Ordinal time-series analysis of low-frequency fluctuations in semiconductor lasers with optical feedback

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We study experimentally the dynamics of a semiconductor laser with time-delayed optical feedback in the regime of low-frequency fluctuations, where the laser intensity displays sudden and irregular power dropouts, that resemble excitable neuronal spikes. We show that, by using the ordinal methodology of nonlinear, simbolic time-series analysis, we can distinguish signatures of determinism and stochasticity in the sequence of intensity dropout events.

Deterministic nonlinearities and noise are present in many natural systems and there is often the need to distinguish their relative influence in observations of a system variable. In the case of time-delayed systems, this is particularly challenging as time delays results in a infinite-dimensional phase space that can make very tricky to distinguish high-dimensional deterministic dynamics from stochastic dynamics.

A semiconductor laser subjected to optical feedback is a well known example of this situation, as it can display complex dynamics in its output intensity that results from the interplay of deterministic, nonlinear light-matter interactions, spontaneous emission noise and time-delayed feedback effects. Close to the laser threshold the laser dynamics, referred to as Low Frequency Fluctuations (LFFs), consists of suden, irregular power dropouts, followed by gradual recoveries: the sequence of intensity dropouts resembling a sequence of excitable neuronal spikes.

We study the LFF dynamics employing a symbolic methodology of time series analysis known as Ordinal Analysis[1]. We have previously used this method for characterizing the complexity of the laser spikes[2,3] . In this work we show that this method can also yield light into the underlying structure of the laser spiking activity and distinguishes signatures of determinism and stochasticity.

We analyze experimentally measured time traces of the laser intensity, when the laser is biased close to threshold and thus stochastic effects are expected to play a crucial role in the LFF dropouts. More specifically, we analyze the sequence of time-intervals, ΔT_i , between consecutive dropouts (referred to as inter-dropout intervals or IDIs) and transform the sequence of IDIs into a sequence of or dinal patterns, or words. We then study the statistics and the transition probabilities among these words. To further analyze the underlying structure in the sequence of spikes we select a threshold ΔT_{th} that separates the IDI sequence into trains (or bursts) of consecutive short interdropout intervals, that are separated by longer intervals that are assumed to correspond to stable, fixed point (FP) behavior. For adequate values of the threshold ΔT_{th} the differences in the statistics of the words formed by the bursts intervals and by the fixed point intervals allow to interpret the full sequence of LFF dropouts as composed by bursts of consecutive spiking events with a deterministic underlying dynamics, that are separated by stochastic spiking events, associated to noise-induced fixed-point escapes. In addition, the comparison of the statistical distribution of the bursts intervals with recent numerical simulations of transient LFF dynamics based on the Lang-Kobayashi time-delayed model[4] allows interpreting the LFFs observed experimentally as a noise-sustained, deterministic transient spiking dynamics.

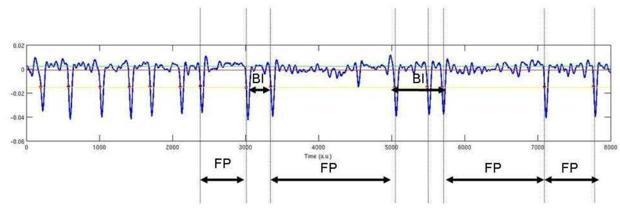

FIG. 1. Experimental time trace of the laser output intensity displaying power dropouts events. The timeintervals between consecutive power dropouts are classified as Fix Point (FP) intervals or Burst Intervals (BI) if they are longer or shorter than a given threshold (ΔT_{th}).

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