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Optimised one-step compression of femtosecond fibre laser soliton pulses around 1550 nm to below 30 fs in highly nonlinear fibre

B. Kibler, R. Fischer, P.-A. Lacourt, F. Courvoisier, R. Ferriere, L. Larger, D.N. Neshev and J.M. Dudley

Optimised compression of femtosecond fibre laser pulses in highly nonlinear fibre is demonstrated. Specifically reported are compressed pulse durations below 30 fs using a simple setup where a single sub-10 cm segment of highly nonlinear fibre is directly spliced to the output pigtail of a commercial femtosecond fibre laser. The compressed pulse quality is confirmed through frequency resolved optical gating measurements.

Introduction: Motivated by diverse applications in spectroscopy, frequency metrology and telecommunications, the development of all fibre-format sources of sub-30 fs pulses around 1550 nm is a subject of much current interest [1]. A number of different techniques for pulse generation in this regime have been reported in recent years, with particularly impressive results being obtained using hybrid soliton-like compression of a primary fibre laser source using multiple segments of photonic crystal and/or dispersion-shifted fibres with differing dispersion values and dispersion slopes [2–4]. Despite the additional control afforded by such complex compression, however, there are nonetheless disadvantages in (i) the need for sometimes difficult-to-obtain non-standard fibre and (ii) the necessity to optimise the lengths and placements of different fibre types. In this Letter, however, we show that high quality nonlinear compressed pulses can be obtained using only one sub-10 cm length of readily-available highly nonlinear fibre (HNLF) directly spliced to the output singlemode fibre pigtail of a commercial femtosecond fibre laser. Frequency resolved optical gating (FROG) confirms that nonlinear soliton compression results in the generation of pulses in the sub-30 fs regime, and this represents an extremely simple experimental modification resulting in a threefold reduction in pulse duration relative to the primary source. An important feature of our setup is the optimisation of the compression through numerical modelling using initial conditions based on FROG measurements of the pulses prior to injection in the HNLF [5].

Results and discussion: The primary pulse source used in our experiments was a passively-modelocked oscillator/amplifier fibre laser system (Precision Photonics PPL) producing nominally 100 fs pulses at 1560 nm with a 35 MHz repetition rate. FROG measurements were used to study compression of these pulses using a multi-segment approach [4], but we found that excellent results could also be obtained using the simple setup shown in Fig. 1 where only one segment of HNLF was directly spliced to a standard SMF-28 pigtail. Fig. 1 also shows the points at which FROG characterisation was performed at the output of the pigtail and the HNLF. Our FROG setup was similar to that described in [5].

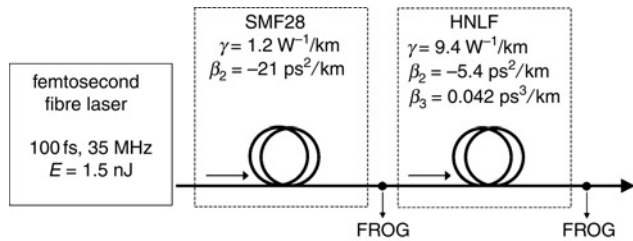


Fig. 1 Experimental setup

Our first experiments studied compression with the source configured to generate output pulses corresponding to near-fundamental solitons for SMF-28 fibre (nonlinearity and dispersion $\gamma = 1.2 \text{ W}^{-1} \text{ km}^{-1}$ and $\beta_2 = -21 \text{ ps}^2 \text{ km}^{-1}$, respectively) so that a standard fibre pigtail could be conveniently used for pulse delivery with minimal distortion over distances of several metres. Specifically, Figs. 2a and b show the spectrum and retrieved intensity and phase from the FROG measurements of the pulses at the output of a 1 m pigtail. (Note that the narrowband peak at 980 nm in the spectrum is residual pump radiation

from the fibre laser source.) From the retrieved temporal pulse characteristics, we obtain a pulse duration (FWHM) of 89 fs and average power of 30 mW (peak power 9.6 kW), yielding a soliton order of $N \approx 1.1$. Although there is some low amplitude structure outside the central lobe, the solitonic nature of the pulse is reflected by the uniform phase across the pulse centre.

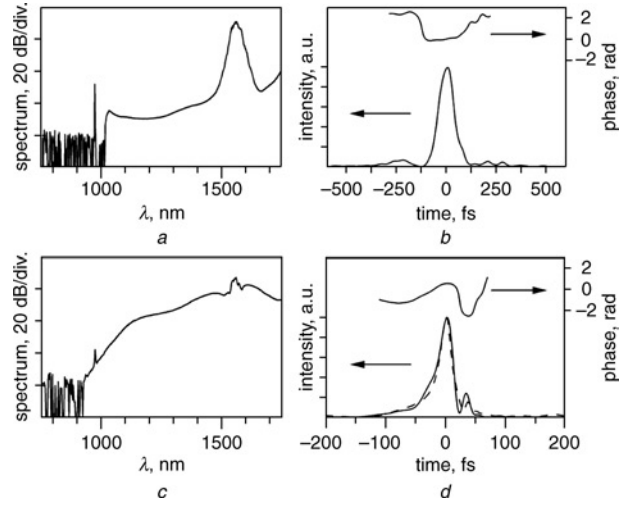


Fig. 2 Spectrum (Fig. 2a) and intensity and phase (Fig. 2b) from FROG measurements (solid lines) at SMF-28 fibre pigtail output for 30 mW average power; and corresponding pulse characteristics after 7 cm propagation in HNLF (Fig. 2c, d). (Dashed line in Fig. 2d shows predicted intensity profile from simulations)

Nonlinear compression of these pulses was carried out using speciality HNLF (OFS Denmark) with nonlinearity $\gamma = 9.4 \text{ W}^{-1} \text{ km}^{-1}$ and zero dispersion wavelength around 1410 nm. At the 1560 nm pump wavelength, the group velocity dispersion was $\beta_2 = -5.4 \text{ ps}^2 \text{ km}^{-1}$ and the HNLF had reduced dispersion slope of $\beta_3 = 4.2 \times 10^{-2} \text{ ps}^3 \text{ km}^{-1}$. The anomalous dispersion HNLF was spliced directly to the fibre pigtail with coupling losses of $< 0.2 \text{ dB}$ and the optimal length of HNLF was determined through numerical simulations of the soliton compression process using the measured input pulse intensity and chirp as the initial conditions [4]. The 89 fs pulses at the SMF-28 output excite a soliton of order $N \approx 6$ in the HNLF, and propagation in 7 cm of HNLF was found to yield significant compression. The measured and retrieved FROG traces of these compressed pulses are shown in Figs. 3a and b, respectively, with very good visual agreement and a low FROG retrieval error of $G = 5 \times 10^{-3}$ [5]. The corresponding spectral and temporal characteristics are shown in Figs. 2c and d, and the intensity FWHM of the compressed pulse is 28 fs. The accuracy of the numerical modelling in predicting the expected temporal intensity characteristics is seen from the good agreement between the experimental results (solid line) and those expected from simulations (dashed line).

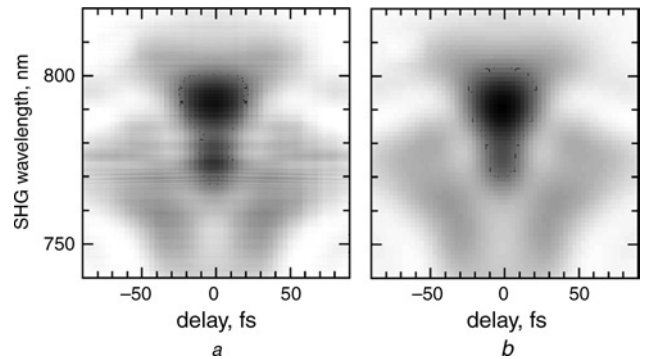


Fig. 3 Experimental (Fig. 3a) and retrieved (Fig. 3b) FROG traces obtained for 28 fs compressed pulses

Nonlinear compression in HNLF was also investigated with the primary fibre laser configured to generate a higher average output power of 50 mW. For this case, the spectral and temporal characteristics of the pulses at the SMF-28 pigtail output are shown in Figs. 4a and b,

respectively, with a pulse temporal FWHM of 98 fs (15 kW peak power). Although at this higher power level these pulses are no longer ideal solitons, the use of numerical simulations based on the retrieved intensity and chirp of these pulses still allows accurate choice of HNLF length for pulse compression. Specifically, at these power levels the (approximate) soliton order in the HNLF is $N \approx 10$, and simulations indicate that only 4.5 cm of HNLF spliced to the SMF-28 pigtail minimises the duration of the nonlinearly compressed pulses to below 25 fs. Note that the increased compression factor and the need for a shorter length of HNLF with a higher input soliton number is consistent with well-known scaling conditions describing soliton compression [6, 7]. The experimental spectral and temporal characteristics (from FROG measurements) of the compressed pulses under these conditions are shown in Figs. 4c and d, respectively, and the temporal intensity FWHM is 22 fs. The dashed line in Fig. 4d shows the expected output compressed pulse profile to verify the accuracy of the numerical modelling and optimisation of the soliton compression process. Although the pulse exhibits increased temporal sub-structure, the central lobe attains a peak power of 52 kW, and the compressed temporal duration of 22 fs corresponds to approximately four optical cycles under the central FWHM.

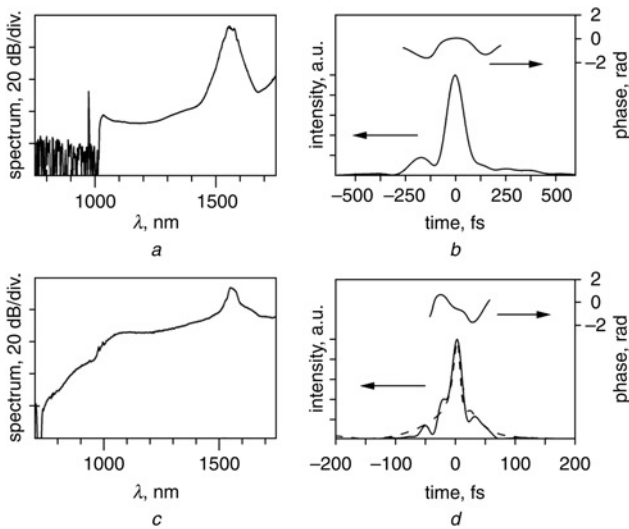


Fig. 4 Spectrum (Fig. 4a) and intensity and phase (Fig. 4b) from FROG measurements (solid lines) at SMF-28 fibre pigtail output for 50 mW average power; and corresponding pulse characteristics after 7 cm propagation in HNLF (Fig. 4c, d). (Dashed line in Fig. 4d shows predicted intensity profile from simulations)

Conclusions: In conclusion, these results report a simple means of exploiting soliton effect compression to generate sub-30 fs pulses in

an all-fibre format using only a commercially-available source and HNLF segment. The use of FROG characterisation allows the HNLF length to be precisely optimised to minimise the compressed pulse duration, avoiding unnecessary trial and error. Numerical simulations indicate that shorter pulses approaching 15 fs duration should be obtainable with reduced HNLF dispersion slope. (Note: the use of commercial product names here is for technical completeness, and does not imply endorsement on the part of the authors).

B. Kibler, P.-A. Lacourt, F. Courvoisier, R. Ferriere, L. Larger and J.M. Dudley (*Département d'Optique P.M. Duffieux, Institut FEMTO-ST, CNRS UMR 6174, Université de Franche-Comté, 25030 Besançon, France*)

E-mail: john.dudley@univ-fcomte.fr

R. Fischer and D.N. Neshev (*Nonlinear Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, 0200 ACT, Canberra, Australia*)

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