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Phase evolution of Peregrine-like solitons in nonlinear fiber optics

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INTRODUCTION

Optical fiber systems are well-known to provide convenient platforms in which one may investigate a large variety of fascinating fundamental nonlinear coherent structures such as solitons or self-similar patterns. Among the nonlinear effects, generation of extreme-value fluctuations and "optical rogue wave" localization processes have stimulated significant number of research studies during this last decade. Interestingly, one of the major conclusions is that the temporal and spectral characteristics of the evolving field could be well described in terms of a particular class of soliton over finite background that undergoes periodic evolution during propagation with periodic energy exchange with a finite background [1]. As stressed by recent studies, these structures, in particular the limiting doubly localized Peregrine breather, are of crucial importance [2-4] and can also be detected in deep water and other nonlinear medium governed by the NLSE.

Given the progress of ultrafast measurement techniques, the longitudinal evolutions of the temporal and spectral profiles of the PS have been characterized. It has also been experimentally verified that at the point of maximum envelope compression, the phase difference $\Delta\phi$ between the central part of the pulse and the continuous background present a typical value of π .

In this contribution, we report an experimental study that complements the analysis of the nonlinear dynamics of the pulse. More precisely, we report here the longitudinal evolution of the phase difference $\Delta\phi$ and confirm some important features of the PS.

THE PEREGRINE SOLITON

The Peregrine breather is a doubly localized structure predicted in 1983 and experimentally demonstrated in 2010 [1] in optical fibers and later in hydrodynamics and plasma physics.

It is an analytical solution of nonlinear Schrödinger equation describing the evolution of light in singlemode optical fibers :

$$\frac{\partial \psi}{\partial z} + \frac{1}{2} \beta_2 \frac{\partial^2 \psi}{\partial t^2} + \gamma |\psi|^2 \psi = 0$$

with β_2 with the second order anomalous dispersion and γ the nonlinear Kerr coefficient.

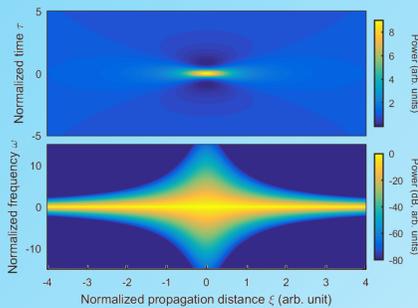
NLSE can be written in its normalized form: $\frac{\partial u}{\partial \xi} + \frac{1}{2} \frac{\partial^2 u}{\partial \tau^2} + u^2 u = 0$

The Peregrine solution is a rational soliton expressed in the temporal domain by :

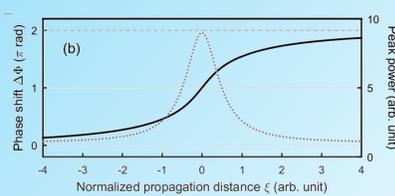
$$u(\tau, \xi) = \left[1 - \frac{4(1+2i\xi)}{1+4\tau^2+4\xi^2} \right] e^{i\xi}$$

A temporal phase difference $\Delta\phi$ between the central part of the pulse and the continuous background exists and evolves as :

$$\tan(\Delta\phi) = -\frac{8\xi}{4\xi^2-3}$$



Longitudinal evolution of the temporal and spectral intensity profiles of the ideal Peregrine soliton.



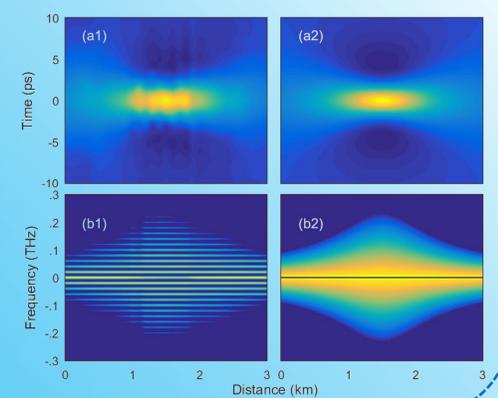
Evolution of the phase shift between the central part of the continuous background $\Delta\phi$ (left, solid black line) and peak intensity (right, dot dashed line).

LONGITUNAL EVOLUTION

Evolution of the temporal and spectral intensity profiles

The temporal compression of the PS is clearly observed, with a spectral broadening.

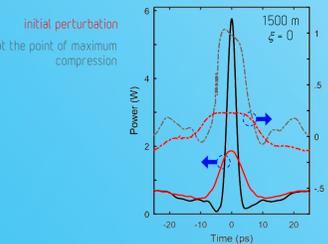
Experimental results are fully in line with the analytical predictions.



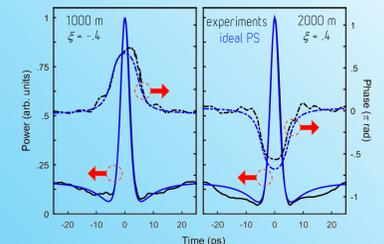
Longitudinal evolutions of the temporal (a) and spectral (b) intensity profiles of a fundamental PS. Experimental results (panels 1) are compared with ideal PS.

Details of the temporal phase and intensity profiles

The phase shift of π at the point of maximum compression is observed, as well as FPU-like behavior.



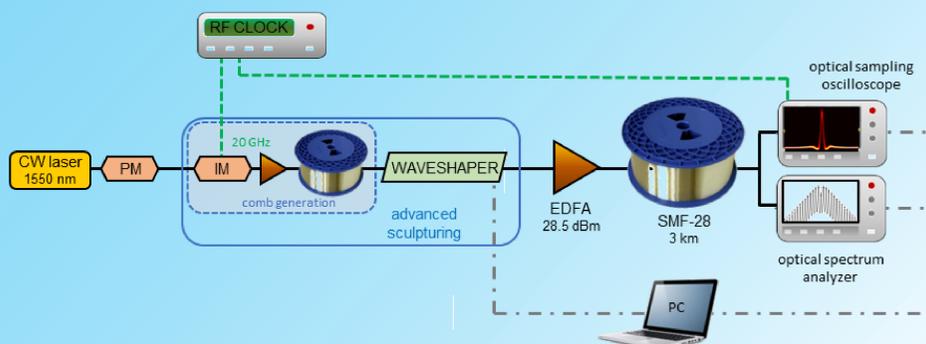
Experimental intensity and phase profiles obtained for the generated PS. The experimental results retrieved at the point of maximum compression are compared with the initial perturbation.



Intensity and phase temporal profiles symmetrically located before and after the point of maximum compression.

EXPERIMENTAL SETUP

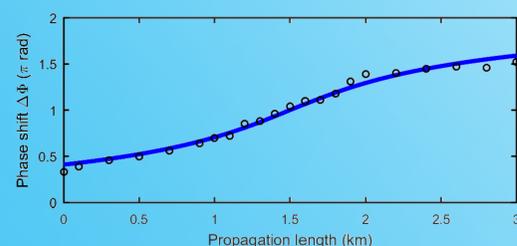
- The all-fiber experimental setup relies on commercially available devices [5].
- We used the widely spread single mode fiber SMF 28 in order to benefit from anomalous dispersion, low losses, low impact of third order dispersion and affordable cost.
- The temporal and spectral intensity profiles are experimentally recorded.
- The temporal phase profile can be recovered using the Gerchberg and Saxton algorithm [6] and is simplified by the comb nature of the spectrum.
- The longitudinal evolution is obtained using a set of various fiber lengths leading to a propagation length up to 3 km.
- In order to achieve a Peregrine-like breather, we used as an initial condition a spectrally shaped comb corresponding to $\xi = -1.2$.
- For an input average power of 28.5 dBm, the maximum compression is observed after 1.5 km.



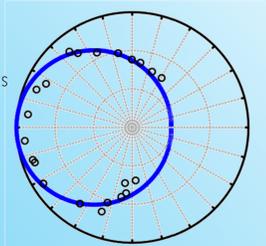
Experimental setup. NLS breather generator based on light wave propagation in a single-mode optical fiber. PM: phase modulator; IM: intensity modulator; EDFA: Erbium-doped fiber amplifier.

Longitudinal evolution of the phase

- The phase excursion experienced by the central peak with respect to the continuous background is confirmed experimentally.
- A convenient way to observe the growth and decay cycle is to use a polar plot of the complex field.



Longitudinal evolution of the phase offset between the pulse central peak and the continuous background $\Delta\phi$



Polar representation of the longitudinal evolution of the complex field recorded at its maximum temporal value (normalized to the continuous background).

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The presented results are detailed in the following reference :
[5] G. Xu, K. Hammani, A. Chabchoub, J.M. Dudley, B. Kibler, C. Finot. "Phase evolution of Peregrine-like breathers in optics and hydrodynamics." *Physical Review E* 99 (1), 012207 (2019).

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