Peregrine soliton in optical fiber-based systems

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Abstract: We report the first observation in optics of the Peregrine soliton, a novel class of nonlinear localized structure. Two experimental configurations are explored and the impact of non-ideal initial conditions is discussed.

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1. Introduction

Although solitons are central objects of nonlinear science and one of the best known solutions of the nonlinear Schrodinger equation (NLSE), other classes of localized structure are admitted by NLSE including soliton solutions existing upon a finite background [1]. One particular structure of this type is the Peregrine soliton (PS) whose existence was predicted over 25 years ago but surprisingly, it has never been the subject of any systematic experimental study and has never been observed in the original hydrodynamic environment in which it was first studied [2]. The Peregrine soliton is of fundamental significance because it exhibits a two dimensional localization, both in time and space, and because it defines the limit of a wide class of solutions to the NLSE.

In the present contribution, we detail two sets of experiments carried out in optical fibers, which allow us to highlight for the first time the observation of the Peregrine soliton dynamics. Using a wide range of initial conditions, we also show that the process of PS formation is quite robust and on the other hand that a non-ideal excitation of the PS structure leads to subpulses splitting beyond the maximum point of compression.

2. Model

Light evolution in an optical fiber is appropriately described by the standard NLSE that can be written in the following normalized form:

$$i\frac{\partial\psi}{\partial\xi}+\frac{1}{2}\frac{\partial^2\psi}{\partial\tau^2}+\left|\psi\right|^2\psi=0 \tag{1}$$

with ψ the complex normalized electric field and ξ and τ normalized distance and time respectively. We consider here a weakly modulated continuous wave (CW) propagating in an anomalous dispersive fiber. Therefore, the longitudinal evolution is strongly affected by induced modulation instability and the initial sinusoidal field experiences a marked temporal compression. At the low-frequency limit of this process [2,3], a Peregrine soliton is excited, associated with a simple polynomial form describing its two dimensional localization:

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

3. Generation in a highly nonlinear fiber at a repetition rate of a several hundreds of GHz

The experimental set-up we implement is simple: two external cavity lasers around 1550 nm create a weakly modulated CW signal (5% intensity modulation for a frequency spacing of the laser diodes of 200 GHz) that is then injected into 900 m of highly nonlinear fiber (β_2 = –0.885 ps^2.km^{-1} and γ = 10 W^{-1} km^{-1}) [4]. An accurate choice of propagation distance and initial power enables us to approach very close to the ideal compressed shape of the Peregrine soliton. Using frequency-resolved optical gating (FROG), we can compare our experimental measurements with the reshaping of the input field towards the solution predicted by Peregrine [2]. These results are shown in Fig. 1a where we plot the temporal intensity and phase profiles of the reshaped field (blue circles) and compare the measurements with the analytic prediction of Peregrine (gray) as well as with realistic simulations using direct integration of the NLSE (red). There is an excellent agreement between experiment, simulation and theory over the central part of the pulse and also in predicting the π-phase jump observed in the wings (see inset).

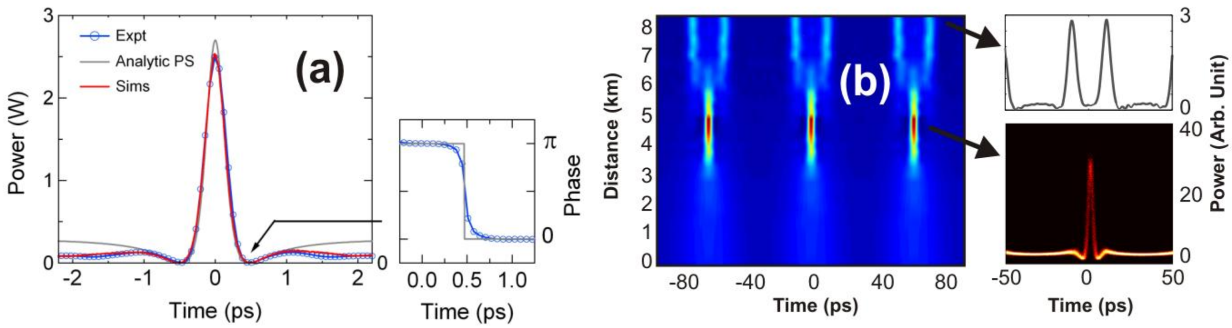

Fig. 1: **(a)** PS temporal characteristics from experiment (FROG measurements), analysis and simulation. Inset shows a π-phase jump in vicinity of wings. **(b)** Longitudinal evolution of temporal profile recorded on an optical sampling oscilloscope (initial power of 0.80 W). Insets show PS temporal characteristics from real time observation (bottom) and the two subpulses at the output of the fiber (top).

3. Observation in standard single mode fiber

To complement the previous observations, we have also tested a second approach where the initial weak modulation is now obtained directly by using a 1550 nm laser diode that is intensity modulated by a sinusoidal clock at 16 GHz. The nonlinear dynamics experienced by the signal is monitored thanks to an ultrafast optical sampling oscilloscope (OSO). The fiber involved in the process is here a standard SMF-28 with $\beta_2 = -21.4\ ps^2/km$ and $\gamma = 1.2\ W^{-1}.km^{-1}$. We have first studied the evolution dynamics over a wide range of initial modulation depth and power and we have shown that PS localization could be achieved through a large number of initial conditions. Moreover, by combining the real time characterization with cut-back measurements along the whole 8.35 km of fiber, we provide the first direct observation of the longitudinal dynamics (as shown in Fig. 1b) of this class of soliton. Quite interestingly, the PS-like structure experiences a breakup into two subpulses after the optimum compression point, each possessing similar characteristics of localization upon finite background.

4. Conclusion

We have provided here the first measurements of a nonlinear Peregrine soliton structure in any non-discrete NLSE soliton-supporting system. They highlight the existence of a strongly localized temporal peak upon a non-zero background, and confirm Peregrine's theoretical predictions expressed more than 25 years ago. Moreover, a longitudinal experimental scan of the dynamics has clearly outlined the compression and the subsequent splitting occurring because of non-ideal conditions. Our results stress how experiments in optics can be used to conveniently test more general theories of nonlinear waves. In a wider context, the fact that an initial Peregrine soliton can break up into two lower amplitude but equally strongly localized soliton pulses may have important implications for further interpretations of hydrodynamic rogue wave observations as well as establishing new links between optical and hydrodynamic extreme events [5].

5. References

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