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## Nonlinear optical reshaping in optical fibers for ultrafast applications

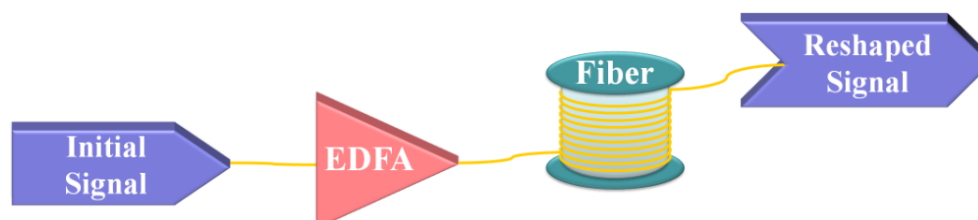
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*Several promising applications demonstrate all the benefits expected from the interaction of dispersive and nonlinear effects in single mode optical fibers: pulse shaping, ultra-short pulse source conception, rogue wave generation and high bit-rate optical communications.*

Generation and shaping of ultra-short optical pulses with temporal duration below ten of picoseconds is a subject stimulating large efforts in order to overcome the existing bandwidth limitations of optoelectronic devices. If the generation of Gaussian or hyperbolic secant waveforms at repetition rates of few tens of megahertz is now widely spread, major difficulties are still arising when the repetition rates are above a few tens of gigahertz or when more elaborate shapes are targeted. Passive linear shaping has provided a first solution to fulfill this challenge: by modifying the spectral intensity and phase contents of a broadband pulse, advanced waveforms have been synthesized. The approach we have decided to work on relies on a nonlinear shaping: taking advantage of the interaction between linear and nonlinear effects occurring through wave propagation in optical fibers, we have therefore demonstrated the generation of high quality optical pulse trains for high-repetition rate telecommunications, optical pulses with parabolic intensity profiles and optical rogue-wave like structures.

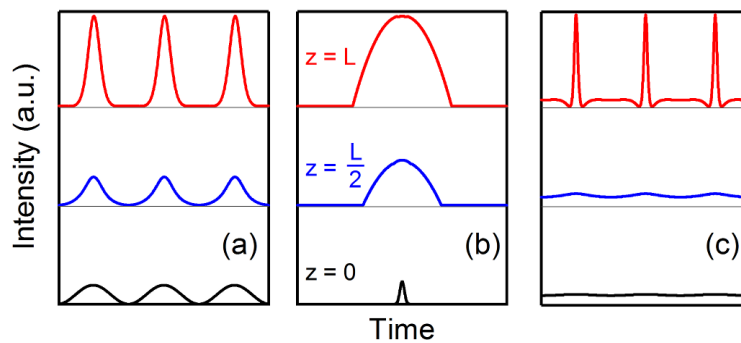
A typical configuration we have implemented is sketched in Figure 1. Our all-fibered solution relies exclusively on cost-effective and commercially available components ready for telecommunication use. A large range of input signals has been tested: beating between two continuous waves, ultra-short pulses or single-frequency partially modulated wave. An erbium doped fiber amplifier is used in order to increase the power up to a level where Kerr nonlinearity occurring in the optical fiber under-test becomes suitably significant. Depending on the targeted application, the segment of fiber under use has normal or anomalous dispersion. Note that it is also possible to benefit from optical gain such as Raman amplification if additional pumping is implemented. Based on this extremely simple configuration, we have been able to highlight the very rich diversity of the waveforms that can be directly generated at the fiber output. We describe in the following of this paper three examples, the numerical and experimental results we achieved as well as the expected applications.



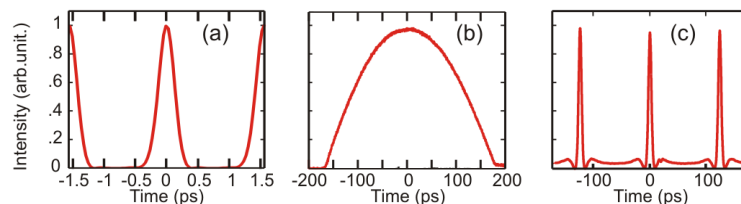
**Figure 1** : Experimental set-up

Let us start with a configuration where two continuous waves separated by a frequency offset  $\Omega$  are initially launched at the fiber input. During the propagation, the interaction between

anomalous dispersion and nonlinearity results in the generation of new harmonics frequency separated by  $\Omega$ . The process involved in these experiments is called multiple four-wave mixing and this spectral enrichment is accompanied by a strong temporal compression of the initial beating into well-separated high-quality short pulses. Figure 2a depicts the results of numerical simulations based on the standard nonlinear Schrödinger equation. For a given initial average power and a precise fiber length, the initial sinusoidal beating is transformed into a train of well defined and nearly transformed limited Gaussian pulses at a repetition rate  $\Omega$ .<sup>1</sup> The low level of pedestals contained into the generated pulses makes them ideal for high speed optical communications. Precise intensity and phase measurements based on the Frequency Resolved Optical Gating technique (FROG) confirm the numerical predictions (see Figure 3). Let us finally stress the flexibility of our approach in terms of repetition rates that can be achieved : the initial demonstration was reported at 160 GHz but further experiments have confirmed the validity of the concept for repetition rates down to 20 GHz and up to several terahertz with similar performances.<sup>2</sup>



**Figure 2 :** Numerical simulations : (a) Temporal compression of an initial beating made of two continuous waves, (b) Reshaping of an initial Gaussian pulse towards a parabolic pulse and (c) Evolution of a partially modulated wave towards a Peregrine soliton.



**Figure 3 :** Experimental temporal intensity profiles of the output pulses : (a) Gaussian pulse train (FROG measurements) (b) Parabolic similariton (recorded with a high-speed photodiode and oscilloscope) (c) Peregrine solitons (recorded with an optical sampling oscilloscope).

A second example is linked to the adiabatic evolution of an ultra-short pulse in an optical fiber with normal dispersion and gain. It is remarkable to observe that in this context, any pulse, whatever its shapes or duration, will reshape asymptotically towards a parabolic intensity profile with a parabolic phase, as can be observed in Figure 2b. This new kind of nonlinear optical structure undergoes a continuous temporal and spectral exponential broadening and is called similariton in regards to its ability to propagate self-similarly in optical fibers.<sup>3</sup> If we now compensate for the parabolic phase, it is possible to obtain ultra-short pulses with very intense peak powers and relatively low sidelobes, which is of a great interest in the domain of high power fiber amplifiers. It is also possible to take advantage of

the robustness of these particular pulses versus the initial fluctuations in order to propose an all-optical reshaping device with an enhanced stability or an optical regenerator.<sup>4</sup> Let us finally note that the presence of a physical gain is not a mandatory requirement and that a passive fiber with a longitudinally decreasing dispersion profile could advantageously replace an active device.<sup>5</sup>

Our final example of powerful reshaping process deals with the dynamics of a partially modulated continuous wave in an anomalous dispersive fiber (see Figures 2c and 3c). We have theoretically and experimentally found that an initially small fluctuated signal could evolve into an extreme spike of light so that a parallel can be drawn with the infamous oceanic rogue waves. More precisely, in the context of the French Manureva ANR project and other international collaborations, we have experimentally demonstrated that the temporal profile of these brief and intense spikes of light are in excellent agreement with the shape of the nonlinear structure mathematically predicted by Howell Peregrine more than 25 years ago.<sup>6</sup>

To conclude, based on the large diversity of the interactions between dispersive effects and Kerr nonlinearity, we have proposed advanced approaches to control the temporal and spectral dynamics of high power ultra-short pulses evolving in optical fibers. If these interactions are often regarded as detrimental in the high bit rates long haul networks, we have shown that they can offer a new degree of freedom in tailoring initial optical waves with a moderate spectral width. Our theoretical and experimental works have highlighted generation of ultrahigh repetition rate Gaussian pulse trains, generation of parabolic self-similar pulses as well as emergence of optical rogue waves. The simplicity of the experimental set-up could be combined in a near future with the compactness offered by highly nonlinear fibers or waveguides based on special glasses such as chalcogenide or bismuth.

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