Generation of similaritons in a nonlinear dispersive optical fibre without gain

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The generation and evolution of self-similar pulses in optical fibres (similaritons) has been studied quite extensively these last years. In these studies, either gain or losses play an important role, or the variation of some parameters along the fibre is mandatory for similaritons to develop. We observed a new kind of similaritons in uniform optical fibres without gain or losses. Spectro-temporal characterisation of these pulses was achieved experimentally. We present an analytical explanation of the measured spectro-temporal shape. These results are in good agreement with the numerics.

Introduction

Parabolic pulses, similaritons and self-similar pulses are three distinct concepts that overlap quite often. Each one of the three concepts leads to interesting practical applications, in the fields of pulse shaping, pulse amplification and, more generally, in the generation of high-power pulses. A recent review article [1] provides more details on the applications of self-similar pulses.

The first studies of self-similar pulses [2, 3] considered the propagation of pulses in an amplifier, which is described by the Generalised Nonlinear Schrödinger Equation (GNLSE). The amplification process is taken into account by a gain term added to the Nonlinear Schrödinger Equation (NLSE). Because of this additional term, the equation is not conservative anymore, and it becomes possible that the propagation of *different input pulses* leads to *identical outputs*. Indeed, the formation of high-power parabolic pulses from any input pulse was predicted and experimentally verified [2, 4, 5]. It was also shown that parabolic pulses could sustain different gain profiles [6].

Another generalisation of the parabolic pulses was made by considering the GNLSE with distributed coefficients, *i.e.* varying along the fibre [7, 8]. An important particular case of this last generalisation is the standard NLSE in dispersion-decreasing fibers, that allows for the generation of parabolic pulses in a passive system [9].

More recently, Finot *et al.* [10] investigated the possibility to reshape different kinds of pulses to parabolic ones by the only effect of propagation in a plain optical fibre with uniform parameters. Quite interestingly, it was shown that when pulses with simple-enough initial profiles are launched into this passive system, they will first evolve towards a parabolic intensity shape. But in a second stage, their profile will differ more and more from this parabolic shape. This behaviour is in good agreement with previous works on “optical wave breakup” [11]. Such “parabolic pulses” are clearly not “self-similar”.

Below, we study self-similar pulses in a passive and uniform optical fibre, with normal dispersion and Kerr nonlinearity. We show that these similariton pulses are of spectronic nature [12, p. 35]. One main difference with the results reported in [10] is that we focus our attention on the parabolic nature of the phase, and cannot therefore avoid to consider non-parabolic intensity profiles.

Spectrons in a nonlinear medium

The spectron is the transposition from the spatial domain to the temporal one of the far-field zone [12, p. 35]: in a linear medium, the temporal intensity of a pulse, after an infinite propagation distance, corresponds therefore to the initial spectral intensity. This pulse is the *spectron* of the input pulse. It is obvious that after a certain distance, the spectron is already formed and that its intensity profile will remain invariant.

In a nonlinear system, depending on the relative importance of nonlinear and dispersive effects, the spectron can appear or not. As described in [11], in some cases, wave breakup occurs.

Here, we consider the case where the nonlinear distance $L_{NL} = 1/(\gamma \cdot P)$ is very small in comparison with the dispersion distance $L_D = T_0^2/\beta_2$, *i.e.* $L_{NL} \ll L_D$, with T_0 the pulse duration,P the pulse power, β_2 the second order dispersion coefficient of the fibre, and γ its nonlinear coefficient. If the fibre length z is such that $z \approx 10\,L_D$, applying textbook formulas and using simple mathematics, we find that the total spectral phase at the output of the fibre is given by $\beta_2\,\omega^2\,z/2$, with a precision better than 1%. Because the nonlinear coefficient does not appear in this expression, we deduce that the essential effect of the nonlinearity is to broaden the spectrum.

In this regime, whatever the initial input pulse profile, the output spectral phase should be identical. Effectively, after a propagation distance $z_{NL} \approx 10\,L_{NL}$, the spectrum should not broaden anymore, and the spectron will form over the remaining distance $z - z_{NL} \approx z$.

Experimental results

In order to observe the spectronic similariton, we injected 200 fs pulses at 722 nm in a 30 m-long single-mode optical fibre, with a repetition rate of 82 MHz, and mean powers varying between 0 mW and 12 mW ($z \approx 30\,L_D \leq 40\,L_{NL}$).

In a first set of measurements, we did record the spectra and autocorrelation traces at the input of the fibre, and the spectro-temporal traces at its output. This last measurement was performed with a 2-f lens-grating setup in front of a streak-scope camera.

Thereafter, we introduced at the output of the laser, a birefringent media followed by a polariser, in order to get double pulses. These strongly modified pulses were sent into the same setup, and analysed in the same way.

Figure 1 shows the autocorrelation traces. The spectro-temporal profiles of the pulses are displayed in Fig. 2. On these traces, the tilt corresponds directly to the chirp of the output pulse. This tilt is the same for the single pulse and the double pulse, while the autocorrelation traces show important variations of the temporal profile.

Finally, on Fig. 3, we compare the output spectra of the double pulse in the linear propagation regime and in the nonlinear one ($z \approx 40\,L_{NL}$). We see that the spectrum broadens and that the spectral shape of the output pulse is almost parabolic.

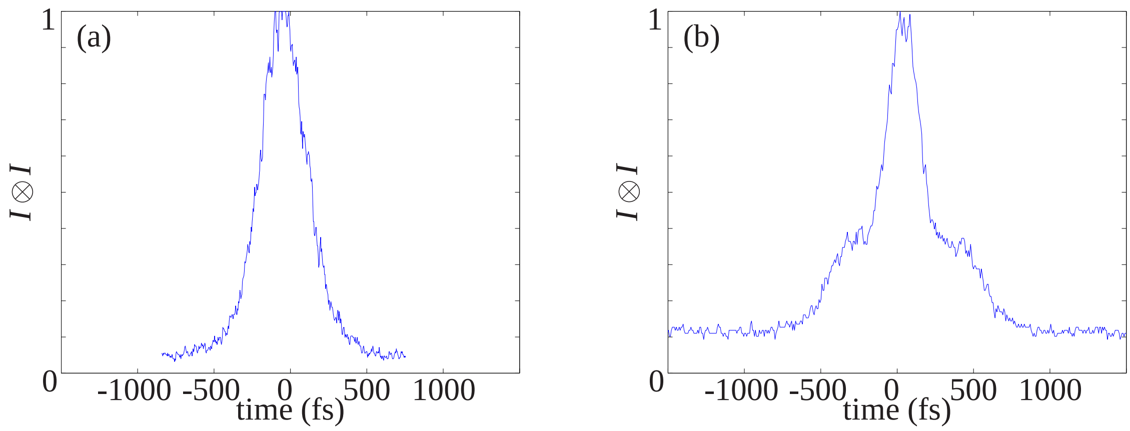

Figure 1: Autocorrelation traces of the pulses launched into the fibre. (a) Single pulse; (b) double pulse.

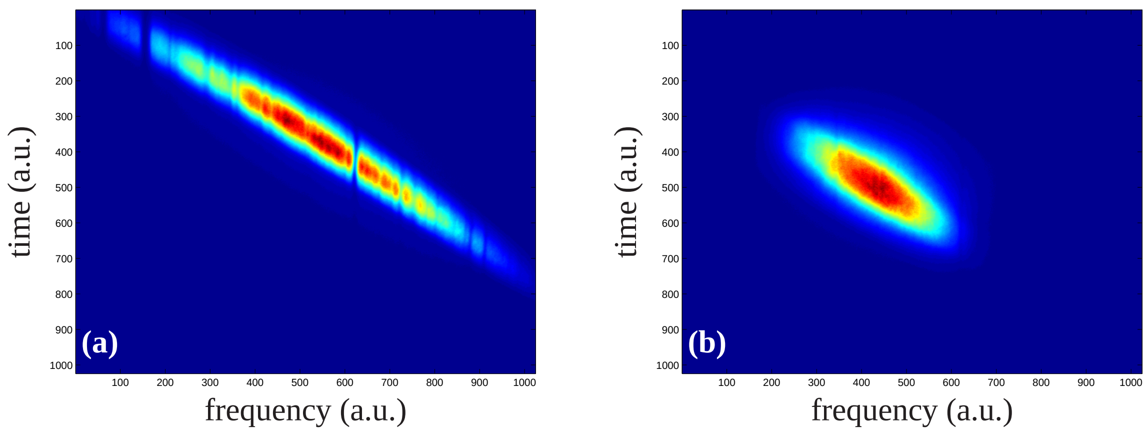

Figure 2: Spectro-temporal trace of the pulses. (a) Single pulse; (b) double pulse. The tilt of the trace is directly linked to the pulse chirp. Units are related to the camera, and identical in the two cases. By the use of masks in front of the grating, we verified with good accuracy that the pulse chirp is identical in both cases.

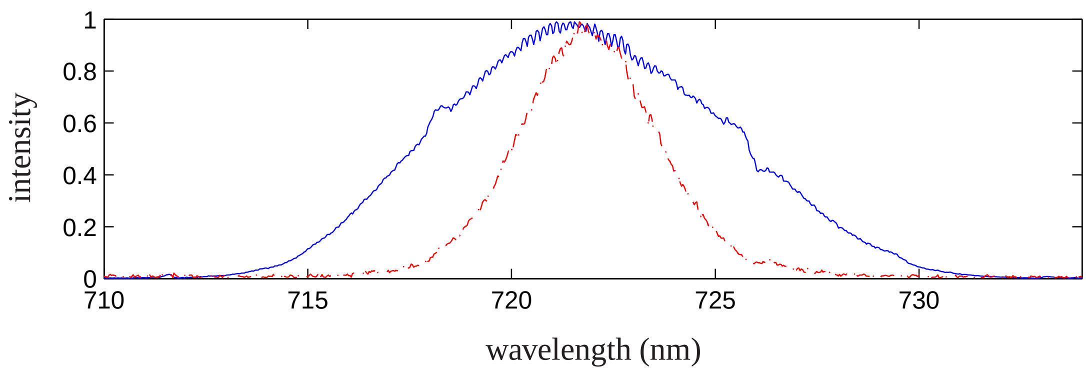

Figure 3: Output spectrum of the double pulse at low power (- -) and in the nonlinear regime (—). The output shape is more parabolic than the input one.

Conclusions

We introduced the concept of spectronic similariton, and provided a detailed comparison of the spectronic similariton with other kinds of self-similar pulses. By simple arguments, we explained the formation of these similaritons, and finally, we presented experimental observation of these self-similar spectronic structures.
We believe that the existence of such structures with well-known phase will reveal very useful for the full characterisation of ultrashort optical pulses.
Finally, we should mention that our results are in very good agreement with the numerical predictions obtained by applying the well-know split-step Fourier method to the NLSE.

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