Few-cycle solitons in supercontinuum generation dynamics

Hervé Leblond [1], ***Philippe Grelu*** [2], ***Dumitru Mihalache*** [3]

[1] *LUNAM Université, Université d'Angers, Laboratoire de Photonique d'Angers, EA 4464, 2 Boulevard Lavoisier, 49000 Angers, France*

[2] *Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR CNRS 6303, Université de Bourgogne, 9 Avenue A. Savary, BP 47870, Dijon Cedex 21078, France*

[3] *Academy of Romanian Scientists, 54 Splaiul Independentei, 050094 Bucharest, Romania , and Horia Hulubei National Institute for Physics and Nuclear Engineering, 30 Reactorului, Magurele, 077125 Bucharest, Romania*

Supercontinuum generation is the matter of extensive research, especially since wideband spectra spanning over more than one octave have been produced using intense femtosecond laser sources such as Ti:sapphire, around the year 2000 [1,2]. The use of photonic crystal fibers, and tapered silica fibers, allowed one to reach very high intensities, which lead to supercontinuum spectra covering a larger domain of the electromagnetic spectrum from ultraviolet to near infrared (350–2400 nm) [3].

Envelope models are not adapted to the modeling of propagation of such broadband spectra. However, models beyond the slowly varying envelope approximation have been proposed to describe few-cycle pulse propagation in transparent media. Both a modified Korteweg–de Vries (mKdV) and a sine-Gordon (sG) equations were initially derived from a two-level quantum mechanical model, assuming that the resonance frequency of the medium was either well above or well below the central pulse frequency, respectively [4]. The derivation has then been generalized to more complicated situations, showing that the mKdV-sG model

$$\partial_z u + c_1 \sin \int^t u + c_2 \partial_t u^3 + c_3 \partial_t^3 u = 0 \qquad (1)$$

can describe few-cycle soliton propagation if it can be assumed that the transparency window is very wide [5,6].

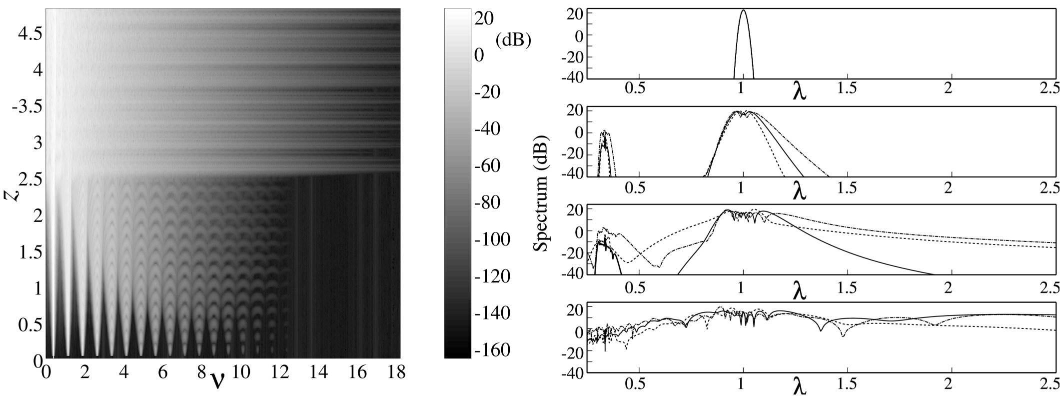

Fig. 1. Left: Evolution of the spectrum of an initial Gaussian pulse according to the sG model (on a logarithmic scale). Notice the high number of harmonics and the oscillations of their amplitudes. Right: Evolution of the spectrum against wavelength λ, according to three models: the mKdV one (dashed line), the sG one (dash-dotted line), and the mKdV-sG one (solid line).

We investigate numerically the evolution of an input pulse with Gaussian profile (which can represent a 100-fs long pulse with wavelength $1\mu\mathrm{m}$) according to Eq. (1), especially in the two limiting cases of the mKdV equation ($c_1=0$) and of the sG one ($c_2=c_3=0$). Supercontinuum generation is observed in both cases (see Fig. 1), and several mechanisms are identified [7].

In a first stage, the broadening is mainly due to the self-phase modulation, as can be shown by evaluating it analytically. Then high harmonics are generated through the cubic nonlinearity, and their spectral width increases with the order of the harmonic. Finally, in the case of the mKdV model, i.e., when the light-matter interaction is due to ultraviolet transitions only, a set of few-cycle solitons emerges from the pulse, and tend to separate temporally (Fig. 2, left).

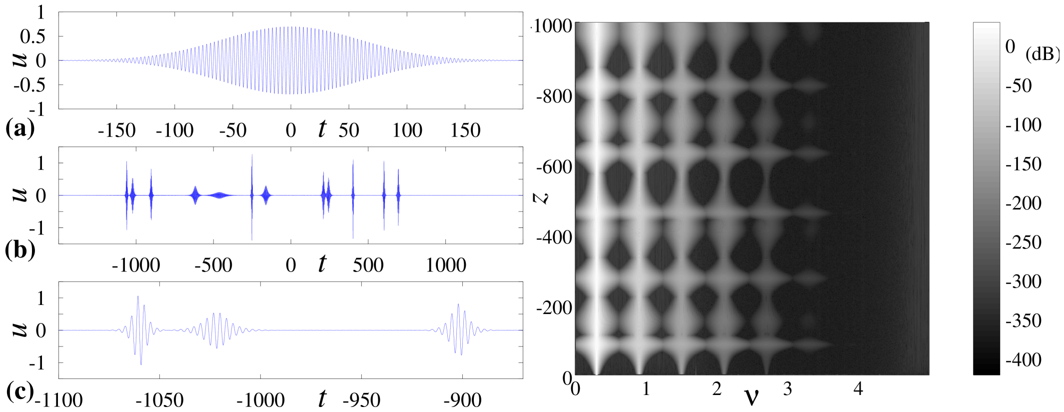

Fig.2 Left: Evolution of an initial Gaussian pulse according to the mKdV model (a) initial pulse (z = 0), (b) set of emerging FCP solitons (z = 999), and (c) zoom on some FCP solitons in (b)Right: at some moderate intensities, a two-soliton complex forms and the spectral broadening evolves periodically, showing some recurrence phenomenon.

The spectral width strongly enlarges as this occurs, leading to a broadband supercontinuum. For a moderate intensity, it may happen that the number of generated solitons is two, in this case oscillations of the spectral width are observed (Fig 2, right).

In the case of the sG model, i.e., if only infrared transitions are taken into account, few-cycle solitons also form, but the dispersion properties of the SG equation are such, that their separate much slower, and inetract together a longer time, while a supercontinum forms as in the mKdV case. Investigation of the low-frequency spectrum shows an appreciable difference between the spectra obtained according either the mKdV or the sG models. The generation of long wavelengths in the first stages of the evolution is much stronger for the sG model, recalling the effect of the Raman broadening (Fig. 1, right).

References:

1. Dudley J. M., Taylor J. R., ed. (2010). Supercontinuum generation in optical fiber. Cambridge University Press.
2. Alfano R. R., ed. (2006). The supercontinuum laser source: fundamentals with updated references. Springer.
3. Møller U., Sørensen S. T., Larsen C., Moselund P. M., Jakobsen C. , Johansen J., Thomsen C. L., Bang O. (2012). Optical fiber technology, 18, 304.
4. Leblond H., Sanchez F. (2003). Physical review A 67, 013804.
5. Leblond H., Sazonov S.V., Mel'nikov I.V., Mihalache D., Sanchez F. (2006). Physical review A 74, 063815.
6. Leblond H., Mihalache D. (2013). Physics reports. 523, 61.
7. Leblond H., Grelu ,P., Mihalache D. (2014).Physical review A 90, 053816.