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Experimental investigation of the noise-driven thermalization of the Fermi-Pasta-Ulam-Tsingou recurrences process

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Abstract: We demonstrate the noise-driven thermalization of the Fermi-Pasta-Ulam-Tsingou (FPUT) recurrences in optical fibers. We highlight the progressive recurrences breakup in favor of an irreversible spectral energy equipartition by driving the input noise level. © 2022 The Author(s)

1. Introduction

The Fermi Pasta Ulam Tsingou (FPUT) recurrences were surprisingly discovered during a numerical study on an oscillators' chain in the 50s [1]. The scientists initially wanted to highlight the energy equipartition between the modes and thus to observe the thermalization of the energy. In fiber optics (and more generally in focusing cubic media), FPUT recurrences are also observed in the framework of coherently driven modulation instability (MI) and energy transfers occur between the Fourier modes of the generated frequency comb [2]. The recurrences can break up if the noise floor power, amplified by spontaneous MI, is not negligible anymore compared to the Fourier modes level. We call it noise-induced thermalization, in the spirit of the original numerical studies. The spontaneous MI enters into competition with the seeded MI and the energy is progressively distributed over the entire spectrum [3]. To the best of our knowledge, no experimental study has been performed yet to observe this thermalization behavior. By driving the initial noise power spectral density, we investigate the progressive evolution from a perfectly coherent recursive regime to an irreversible thermalized state.

2. Experimental setup

To observe the transition from a recursive regime to a thermalized state, we implemented experiments with a setup similar to the one used in [2]. A CW pump from a 1550 nm laser diode is first modulated into tens of ns square pulses through an electro-optic intensity modulator. To trigger the coherently-driven MI regime, it is then phase modulated at the frequency $f_m=38.2$ GHz and tuned in relative power and phase into a 3 waves signal (the pump and two symmetric sidebands to have a sine modulation) thanks to a Waveshaper. This is combined with noise pulses, generated from an additional intensity tunable source of white noise. The signal is finally amplified before being injected in a 16.8 km long standard monomode fiber with a group velocity dispersion $\beta_2 = -21$ ps² km⁻¹, a nonlinear coefficient $\gamma = 1.3$ W⁻¹ km⁻¹ and a loss coefficient $\alpha = 0.2$ dB/km. To neglect the attenuation suffered by the signal all along the fiber length, an active loss compensation scheme is also implemented through a counter-propagating Raman amplifier. We then recover the Rayleigh backscattered signal, as in optical time domain reflectometry, and put it into a beating with a frequency comb local oscillator. It allows to retrieve both the relative power and phase evolutions along the fiber length by heterodyning of multiple frequencies of interest (here the pump and seed waves).

3. Results

The input noise is varied from -121.3 to -91.39 dBm/Hz. In Fig. 1 (a), the experimental fiber output spectra are displayed as a function of the input noise power spectral density. It highlights the progressive disappearance of the higher order Fourier modes at the expense of the noise floor when we increase the initial noise. The evolutions of the main Fourier modes (pump and seed waves) are plotted in Figs. 1. (b)-(d) for three specific input noise values. Without adding noise at the fiber input, we notice 3.5 recurrences along the fiber length (Fig. 1 (b)). The process is highly coherent, dominated by the coherently-driven MI. When the input noise level is increased, the energy transfer efficiency between the Fourier modes decreases so that we are able to record only one FPUT recurrence at low

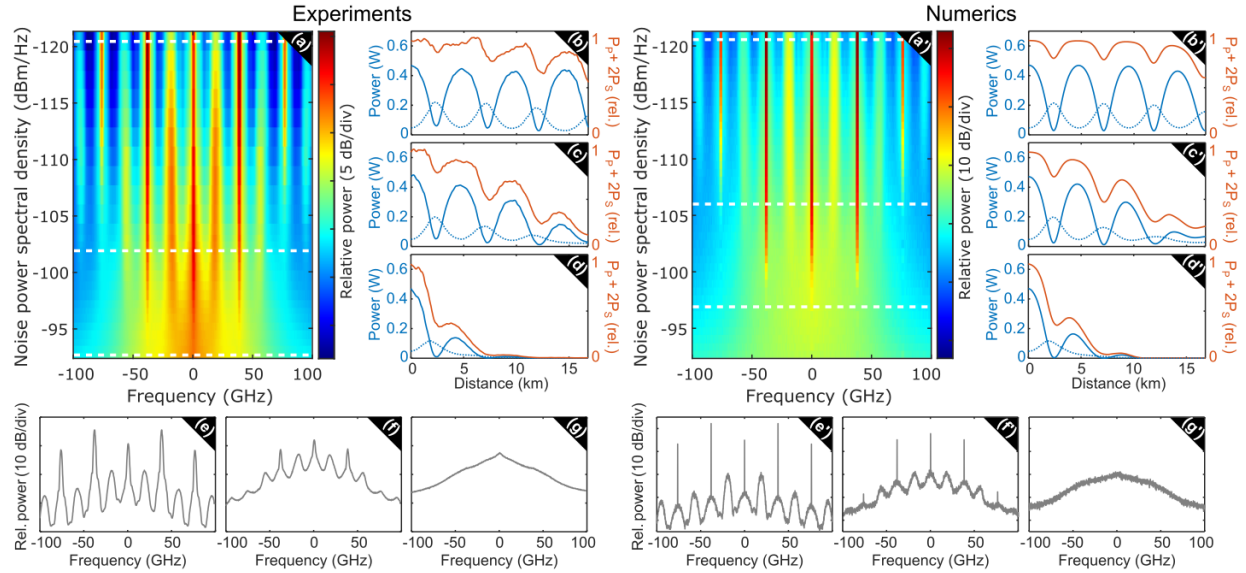


Figure 1. (a,a') Fiber output spectra as a function of the noise power spectral density. (b,b'), (c,c'), (d,d') Power evolutions along the fiber length of the laser pump (solid blue line), the first order modulation sideband, the signal (dotted blue line) and the total power of the initial three waves (pump, signal and idler). (e,e'), (f,f'), (g,g') Output spectra. The left panel is corresponding to the experimental recordings, with the noise power densities which are respectively (-121.3, -101.8, -92.4) dBm/Hz; the right panel is corresponding to numerics, with (-121.3, -106.4, -97.3) dBm/Hz respectively.

initial SNR (Fig. 1 (d)). All the Fourier modes are then dropping into the noise floor because the noise-driven MI is the dominating process there. The output spectra corresponding to the same three distinct values of noise power spectral density, are shown in Figs. 1.(e)-(g). From a frequency comb with Fourier modes much higher than the noise floor at low initial noise, the system evolves until reaching a triangular shaped frequency continuum without distinguishable Fourier modes. We can infer the system reaches an irreversible thermalized state. Those experimental results are in very good agreement with numerical ones (shown in the right panel of Fig. 1), performed by integrating the NLSE.

4. Conclusion

We reported the first experimental observation of a thermalized state of the FPUT recurrences in optical fibers. Thanks to a multi-heterodyning time domain reflectometer system combined with an active loss compensation scheme, we managed to record the irreversible disappearance of the FPUT recurrences at the expense of the noise-driven MI process along the fiber length.

5. References

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