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Optimizing input and output chirps up to the third-order for sub-nanojoule, ultra-short pulse compression in small core area PCF

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ABSTRACT Compression of sub-nanojoule laser pulses using a commercially available photonic crystal fiber (PCF) with zero dispersion wavelength of 860 nm is discussed. A twofold pulse compression starting from 24 fs transform limited seed pulses around 800 nm is experimentally demonstrated as a verification of our simulations. Theory shows that by the optimization of input and output chirp parameters up to the third order, high quality, 5.7 fs pulses can be generated from a cost efficient experimental setup. Further calculations show that 1 ps pulses with central wavelength of 800 nm can be compressed down to 50 fs in the normal dispersion regime of the fiber with proper dispersion compensation. Calculations also show that dispersion flattened fibers can improve both the quality and the duration of compressed pulses.

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1 Introduction

Pulse compression of optical pulses down to 5 fs were demonstrated in a wide variety of experimental arrangements using standard single mode optical fiber (SMF) [1] or gas filled hollow core fiber as a nonlinear medium [2]. The common feature with previous studies in this time scale 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. As a result of recent development of small effective core area, single mode photonic crystal fibers (PCF), tenfold pulse compressions were demonstrated in a few experiments [3, 4] at nJ or sub-nJ optical pulse energies, which resulted in typical compressed pulse durations of 20 to 35 fs. Recently, the possibility of compressing supercontinuum generated in a 5 mm long microstructured fiber was also reported [5]. In this later experiment, 15 fs transform limited pulses obtained from a low repetition rate Ti:sapphire oscillator were compressed down to 5.5 fs using an adaptive compression technique based on spectral-phase interferometry for direct electric–field reconstruction (SPIDER).

In this paper, we show that it is possible to obtain compressed sub−6 fs pulses using nanojoule or sub-nanojoule seed pulses around 800 nm by utilizing only small core area PCF and prism pair/chirped mirror compressors. In a previous study [3], we have found that the compressed pulse duration was primarily limited by the maximum available wavelength difference between the laser central wavelength (750 nm) and the zero dispersion wavelength (767 nm) of the PCF sample. Novel PCFs with red-shifted zero dispersion wavelengths, however, can improve both the quality and the duration of the compressed pulses when we choose input and output chirp compensation parameters properly. It is worth pointing out that 1 nJ seed pulse energies with the required pulse durations can be obtained easily from low pump threshold, mode-locked Ti:sapphire laser oscillators pumped by only 1.2 W at 532 nm [6].

As a proof of our calculations, we describe our corresponding experiment with similar experimental conditions as the simulations had. We also extend our studies for compression of sub-nJ pulses with initial time duration at around 1 ps. Later, we discuss the possibility of building cost efficient, compact sub−100 fs laser sources by utilizing nonlinear spectral broadening and dispersion compensation. As a seed pulse, we consider low cost, compact ultrashort pulse laser diodes with transform limited pulse duration of around 1 ps [7, 8]. Their typical pulse energy is well below 1 nJ, which does not result in considerable spectral broadening in standard single mode-fibers. However, nonlinear spectral broadening (and possibly amplification) in doped [9] small core area PCFs allows the reduction of the pulse duration to the sub-100 fs regime. Previously, this time domain could only be achieved by more expensive solid-state lasers.

2 Theory

We calculate the pulse propagation through PCFs as a nonlinear Schrödinger type system [10]. The input pulses used in our simulation exhibit a sech^2 temporal intensity envelope function that is typical for femtosecond solid-state laser oscillators. We used dispersion data provided by the manufacturer (type “2.2 nonlinear PCF” fiber, crystal fibre, Denmark [11]) in our calculations. Since the dispersion was not

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available for the required broad spectral range necessary for our calculations, it was approximated by a Taylor-expansion:

$$D(\lambda) = D_0 + S(\lambda - \lambda_0) + \frac{T}{2}(\lambda - \lambda_0)^2 + \frac{F}{6}(\lambda - \lambda_0)^3 \,. \tag{1}$$

In (1), λ_0 is the reference wavelength chosen as the central wavelength of the seed pulse, D_0 is the dispersion at the central wavelength, S is the dispersion-slope, T is the third-order dispersion and F is the fourth-order dispersion having the corresponding values of $D_0 = -27.15 \times 10^{-6}\,\mathrm{s/m^2}$, $S = 0.51772 \times 10^3\,\mathrm{s/m^3}$, $T = -3.277854 \times 10^9\,\mathrm{s/m^4}$, $F = 1.642713 \times 10^{16}\,\mathrm{s/m^5}$, respectively.

We found that the compression level strongly depends on the initial chirp of the pulse injected into the fiber for transform limited pulse durations in the sub-100 fs regime. This is in agreement with our previous studies [3, 12]. Providing a small 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 (the distortion is caused by the strong third-order dispersion of the PCF). However, the required linear pre-chirp may result in less efficient spectral broadening during propagation. One may control the spectral broadening at a certain energy level in this way, and avoid frequency components that may harm the quality of the compressed pulse.

In our calculations, the following expression was used for describing the pre-chirp of the laser pulse seeding the PCF sample:

$$A_{\text{chirped}}(0, T) = \mathcal{F}^{-1}\left(\exp\left(\mathrm{i}\phi_2^{\text{in}}\omega^2 + \mathrm{i}\phi_3^{\text{in}}\omega^3\right)\mathcal{F}\left\{A(0, T)\right\}\right) \,, \tag{2}$$

where $\mathcal{F}$ stands for Fourier transformation, $A(z, T)$ is the complex envelope function of the seed pulse with no chirp (where z is the space coordinate in the propagation direction and T is the retarded time), ω is the angular frequency and φ_2^{in} and φ_3^{in} are the second- and third-order pre-chirp parameters (group-delay dispersion (GDD) and third-order dispersion (TOD)), respectively.

Compression after the fiber sample is described in the same way for the complex envelope function using output chirp parameters φ_2^{out}, φ_3^{out}.

3 Experiment

Our Ti:sapphire laser oscillator (FemtoRose 20 MDC [13]) operated at 797 nm, and delivered 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 cleaver, although the optimal length predicted by our simulation was shorter (see Sect. 4.1 below). Accordingly, the input pulse energy had to be further reduced in order to get spectral shapes similar to what can be obtained with a 6 mm long PCF used in our simulations.

The experimental setup is shown in Fig. 1. In order to provide the optimal pre-chirp parameters, a pre-compressor was built comprising of an SF10 prism pair and a pair of chirped mirrors. A Faraday isolator (FI) was also installed into the pre-compressor to avoid feedback from the fiber [3]. The positive dispersion introduced by the FI (GDD of 2700 fs^2) had to be compensated as well during pre-compression. We could set the pre-chirp between 100 fs^2 and 400 fs^2 in this way. The pre-compressor provided an input TOD of approximately $-6000\,\mathrm{fs}^3$.

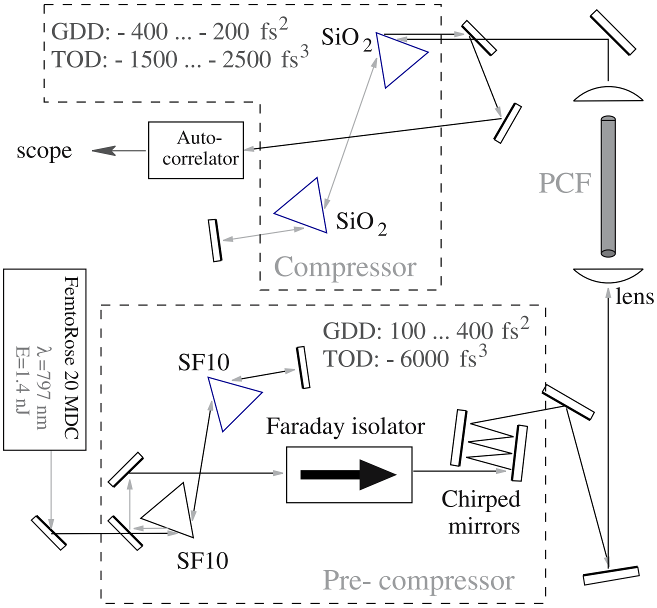

FIGURE 1 Experimental setup. An SF10 prism pair in combination with chirped mirrors are used for pre-compression of a 24 fs pulse with central wavelength of 797 nm. The spectrally broadened pulse exiting the PCF is compressed by a fused silica pair/chirped mirror compressor resulting in a two-fold temporal compression

We obtained twofold compression starting from 24 fs pulses with $\varphi_2^{\text{in}} = 400\,\mathrm{fs}^2$ and $\varphi_3^{\text{in}} = -6000\,\mathrm{fs}^3$. The measured and computed autocorrelation traces are shown in Fig. 2 and the corresponding spectra are plotted in Fig. 2. In the inset, the retrieved temporal pulse shape is shown with FWHM pulse duration of 12 fs.

We note that in order to fit our simulations to the measured experimental data, we had to increase the effective core area of the PCF in our model: it had to be doubled to the new value of around 10 $\mu\mathrm{m}^2$. It might have been partially caused by improper orientation of the PCF sample (see [3]). An additional practical problem originated from the use of the Faraday-isolator that had to be placed in front of the PCF: its relatively high dispersion had to be compensated by an SF10 prism pair which limited the bandwidth and hence the transform limited pulse duration of the seed pulse at around 25 fs.

Because of the relatively good agreement between the experiment described and our corresponding simulations, we continue our investigations with numerical modeling in the following section. The same fiber parameters and different input pulse durations and chirp parameters are used for our investigations in the simulations.

4 Modeling

4.1 *Optimization*

For the optimization of the input chirp parameters φ_2^{in}, φ_3^{in} and compression parameters φ_2^{out}, φ_3^{out} at a given fiber length, input pulse energy and pulse duration, we assumed that the shortest compressed pulse exhibits the highest peak

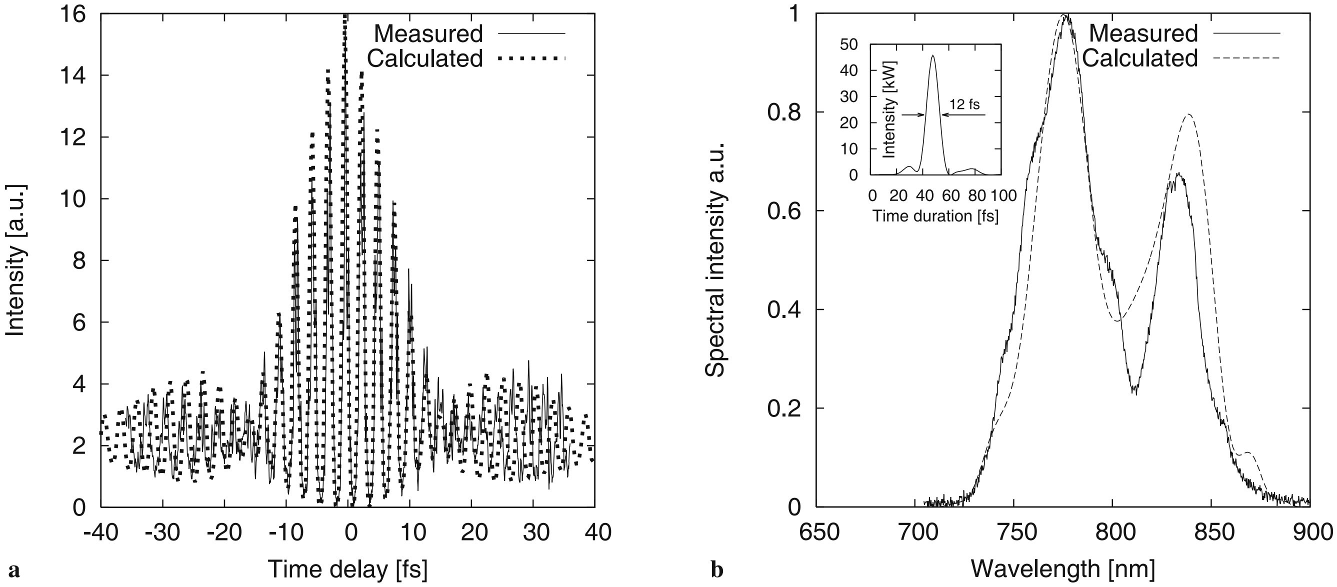

FIGURE 2 Measured and computed autocorrelation traces and the corresponding spectra. Input pulse parameters: 0.6 nJ, 24 fs. $\varphi_2^{\text{in}} = 400\ \text{fs}^2$ $\varphi_3^{\text{in}} = -6000\ \text{fs}^3$. Fiber length 22 mm. $\varphi_2^{\text{out}} = -320\ \text{fs}^2$ $\varphi_3^{\text{out}} = -2000\ \text{fs}^3$. Inset: retrieved compressed pulse shape

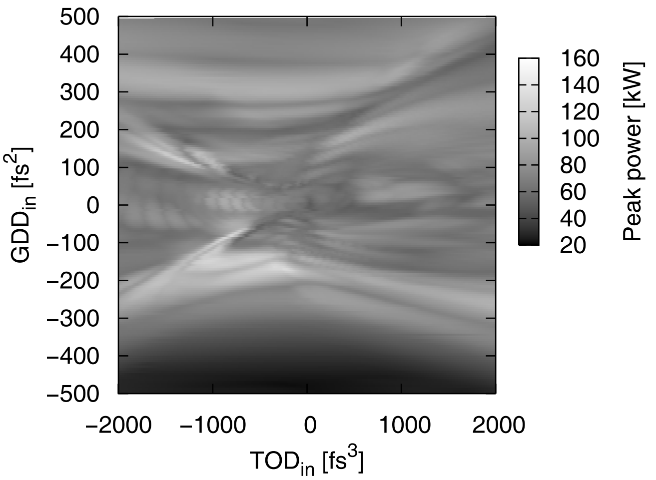

FIGURE 3 Peak intensity of 1 nJ optimally compressed pulses as a function of input GDD and TOD. The result corresponds to a small core area PCF with zero dispersion wavelength of 860 nm. The seeding laser pulse has a central wavelength of 760 nm and a transform limited FWHM pulse duration of 12 fs

power. This assumption was used in a brute-force optimization method to find the best second- and third-order input and output GDD and TOD parameters of a sech^2 input pulse through a given range of the chirp parameters. Fig. 3 shows the peak intensity of the compressed pulse as a function of input GDD and TOD after providing the best compression parameters for each calculated point.

In our calculations, the length, nonlinear refractive index and effective core area of the fiber were respectively chosen as 6 mm, $2.5 \cdot 10^{-20}\ \text{m}^2/\ \text{W}$ and $2.5\ \mu\text{m}^2$. The seeding laser pulse has a central wavelength of 760 nm, pulse energy of 1 nJ that corresponds to 76 mW average output power at a repetition rate of 76 MHz. The full width at half maximum (FWHM) pulse duration was chosen to be 12 fs. Such pulse durations can be obtained from a mirror-dispersion controlled Ti:sapphire oscillator, see Ref. [6]. We must note that the pulse parameters used in the presented optimization process corresponding to Fig. 3 and 4 are slightly different from our experimental conditions. The effective core area is the same used in [3].

According to the optimization map (see Fig. 3), the shortest compressed pulses can be generated at around $-200\ \text{fs}^2$ input GDD and $-200\ \text{fs}^3$ input TOD. The best compression values that correspond to this peak are $\varphi_2^{\text{out}} = -100\ \text{fs}^2$ and $\varphi_3^{\text{out}} = -350 - 400\ \text{fs}^3$. The corresponding computed temporal and spectral intensity distributions are shown in Fig. 4a. The compressed pulse that belongs to the light spot around $\varphi_2^{\text{in}} = 140\ \text{fs}^2$ and $\varphi_3^{\text{in}} = -1530\ \text{fs}^3$ is shown in Fig. 4b. In this latter case, the compressed pulse width is quite short (4.7 fs), but the quality of the pulse is worse than that of the compressed laser pulse shown in Fig. 4(a). The reason for this is that the spectrum displayed in Fig. 4b extends well above the zero dispersion wavelength (860 nm) into the anomalous dispersion region of our PCF sample. This part of the spectrum cannot be compressed properly, which results in a pedestal and satellite pulses of the compressed pulse. The obvious asymmetric spectral broadening both in Fig. 4(a) and Fig. 4(b) is caused by the considerable third-order dispersion of our PCF around 800 nm.

4.2 *Compression of longer pulses*

In the following, we present some attractive features of pulse compression using small core area PCFs with the same parameters described in Sect. 3. We performed a number of calculations using different input pulse widths, and we searched for the shortest compressed pulse durations as described in the previous section. We started our investigation with 1 ps pulses that can be obtained from ultrafast laser diodes. Then we used shorter and shorter pulses which could be related to different types of fs pulse solid-state laser oscillators. The compression results are summarized in Table 1 and Fig. 5.

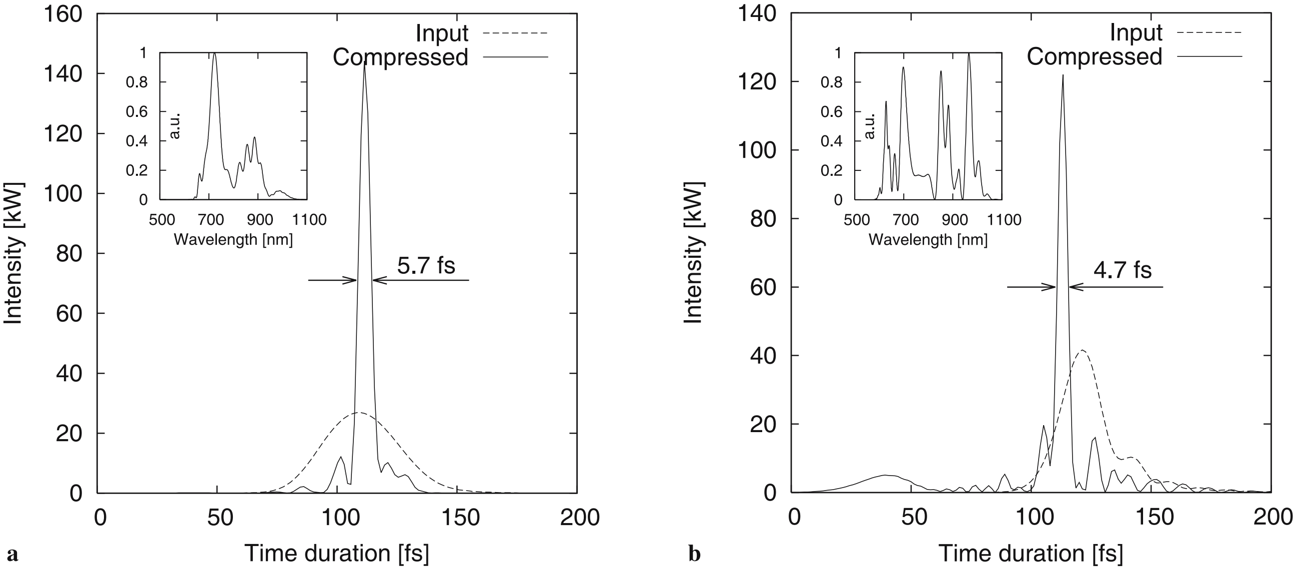

FIGURE 4 Computed temporal and spectral intensity distributions corresponding to two data points depicted from Fig. 3. $\varphi_2^{\text{in}} = -170\,\text{fs}^2$, $\varphi_3^{\text{in}} = -220\,\text{fs}^3$ with $\varphi_2^{\text{out}} = -110\,\text{fs}^2$ and $\varphi_3^{\text{out}} = -340\text{-fs}^3$ compensation **b** $\varphi_2^{\text{in}} = 140\,\text{fs}^2$, $\varphi_3^{\text{in}} = -1530\,\text{fs}^3$ and $\varphi_2^{\text{out}} = -100\,\text{fs}^2$, $\varphi_3^{\text{out}} = -300\,\text{fs}^3$. An input pulse with transform limited pulse duration of 12 fs is used in the calculations (dotted-line is a pre-chirped pulse at the fiber input)

FWHM_{in}[fs]	L [m]	ϕ_2^{in} [fs^2]	ϕ_2^{in} [fs^2]	ϕ_2^{in} [fs^2]	ϕ_2^{in} [fs^2]	FWHM_{out} [fs]	QF [%]
1000	1.000	0	0	−18 600	−170 000	61.1	74.7
1000	1.100	0	0	−19 200	−200 000	57.9	76.3
1000	1.200	0	0	−19 700	−195 000	55.2	77.6
1000	1.300	0	0	−20 300	−220 000	53.2	79.4
1000	1.400	0	0	−21 000	−245 000	51.6	80.8
1000	1.500	0	0	−21 700	−245 000	49.9	81.4
1000	1.600	0	0	−22 400	−265 000	48.8	82.2
500	0.450	0	0	−7100	−75 000	36.2	80.1
500	0.500	0	0	−7500	−80 000	33.8	80.2
500	0.550	0	0	−7800	−85 000	31.6	78.7
500	0.600	0	0	−8200	−91 000	29.6	72.9
250	0.14	0	0	−2400	−21 000	25.2	78.3
250	0.14	0	−300 000	−2450	−21 500	24.5	78.1
250	0.16	0	0	−2500	−22 500	22.1	73.5
250	0.16	−2000	−300 000	−2500	−22 000	21.6	72.1
100	0.030	100	−4000	−600	−3800	15.2	77.0
100	0.035	640	−3600	−610	−4100	14.0	72.6
100	0.040	1430	−2600	−700	−4550	14.2	75.7
100	0.040	−1100	−3800	−660	−4300	13.8	72.9
100	0.040	−1400	−2400	−700	−4500	15.3	79.8
100	0.042	−1400	−3000	−700	−4500	14.3	76.0
50	0.009	40	−3000	−200	−1000	11.8	80.5
50	0.010	40	−2800	−200	−1050	10.8	77.6
50	0.011	90	−2050	−200	−1090	10.1	74.4
25	0.005	200	−140	−120	−520	8.8	88.8
25	0.005	120	−200	−90	−440	7.1	77.3
12	0.004	−80	−170	−60	−250	6.4	88.5
12	0.005	−100	−200	−70	−290	6.6	88.2
12	0.005	−90	−200	−60	−290	6.0	78.4

TABLE 1 Pulse compression in PCF with zero dispersion wavelength of 860 nm computed for 1 nJ seed pulses of different transform limited pulse durations with a central wavelength of 797 nm and for different fiber lengths. The optimal pre-chirp, compression parameters and the quality factors are listed along with the shortest compressed pulse durations

Here, we define the quality factor of a compressed laser pulse as the ratio of the energy in the main peak and the total energy of the pulse taking on values between 0–1:

$$QF = \frac{\int_a^b |A(z,T)|^2 \,\mathrm{d}T}{\int_{-\infty}^{\infty} |A(z,T)|^2 \,\mathrm{d}T} \tag{3}$$

In (3), the numerator is computed as a temporal integral of the intensity function between time a and b corresponding to the two local intensity minima around the main peak. The quality factors calculated for the different compression and pulse parameters are listed in Table 1.

We found that 1 ps, 1 nJ pulses can be compressed to 50 fs resulting in a 20 fold compression ratio (see Table 1).

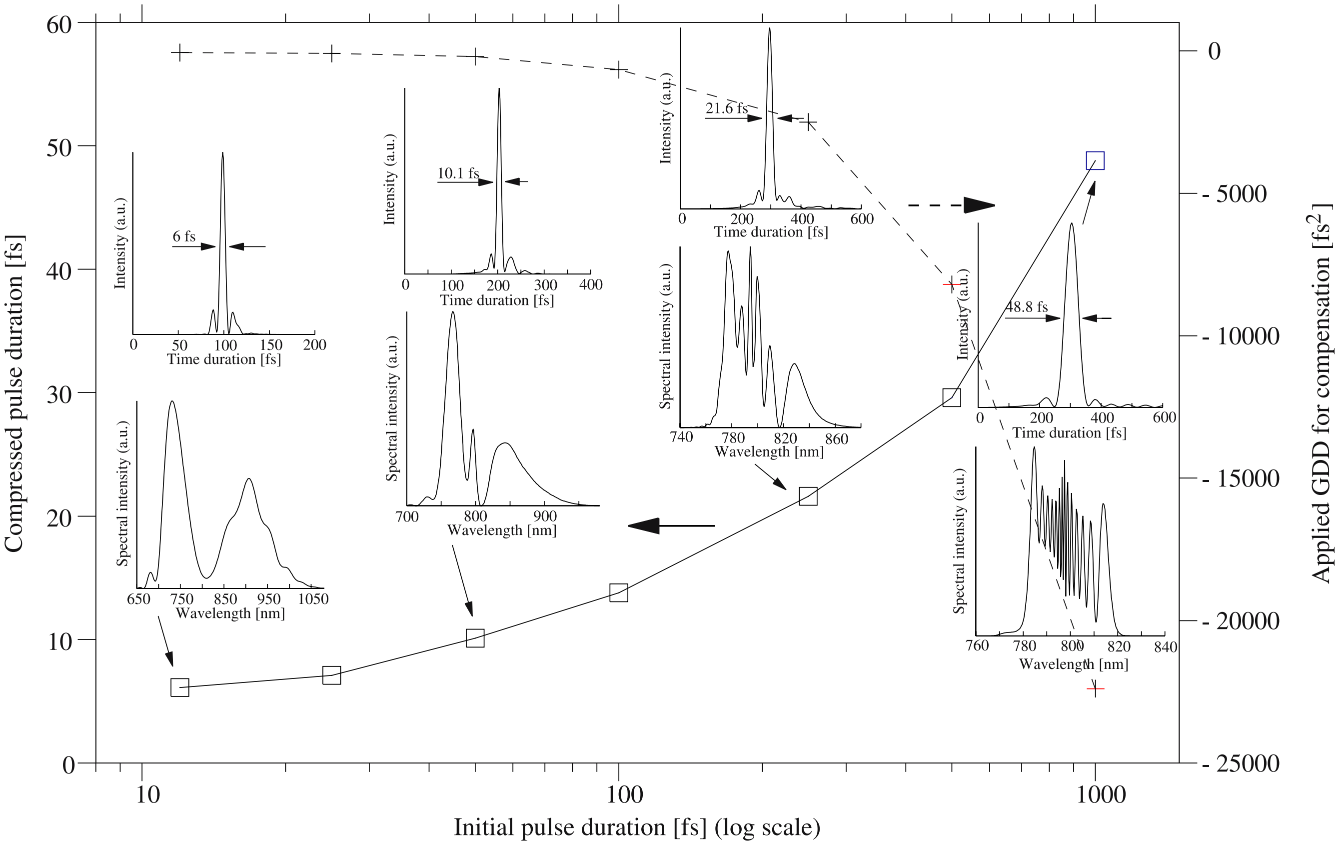

FIGURE 5 Compressed pulse width and applied GDD for the best compression as a function of initial pulse duration. We plotted also the temporal and spectral shape of some results. Strong asymmetric spectral broadening is also presented due to the higher order dispersions in the relatively wide spectral ranges

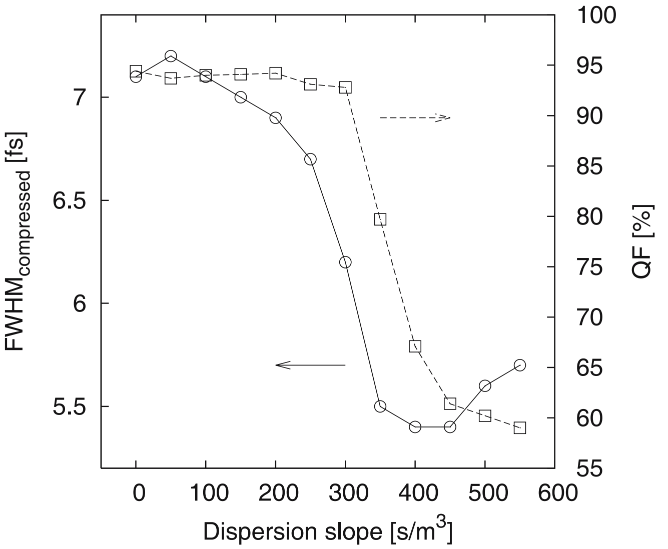

FIGURE 6 Compressed shortest pulse duration and the quality factor of the pulse as a function of dispersion slope

We note that a similar compression was experimentally demonstrated at around 1550 nm using soliton compression in a dispersion flattened fiber [14]: a 965 m long polarization maintaining single mode fiber was used and 54 fs pulses were obtained after the propagation along the slow axis with 71 mW input power at a repetition rate of 10 GHz.

In the case of our PCF sample, the compression ratio and the quality factor are strongly limited by third-order dispersion in the fiber. Although the PCF that we used in our simulations has much higher third-order dispersion at around 800 nm than the dispersion flattened fiber at 1550 nm, our simulation shows that it is still possible to obtain 50 fs compressed pulses.

We note that no pre-chirp was needed for the pulses with transform limited time durations between 100 fs and 1 ps, as it had no measurable effect on the spectral broadening process in the fiber. For instance, we tried to optimize pre-chirp for 250 fs seed pulses, but only extremely large negative TOD resulted in slight reduction of the final compressed pulse duration. Short seed pulses with time durations below 100 fs, however, suffer irreversible distortions during propagation due to higher-order dispersion. Therefore we have to use some linear pre-chirp to stretch the seed pulse slightly. We note that for shorter seed pulses, we need higher optimal relative temporal stretching ($\tau_{\text{streched}}/\tau_0$). During optimization we also aimed for minimum necessary pre-chirp.

One can observe in Table 1 that high compression ratios can be obtained for considerably different linear and higher order pre-chirp parameters (see, for instance, the different parameters for 100 fs seed pulses resulting in compressed pulse durations in the 13.8–15.3 fs range). These results are similar to the calculations presented in Fig. 5. Having a 100 fs seed pulse the shortest compressed pulse is 13.8 fs long, which is slightly longer than what was presented in [3] (13 fs). Shorter pulses can be generated only at the expense of quality (like in Fig. 4 a and b).

We note that the presented results may vary slightly with the inclusion of Raman nonlinearity because the used fiber parameters provide a threshold for Raman shift just around the magnitude of pulse peak powers (800–900 W for 1 ps, 1400–1600 W at 500 fs; simulations for shorter pulses are well below the Raman threshold).

4.3 *Compression with dispersion flattened PCFs*

Our PCF sample had large higher-order dispersion contribution to the pulse evaluation which limited the usable length of the fiber because of the irreversible pulse shape distortions. This also limits spectral broadening obtained by SPM on a shorter fiber length.

This harmful effect can be avoided using such PCFs in that the waveguide dispersion is suited by mature structural modifications [15]. This can result flat total dispersion of the waveguide and improve the quality of pulse compression significantly.

We present calculations here using the same parameter set done in Sect. 3. An unchirped ($\varphi_2^{\text{in}} = 0$ fs^2, $\varphi_3^{\text{in}} = 0$ fs^3) 24 fs input pulse with 1 nJ is lunched in a 6 mm length PCF whose dispersion is characterized by (1). Nonlinear refractive index and effective core area are $2.5 \cdot 10^{-20}$ m^2/W and 5 µm^2, respectively. We only changed the dispersion slope parameter (S) characterizing the fiber dispersion and searched for the optimum compression parameters (φ_2^{out} and φ_3^{out}) after the propagation. Results are summarized in Fig. 6.

After a certain dispersion slope value, pulses can not be compressed in a good quality anymore. Although the main peak could be quite short, less than 6 fs actually, but 30%–40% of pulse energy is outside of the main peak. This is the case when pre-chirp is required in order to broaden the pulse not to suffer unwanted, irreversible distortions caused by higher-order dispersions. This limits, however, the spectral broadening.

Summarizing our simulations, we can conclude that using a PCF with zero dispersion wavelength of 860 nm and dispersion properties described by (1) 20 fold pulse compression can be obtained in case of 1 nJ input pulses with time duration of 1 ps. Additionally, starting from 12 fs transform limited seed pulses, which can be obtained from a relatively low cost fs pulse Ti:sapphire laser, 6 fs compressed pulses can be generated. By the reduction of the higher-order dispersion in a small core-area fiber, high quality ($\geq 94\%$) 6–7 fs pulses can be generated starting from 24 fs transform limited pulse duration which means a four fold compression in this region.

5 Conclusion

In conclusion, we can say that using commercially available photonic crystal fibers and cost effective, low pump threshold ($P_{\text{pump}} \approx 1.2$ 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 an non-dynamic compression technique. 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 PCFs with red-shifted zero-dispersion wavelengths and lower third-order dispersion values.

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