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Single-Shot Time-Resolved Phase and Intensity Measurement of Breathers in the Nonlinear Stage of Modulation Instability

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The development of real-time measurement techniques for ultra-fast optical signals has attracted considerable interest over the last few years and has contributed to outstanding progresses in both applied and fundamental research. For instance, single-shot spectral recordings of modulation instability (MI) seeded by short pulses in a nonlinear fiber have revealed strong shot-to-shot fluctuations confirming the stochastic nature of the process [1]. Soon after, the development of so-called time-lens systems has enabled temporal observations of ultra-short extreme events originating from the noise-seeded MI in a cw (continuous wave) configuration [2].

In this work, even further insight is obtained thanks to the single-shot recording of the time-resolved complex field at the output of an optical fiber. This is done using an upgraded time-lens system called *Spatial Encoding Arrangement with Hologram Observation for Recording in Single shot the Electric field* (SEAHORSE) [3]. Using this technique, acquisitions over a large temporal window of 200 ps with a resolution of the order of 1 ps can be realized covering an unprecedented number of adjacent nonlinear structures. Access to the phase is enabled by creating a beating between the signal to analyse and a reference beam [Fig. 1(a)].

We investigate here the cw noise-seeded MI in a 500-m-long optical fiber. A broad range of solutions of the 1D nonlinear Schrödinger equation (1D-NLSE) have been theoretically predicted to occur in this system including Peregrine solitons (PS), the Kuznetsov-Ma (KM) solitons or Akhmediev breathers (AB) [4]. In the present case, we leverage the large recording window of our setup to capture some signatures of coherent structures close to the latter at the early stage of MI saturation [5].

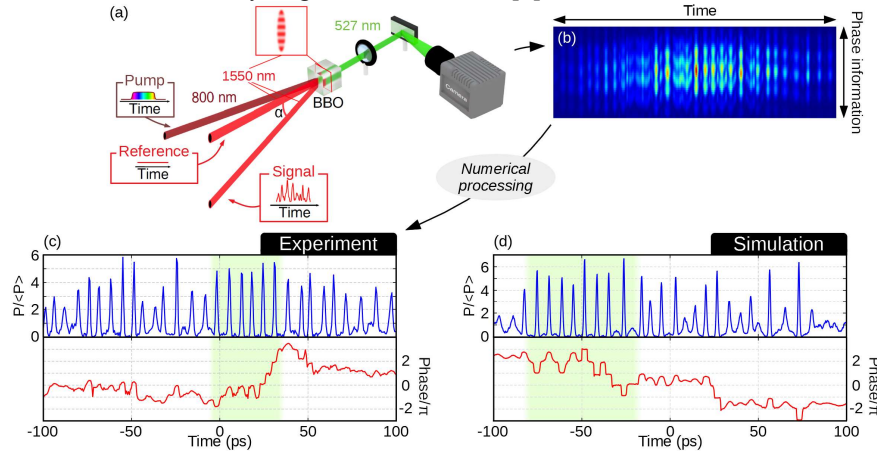


Fig. 1 (a) Schematic of the setup used for the single-shot acquisitions (SEAHORSE) [3]. The interference between the signal and the reference beams results in horizontal fringes, second harmonic generation is performed between the signal and the pump in a BBO crystal to obtain the time-lens effect and a diffraction grating realizes the spatial encoding on the camera. (b) A typical recorded frame, the fast intensity evolution is visualized horizontally and the phase information is retrieved from the fringes. (c) Intensity and phase evolution extracted from (b). (d) Typical numerical simulation of the 1D-NLSE in the same range of parameter. $\beta_2 = -21.7 \text{ ps}^2/\text{km}$, $\gamma = 1.3 \text{ /W/km}$, $P_0 = 7.25 \text{ W}$.

To do so, we tune the power at the input of the fiber so that the distance at which AB-like structures are most likely to be observed corresponds to the length of the fiber under test. An example of a single-shot recording is shown in Fig. 1(b). The evolution of both the intensity and phase of the complex field can be extracted from this frame and are plotted in Fig. 1(c). (d) shows a typical numerical simulation of the 1D-NLSE in remarkable qualitative agreement. Most noteworthy is the π phase shift surrounding each pulse in trains of breathers that are locally periodic and close to AB (highlighted in green).

The setup described here, with such a large temporal recording window, straightforwardly applies to different regimes and can be used to study the impact of various parameters, such as the noise level which is expected to play a crucial role for the dynamics and statistical properties of the system.

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