Sub-nanojoule pulse compression down to 6 fs in photonic crystal fibers

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Abstract: A photonic crystal fiber with zero dispersion wavelength of 861 nm is used for pulse compression of sub-nanojoule laser pulses. Theory shows that sub-6 fs pulses can be generated using a 6 mm long fiber.

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1. Introduction

Pulse compression of optical pulses down to 5 fs has been demonstrated in a wide variety of experimental arrangements [1,2]. The common feature of previous studies in this time domain is that they require laser pulses at energy levels well above 10 nJ, i.e., pulse energies that are difficult to obtain directly from a femtosecond pulse laser oscillator. However, by utilizing novel small effective core area, single mode photonic crystal fibers (PCF) [3], tenfold pulse compression has been demonstrated in recent experiments [4,5] at nJ or sub-nJ optical energies with typical compressed pulse durations of 20 to 35 fs. In this paper we show that this latter technology can result in sub-nJ compressed optical pulses with time duration as short as 6 fs.

In our previous studies [4], we found that the compressed pulse duration was ultimately limited by the difference between the laser central wavelength (750 nm) and the zero dispersion wavelength (767 nm) of our PCF sample. By application of recently developed commercial PCF-s with red-shifted zero dispersion wavelengths, we demonstrate that it is possible to obtain sub-6 fs pulses at sub-nanojoule energy levels by optimization of input and output chirp parameters up to the third-order. Such input pulse energies with the required pulse durations can be easily obtained from low pump threshold, mode-locked Ti:sapphire laser oscillators pumped by a 532 nm pump laser with output power of as low as 1.3 W [6].

2. Modelling

We calculate the pulse propagation through PCF as a nonlinear Schrödinger type system [7]. In the simulations, the input pulse has a sech^2 temporal envelope function. During our calculations, dispersion data provided by the manufacturer (type "2.2 Nonlinear PCF" fiber, Crystal Fibre, Denmark [8]) is used. Since the dispersion data was not measured for the required broad spectral range necessary for our simulations, the dispersion function was approximated by a linear combination of two exponential terms:

$$D(\lambda) = a_1 \exp[b_1\lambda] + a_2 \exp[b_2\lambda] \tag{1}$$

where $a_1 = 7940.5139$. $a_2 = 75.5636$, $b_1 = -0.0055$ and $b_2 = -0.0001$. We must note that the generally used Sellmeier formulas could not be fitted to the provided data.

In agreement with previous studies, we found that the compression level strongly depends on the initial chirp of the pulse injected into the fiber: if we provide some linear chirp to the input pulse, the pulse duration becomes slightly longer, but it results in lower pulse shape distortion during propagation in the fiber, which distortion is caused by the strong third-order fiber dispersion. For optimization of the input/output chirp parameters (GDD_{in}, TOD_{in}, GDD_{out} and TOD_{out}) at a given fiber length and pulse parameters, we assume that the shortest compressed pulses correspond to the highest peak powers. One of the main results of our simulation is the following: if we apply 1 nJ, 12 fs input pulses with central wavelength of 760 nm, sub-6 fs pulses can be generated using a PCF with a length of 6 mm and by proper dispersion compensation (see Fig. 1, left). The corresponding optimization map (see

Fig. 1, right) shows the peak intensities of the compressed pulses as the function of pre-compression parameters (GDD_{in} and TOD_{in}), when an optimal compression is applied. The lightest areas show the highest peak powers that correspond to the shortest pulse durations.

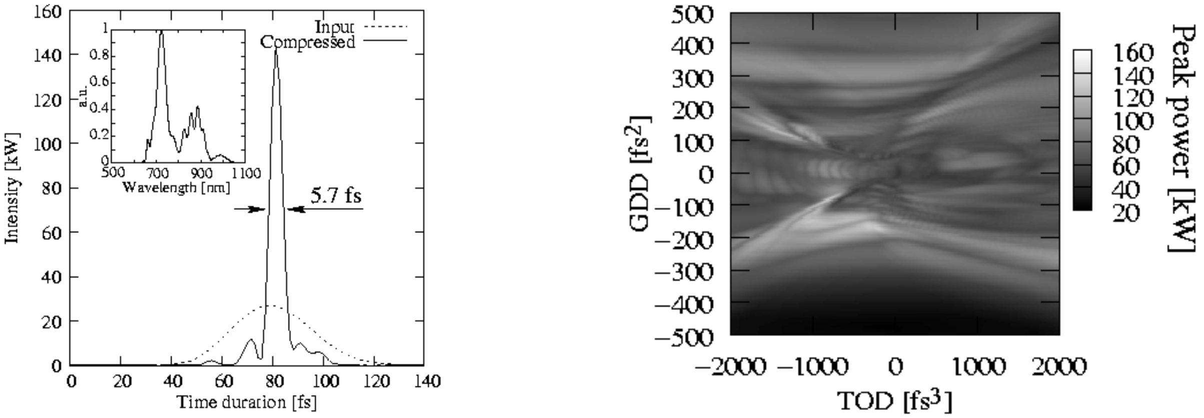

Fig. 1. Computer simulation results for pulse compression with a PCF: temporal input and compressed pulse shapes (left); output spectra (left, inset); optimization map (right).

3. Experiment

Because of practical issues, we could not fully provide the optimum experimental parameters we obtained from our simulations: our Ti:Sapphire laser oscillator (FemtoRose 20 MDC [6]) operated at 797 nm, and provided 24 fs $sech^2$ pulses at a repetition rate of 76 MHz. A PCF piece with a length of 22 mm was the shortest that could be cut with our fiber cutter. Accordingly, the input pulse energy had to be further reduced in order to get spectral shapes similar to that obtained with a 6 mm long PCF used in simulations.

The experimental setup is shown in Fig. 2. In order to provide optimal input chirp parameters, a pre-compressor was built comprising an SF10 prism pair and a pair of chirped mirrors. A Faraday isolator (FI) was also installed into the pre-compressor to avoid feedback to the laser from the fiber [4]. The positive dispersion introduced by the FI (GDD of ~2700 fs^2) had to be compensated as well during pre-compression. In this way, we could set the input chirp between 100 fs^2 and 400 fs^2. The pre-compressor provided an input TOD of -6000 fs^3.

At the fiber output, our compressor consisted of a fused silica prism pair providing an adjustable GDD of -400 fs^2 to -200 fs^2 and constant TOD of -2000 fs^3, which values are close to the optimal values.

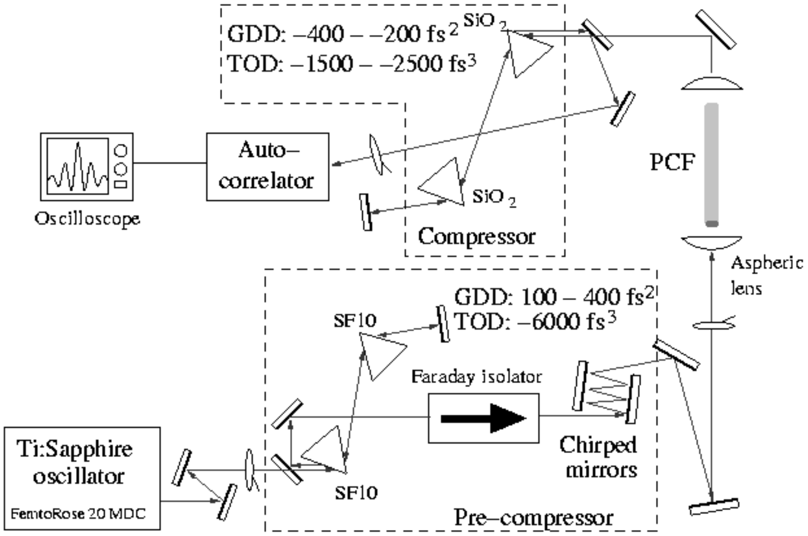

Fig. 2. The experimental setup.

In this way, we obtained twofold compression starting from 24 fs pulses with GDD_{in}=400 fs^2 and TOD_{in} = -6000 fs^3. The measured and computed autocorrelation traces are shown in Fig. 3 (left) and corresponding spectra are plotted in Fig. 3 (right). In the inset, the retrieved temporal pulse shape is shown with FWHM pulse duration of 12 fs.

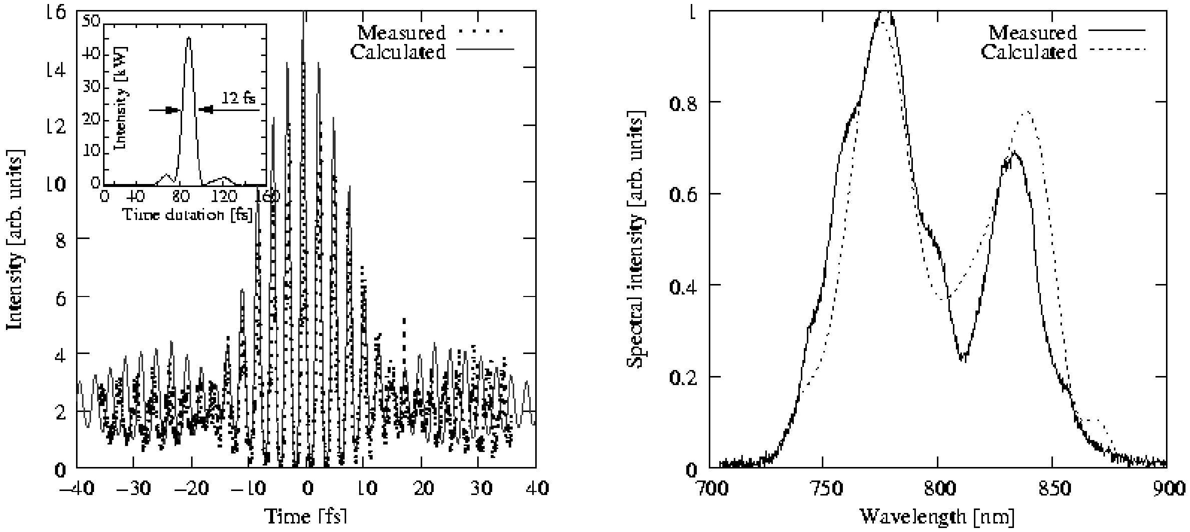

Fig. 3. Measured and computed autocorrelation traces (left) and the corresponding spectra (right). Input pulse parameters: 0.6 nJ, 24 fs. GDD_{in}= 400 fs^2 TOD_{in} = -6000 fs^3. Fiber length 22 mm. GDD_{out} - 320 fs^2 TOD_{out} -2000 fs^3.

In conclusion, we can say that using commercially available photonic crystal fibers and cost effective, low pump threshold ($P_{pump} \approx$ 1.2 W) Ti:sapphire lasers with sub-nanojoule pulse energies, it is feasible to generate compressed optical pulses in the sub-12-fs regime. Theory shows that by optimization of input and output chirp parameters, high quality, sub-6 fs pulses can be generated using a 6 mm long fiber piece. In our experiment, we obtained a twofold pulse compression resulting in 12 fs compressed pulses due to practical constrains on the experimental conditions. Further reduction of the compressed pulse duration at such energy levels seems to be feasible by application of new PCF-s with red-shifted zero-dispersion wavelengths and lower third-order dispersion values.

4. References

1. Baltuska, Z. Wei, M. S. Pshenichnikov, D.A. Wiersma and R. Szipőcs, “All-solid-state cavity-dumped sub-5-fs laser,“ Appl. Phys. B **65**, 175-188 (1997).
2. M. Nisoli, S. De Silvestri, O. Svelto, R. Szipőcs, K. Ferencz, C. Spielmann, S. Sartania and F. Krausz, “Compression of high-energy laser pulses below 5 fs,” Opt. Lett. **22**, 522-524 (1997).
3. J. C. Knight, T. A. Birks, P. St. J. Russel and D. M. Atkin, “All-silica single-mode optical fiber with photonic crystal cladding,” Opt. Lett. **21**, 1547-1549 (1996).
4. S. Lakó, J. Seres, P. Apai, J. Balázs, R. S. Windeler and R. Szipőcs, “Pulse compression of nanojoule pulses in the visible using microstructure optical fiber and dispersion compensation,” Appl. Phys. B **76**, 267-275 (2003).
5. G. McConnell and E. Riis, “Ultra-short pulse compression using photonic crystal fibre,” Appl. Phys. B **78**, 557-563 (2004).
6. www.fslasers.com
7. P. Agrawal, *Nonlinear-Fiber Optics*, (Academic Press, 2001).
8. www.crystalfiber.com