Real-time measurement of long parabolic optical similaritons

K. Hammani, C. Finot, S. Pitois, J. Fatome and G. Millot

Long optical similaritons using a Raman fibre amplifier are generated. These pulses, with a highly parabolic profile, are monitored in real time on a high speed oscilloscope. Tunability of both the temporal and spectral widths of the pulses is then investigated.

Introduction: Since their first experimental demonstration in 2000 [1], parabolic similaritons have stimulated a growing interest in the field of fibre amplification of high-power ultrashort pulses. This new type of optical pulse is asymptotically generated in an amplifier as the result of the combined interaction of normal dispersion, Kerr nonlinearity and gain. The pulse can then experience temporal and spectral self-similar dynamics and can evolve without suffering from the deleterious effects of optical wave-breaking which usually deteriorates the pulse shape propagating in the normal dispersion regime [2].

Experimental demonstrations have been carried out both in rare-earth-doped fibres (with ytterbium [1] and erbium [2] dopants) as well as in Raman fibre amplifiers [3]. The use of the frequency resolved optical gating (FROG) technique based on iterative algorithms has enabled a precise but indirect intensity and phase characterisation of the amplified pulses which exhibit a parabolic intensity profile combined with a strictly linear chirp. Parabolic pulse durations ranging from 500 fs to 50 ps have then been demonstrated.

In this Letter, we generate and characterise long (> 200 ps) parabolic pulses. To this aim, the use of distributed Raman amplification is particularly well suited to adiabatically reshape initial picosecond pulses into the targeted parabolic profile. Thanks to a 50 GHz high-speed oscilloscope coupled with an optical spectrum analyser, we have for the first time monitored in real time the parabolic pulse shape. We have also checked that the pulse duration and spectral width can be easily tuned over a wide range by simply adjusting the gain and the initial pulse energy.

Experimental setup: The all-fibred experimental setup is sketched in Fig. 1 and relies only on telecommunication-ready devices. Initial pulses are delivered by an erbium fibre laser working at a repetition rate of 22 MHz. The pulses are transform-limited with a temporal duration of 12 ps and a central wavelength of 1550 nm. They are amplified in a 15 km Raman amplifier based on a dispersion compensating fibre (normal dispersion $\beta_2 = 16.6 \times 10^{-3}$ ps^2/m and nonlinear coefficient $\gamma = 4$/W/km). The amplifier is pumped by a continuous fibre laser with an output power up to 1 W. A counter-propagative pumping scheme is used to avoid deleterious temporal depletion effects [4]. This also prevents detrimental noise transfer from the pump to the signal so that the amplified pulse train exhibits very low amplitude and timing jitters as can be seen experimentally (insets Fig. 1) on a high-speed oscilloscope (50 GHz optical bandwidth). Output pulse spectra are also recorded.

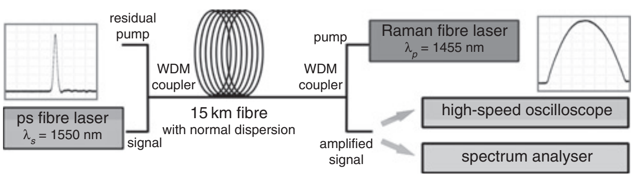

Fig. 1 *Experimental setup*

Insets: Oscilloscope records of initial and amplified pulses (persistence mode)

Experimental results: Experimental results are summarised in Fig. 2 for a small signal gain of 28 dB (1 W pump) and for two values of the input pulse energy E_{ini} (7.3 pJ, solid black line and 0.6 pJ, solid grey line). Experimental properties of input pulses are plotted in the black dashed line. The output intensity profile directly recorded by our high-speed photodiode (Fig. 2*a*) clearly illustrates the excellent agreement between the pulse shape (solid black line) and a parabolic fit (circles). From Fig. 2*a*, we can make out that an increase in initial pulse energy leads to an increase of peak power of the amplified pulse as well as its temporal duration, which is a signature of the intrinsic nonlinear nature of the self-similar pulse propagation. In contrast to the anomalous dispersion regime where the amplified shape is highly affected by the solitonic compression effect, let us outline that the parabolic shape is here remarkably maintained over a wide range of input power.

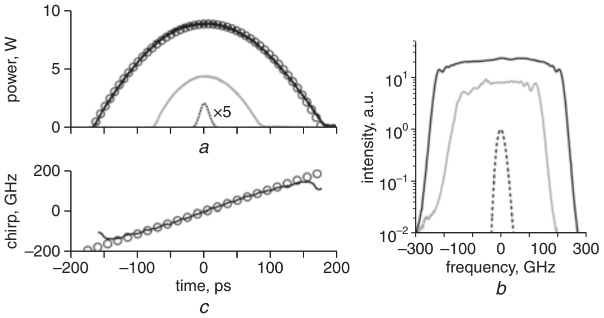

Fig. 2 *Experimental properties of 7.2 pJ initial pulse (black dashed line) and of amplified pulses for initial pulse energy of 0.6 and 7.2 pJ (solid grey line and solid black line, respectively)*

a Temporal intensity profiles recorded on high-speed oscilloscope
b Optical spectra
c Frequency chirp
Output temporal results obtained for 7.2 pJ initial pulse are compared with parabolic fit for intensity profile and with linear fit for chirp (circles)

The Kerr nonlinearity also leads to an enhanced spectral broadening as illustrated in Fig. 2*b* (a 15 times spectral broadening is recorded for a 7.2 pJ initial pulse energy). The spectra of the amplified pulse exhibit the characteristic shape of similariton pulses, i.e. rapidly decreasing wings combined with reduced oscillations in the central part of the pulse. Using a Gerchberg-Saxton algorithm [5] and given the temporal and spectral intensity profiles, one can infer the temporal chirp of the pulse. Results are plotted in Fig. 2*c* and highlight the high linearity of the chirp of the amplified pulses.

Given the ability to directly visualise the amplified pulses, we have studied the influence of the initial pulse energy E_{ini} for different values of small-signal gain g. Temporal and spectral full-widths at half-maximum were recorded and results are plotted in Fig. 3. Output temporal width can be continuously varied over a wide range, from 50 to 250 ps. The experimental results are in good agreement with a fit based on a $E_{ini}^{1/3}$ function which is typical of the self-similar analytical evolution of the parabolic pulses [1]. However, we note that for pulse durations below 100 ps, the asymptotic parabolic profile is not fully reached. The maximum temporal duration of 250 ps was only limited by the power available from the picosecond fibre laser so that larger temporal broadenings could potentially be achieved with more powerful seeds.

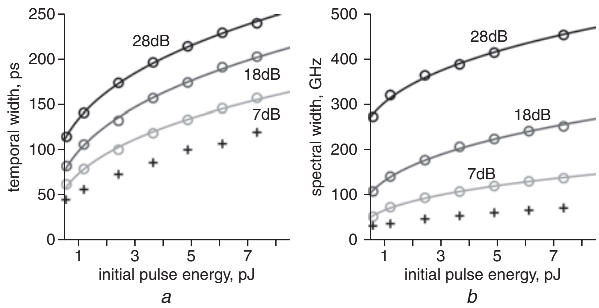

Fig. 3 *Temporal and spectral full-widths at half-maximum of output pulses against initial pulse energy*

Experimental results without gain (black crosses) and with different values of gain (7, 18, 28 dB, light grey, grey, black circles, respectively)
Experimental results are compared with $E_{ini}^{1/3}$ fit function

Whereas similar temporal broadenings can be obtained for pulses with initial energy of 3.6 and 7.2 pJ associated with 28 and 18 dB gains, respectively, the resulting spectral broadenings are rather different: pulses amplified in the 28 dB configuration are significantly more broadened than for the 18 dB configuration. This highlights that higher gains lead to pulses with a higher temporal chirp, which is qualitatively consistent with the g/β_2 expression of the linear chirp coefficient of the parabolic pulse [1].

Conclusion: We have generated long 230 ps parabolic similariton pulses using an all-fibred device at telecommunication wavelengths. The parabolic profile has been assessed by direct visualisation on a 50 GHz oscilloscope and by monitoring the optical spectrum. The high quality of the temporal and spectral profiles will be a key element for future applications such as retiming processes [6] or pulse shaping applications. Temporal and spectral properties of the similaritons can be instantaneously tuned over a wide range by simply adjusting the initial pulse energy or the Raman pump power.

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K. Hammani, C. Finot, S. Pitois, J. Fatome and G. Millot (*Institut Carnot de Bourgogne, UMR 5209 CNRS-Université de Bourgogne, 9 Av. A. Savary, BP 47 870, F-21078 Dijon Cedex, France*)

E-mail: christophe.finot@u-bourgogne.fr

References

1 Fermann, M.E., Kruglov, V.I., Thomsen, B.C., Dudley, J.M., and Harvey, J.D.: 'Self-similar propagation and amplification of parabolic pulses in optical fibers', *Phys. Rev. Lett.*, 2000, **84**, pp. 6010–6013
2 Dudley, J.M., Finot, C., Millot, G., and Richardson, D.J.: 'Self-similarity in ultrafast nonlinear optics', *Nat. Phys.*, 2007, **3**, pp. 597–603
3 Finot, C., Millot, G., Pitois, S., Billet, C., and Dudley, J.M.: 'Numerical and experimental study of parabolic pulses generated via Raman amplification in standard optical fibers', *IEEE J. Sel. Top. Quantum Electron.*, 2004, **10**, pp. 1211–1218
4 Finot, C.: 'Influence of the pumping configuration on the generation of optical similaritons in optical fibers', *Opt. Commun.*, 2005, **249**, pp. 553–561
5 Gerchberg, R.W., and Saxton, W.O.: 'A practical algorithm for the determination of the phase from image and diffraction plane pictures', *Optik*, 1972, **35**, pp. 237–246
6 Parmigiani, F., Petropoulos, P., Ibsen, M., and Richardson, D.J.: 'Pulse retiming based on XPM using parabolic pulses formed in a fiber Bragg grating', *IEEE Photonics Technol. Lett.*, 2006, **18**, pp. 829–831