained by numerical simulations of the nonlinear compression in the 5 cm long rod-type fiber for initial chirp of: +15000 fs^2(green line), 0 fs^2 (blue line), -15000 fs^2 (red line).

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When higher energy pulses were injected in the rod-type fiber, we could not get a clean spatial beam profile at the output, probably because of self-focusing in the fiber. This, due to the small numerical aperture of the rod central core, resulted in the increase of the beam coupling into the microstructured pump core that severely degraded the output beam quality generating a spatial halo around the main central part of the beam. Indeed, the threshold for self focusing is about 4 MW corresponding to about 2 µJ pulses of 515 fs in the rod and therefore to the case of maximum input energy in our setup (if we roughly assume 75% coupling efficiency and 50% increase of the input pulse duration due to the overcompensation of second order dispersion). This phenomenon limits the achievable pulse energy with our setup.

4. Conclusion

In conclusion, we have generated 49 fs pulses at 200 kHz using, for the first time, nonlinear compression based on a 5-cm long rod-type photonic crystal fiber and a prism compressor. The guiding nature of the nonlinear medium allows us to avoid detrimental spatial effects, while the large mode effective area permits scaling the energy to the µJ range. The compressed pulses have an energy of 2 µJ and an effective peak power of 41 MW. The result was achieved using 300 fs pulses generated by an YDFA system. The obtained peak power already enables high-field physics experiments at a high repetition rate using a simple laser system.

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