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Non-destructive phase and intensity distributed measurements of the nonlinear stage of modulation instability in optical fibers

Arnaud Mussot¹, Corentin Naveau¹, Pascal Szriftgiser¹, François Copie¹, Alexandre Kudlinski¹,
Matteo Conforti¹ and Stefano Trillo²

1. Univ. Lille, CNRS, UMR 8523-PhLAM – Physique des Lasers Atomes et Molécules, F-59000
Lille, France

2. Department of Engineering, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy
Author e-mail address: arnaud.mussot@univ-lille1.fr

ABSTRACT

We report a novel experimental setup to perform distributed characterization in intensity and phase of the nonlinear stage of modulation instability by means of a non-invasive experimental setup : a heterodyne time domain reflectometer.

Keywords: Nonlinear fiber optics, four wave mixing, modulation instability, soliton

1. INTRODUCTION

Modulation instability (MI) is a key nonlinear process in physical systems where the dynamic is ruled by the focusing nonlinear Schrödinger equation (NLSE) [1]. It consists in the exponential growth of a small modulation at the expense of a strong pump wave, leading to the amplification of subsequent harmonics of the sidebands due to four-wave mixing (FWM). By further propagating in the fiber, this energy exchange between modes is reversible, the system being able to return back to its initial state. By analogy, it is usually referred to as Fermi-Pasta-Ulam (FPU) recurrence process [2,3] that is strongly connected with many complex nonlinear effects of high interest such as rogue wave generation or frequency comb generation for instance. The first experimental observation of FPU in optical fibers has been achieved in 2000's with an indirect recording of the longitudinal evolution of the pump and signal intensities. To our knowledge, the longitudinal evolution of the relative phase of these waves that is at the heart of the reversibility has never been observed. In this work, we report a full longitudinal characterization in phase and intensity of the FPU recurrence process by means of a newly designed experimental setup based on an original heterodyne detection technique.

We consider the NLSE :

$$i \frac{\partial E}{\partial Z} - \frac{\beta_2}{2} \frac{\partial^2 E}{\partial T^2} + \gamma |E|^2 E = 0 \quad (1)$$

where $E(Z,T)$ is the electric field envelope, Z and T the distance along the fiber and the retarded time, respectively. β_2 is the group velocity dispersion which is anomalous in our case and γ the nonlinear coefficient. By means of a linear stability analysis, one can find that MI occurs when the modulation frequency Ω is such that $\Omega < \Omega_c$ with $\Omega_c = 2\sqrt{\gamma P_p / |\beta_2|}$, P_p being the pump power. The MI gain peak is located at $\Omega_{max} = \Omega_c / \sqrt{2}$. Fig. 1. shows a numerical integration of the NLSE in the case of an initial pure frequency modulation (that is to say with a relative phase between the pump and the sideband of $\Delta\phi = \pi/2$) with a modulation frequency close to Ω_{max} and an initial sideband to pump ratio of -20 dB ($\eta = 0.01$).

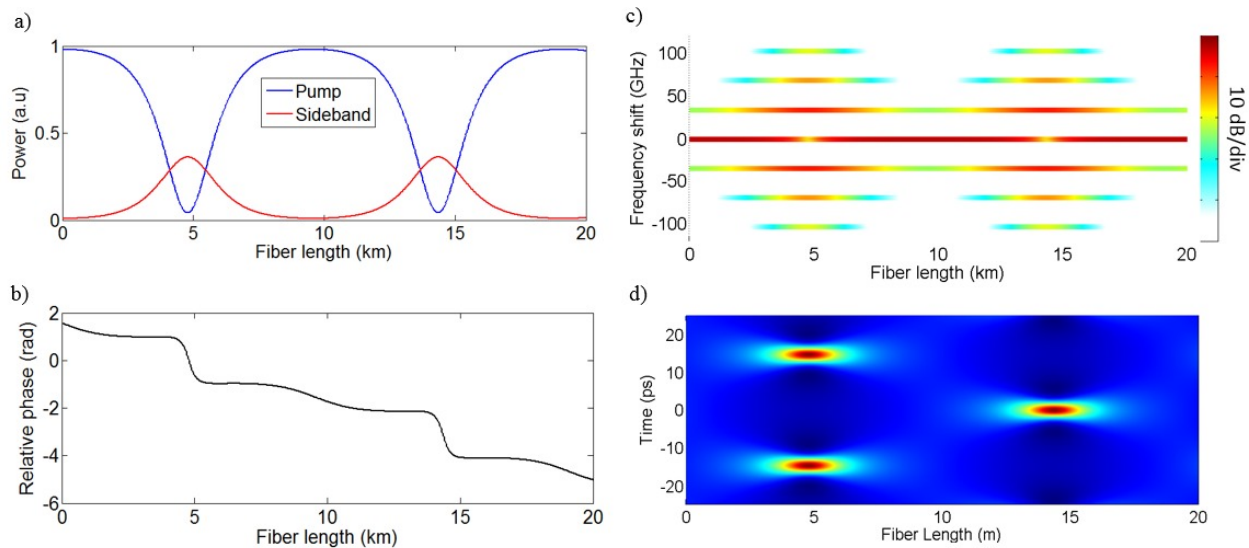


Fig. 1. Longitudinal evolution of (a) the normalized pump and sideband powers and (b) the pump-sideband relative phase. (c) and (d) shows the spectral and the temporal evolution of the intensity along the fibre, respectively. Parameters: fibre length $L = 20$ km, $\beta_2 = -19 \times 10^{-27} \text{ s}^2/\text{m}$, $\gamma = 1.3 \times 10^{-3} \text{ /W/m}$, $P_p = 450 \text{ mW}$, sideband to pump ratio $\eta = 0.01$, sideband detuning 35 GHz. Powers are normalized to their maximum values.

The evolution of the pump powers (Fig. 1.a.) clearly exhibits FPU recurrences. A first return to the initial state is observed around 10 km and another one at 18 km.

The first experimental observation of the FPU stage of modulation instability in fiber optics was reported in 2001 [3]. Various studies have since reported distributed measurements of the FPU stage of MI but only in intensity [4]. To date evolution of the phase was not taken into account although it can drastically affect the dynamics of the system [5]. Moreover, they were limited to the observation of only one recurrence, due to the intrinsic losses of fibres which kill the FPU process [4]. Here we propose a non-invasive method to perform distributed measurements of both intensity and phase of the MI process with compensation of the losses: a heterodyne optical time domain reflectometer (HOTDR). OTDRs use the Rayleigh backscattered signal which is directly proportional to the propagating signal. A simplified sketch of the experimental setup is presented in Fig. 2:

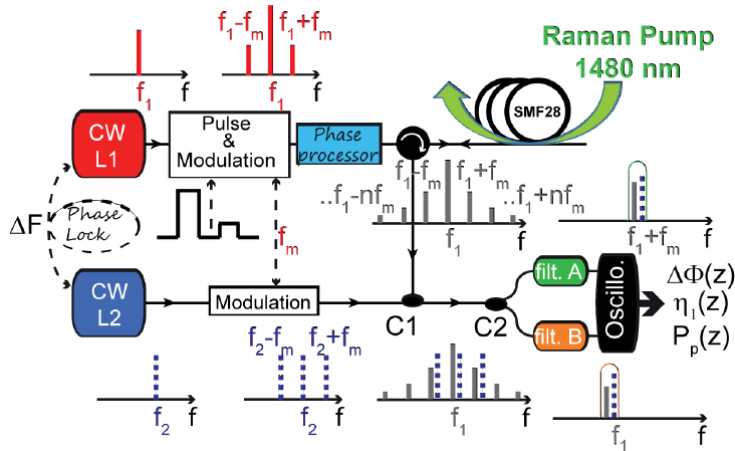


Fig. 2. Simplified sketch of the experimental setup. $f_{1,2}$ are the frequencies of the pump laser and the local oscillator laser, respectively, with $\Delta F = f_1 - f_2 = 800 \text{ MHz}$. Here $f_m = 35 \text{ GHz}$ is the input modulation frequency. MI evolution is studied in a 7.7-km-long single mode fibre (SMF28). The backscattered signal from the SMF28 goes through a circulator and is analysed via heterodyning (beating with the local oscillator) and then filtered (filt. A and B) to isolate the power and phase evolutions of the pump and the first order sideband in the MI spectral comb.

Intensity modulation of a CW laser (pump laser) centred at 1555 nm is used to generate 50-ns-long pulses. This duration is small enough to prevent any detrimental Brillouin scattering. The pump is then phase modulated in order to generate two sidebands symmetrically located around the pump and whose relative intensity and phase (compared to the pump) are controlled by an all fiber phase controller (wavershaper). After amplification, the modulated wave is launched into a 7.7-km-long SMF28 fibre. To compensate for the losses, we use a counter-propagating Raman pump centred at 1480 nm. The Rayleigh backscattered signal is mixed with a detuned local oscillator to perform heterodyne detection. This local oscillator consists in a CW laser which is detuned by 800 MHz and phase locked with respect to the pump. An intensity modulator driven by the same radio frequency source than the previous phase modulator is used to provide local oscillators for the previous sidebands or their harmonics.

Experimentally, the parameters we used are the same than in the simulation of Fig. 1. except for a shorter fibre length (in order to perform a good compensation of the losses) and an increased initial sideband to pump ratio (-8.5 dB) in order to scale down the recurrences. The experimental results are presented in Fig. 3. Fig. 3.a. shows that we were able to observe almost two recurrences in intensity. Moreover we managed to obtain the evolution of the relative phase as shown in Fig 3.b. By combining the evolution of the sideband power with the evolution of the relative phase, we can establish the phase portrait of the sideband, as displayed in Fig 3.c. Good agreement between experimental results (solid lines) and numerical simulations (dashed lines) is obtained, which validates the consistency of our measurement.

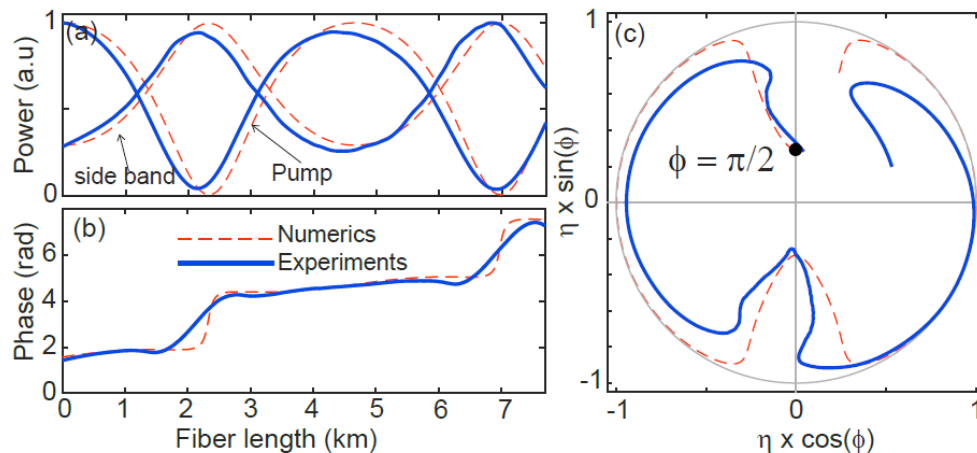


Fig. 3. Longitudinal evolution of (a) the normalized pump and sideband powers and of (b) the pump-sideband relative phase. (c) Phase portrait of the sideband corresponding to (a) and (b). Solid lines corresponds to experimental data and dashed one to numerics. Parameters: fibre length $L = 7.7$ km, $\beta_2 = -19 \times 10^{-27} \text{ s}^2/\text{m}$, $\gamma = 1.3 \times 10^{-3} / \text{W}/\text{m}$, $P_p = 450$ mW, sideband to pump ratio $\eta = 0.14$, sideband detuning 35 GHz. Powers are normalized to their maximum values.

In summary, our original novel experimental setup allowed us to perform the first complete distributed characterization, in phase and intensity, of the Fermi Pasta Ulam recurrence. We have been able to record the longitudinal evolution of the pump and sidebands intensities and their relative phase. Our setup is then a good test bed compare to other experimental systems to further investigate the nonlinear dynamics of modulation instability, that is directly with other complex nonlinear processes of high interest such as rogue waves, supercontinuum generation or frequency comb generation.

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