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Experimental study of the spiking activity of semiconductor lasers with time-delayed optical feedback

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Abstract—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 neuron-like spikes. We show that, by using ordinal time-series analysis, we can distinguish signatures of determinism and stochasticity in the sequence of spikes.

1. Introduction

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

A semiconductor laser subjected to time-delayed optical feedback from an external reflector (see Fig. 1) is a well known example of this situation. It displays 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 dynamics, referred to as Low Frequency Fluctuations (LFFs), consists of sudden, irregular power dropouts, followed by gradual recoveries (see Fig. 2). This spiking dynamics resembles that of excitable neurons and has received a lot of attention. Several authors have analyzed the LFF dropouts [1, 2, 3, 4, 5, 6, 7, 8] by studying the statistics of the intensity fluctuations and of the time intervals between consecutive dropouts (in the following, referred to as inter-dropout intervals or IDIs).

Here we use the methodology of symbolic time-series analysis to identify signatures of determinism and stochasticity in the LFF dynamics. We transform the sequence of IDIs into a sequence of Ordinal Patterns (OPs, or "words") [9] and study the statistics of this symbolic sequence. In a previous study [8] we found a statistics consistent with fully stochastic dropouts close to threshold, and signatures of a more deterministic behavior at higher current values. Here we present a detailed experimental study of the influence of pump current and temperature variations and find signatures of determinism in all the parameter region studied. A main difference with our previous experiment [8] is that here a grating provides optical feedback. In comparison with a mirror (as used in [8]), the grating significantly reduces the number of active modes, and thus, the stochasticity of the dynamics.

2. Experimental setup

We consider a semiconductor laser (Hitachi Laser Diode HL6724MG) subject to optical feedback from a diffraction grating placed at 45 cm from the laser, which gives a round trip delay time of 3 ns (see Fig. 1). This delay is longer than the intrinsic characteristic time-scales of the solitary laser (the relaxation oscillations being in the pico-second time scale). The solitary laser threshold at 18 C is 27.6 mA. To detect the laser output we use a 50-50 beam-splitter (B. S.), which sends 50% of the incident light to the oscilloscope (Agilent Infiniium 9000, 2.5 GHz, 20 MHz bandwidth) and transmits 50% to the grating. The temperature and pump current are controlled to an accuracy of 0.01 C and 0.01 mA respectively, with a ITC502 Thorlabs laser diode combi controller.

The oscilloscope captured time series of 16 milliseconds that contain about 45,000 power dropouts at low pump currents, and 225,000 power dropouts at high pump currents, allowing to perform a robust statistical analysis.

3. Ordinal pattern analysis of LFFs dropouts

We analyze the sequence of inter-dropout intervals, ΔT_i, (or IDIs, see Fig. 2a) and transform the sequence of IDIs into a sequence of ordinal patterns (OPs) or 'words' using ordinal analysis [9]. The procedure is as in Ref. [8]. For OPs of length $D = 2$ there are only

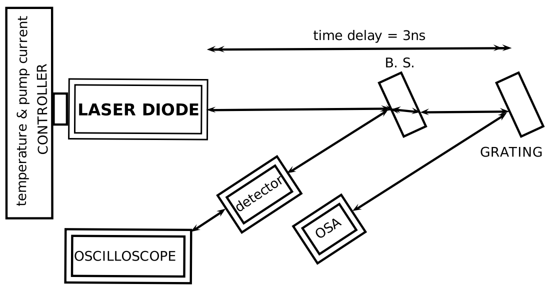

Figure 1: Experimental setup. The beamsplitter (B.S.) sends the light to the oscilloscope and to the grating. The grating sends the light back to the laser and to the optical spectrum analyzer (OSA).

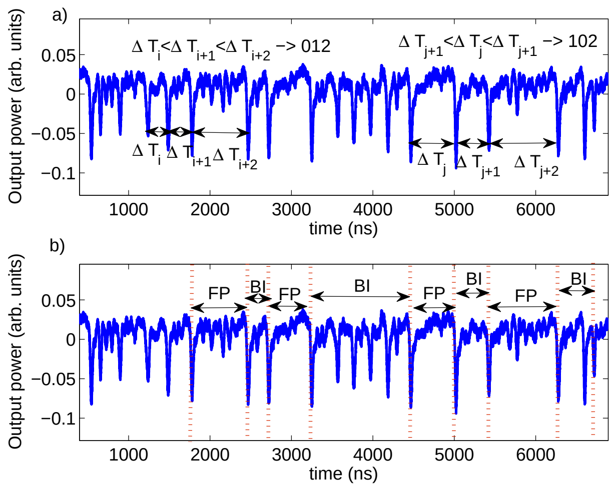

Figure 2: Experimental time trace showing the sudden power dropouts. (a) Transformation of IDIs into ordinal patterns. (b) Splitting of the IDIs into BIs and FPs for the same time trace.

two patterns: $\Delta T_i < \Delta T_{i+1}$ stands for '01' and $\Delta T_i > \Delta T_{i+1}$ stands for '10'. For $D = 3$ there are 6 patterns, and, e.g., $\Delta T_i < \Delta T_{i+1} < \Delta T_{i+2}$ stands for '012', while $\Delta T_i > \Delta T_{i+1} > \Delta T_{i+2}$ stands for '210' (see Fig. 2a). The statistical analysis of the probabilities of the OPs provides information about the correlations among LFFs and the memory of the system between consecutive dropouts.

4. Results

Figure 3 displays the probabilities of the six OPs of length $D = 3$ vs. the pump current for two values of the laser temperature. The left column displays the OP probabilities computed from the original data, and the right column, those computed from surrogated

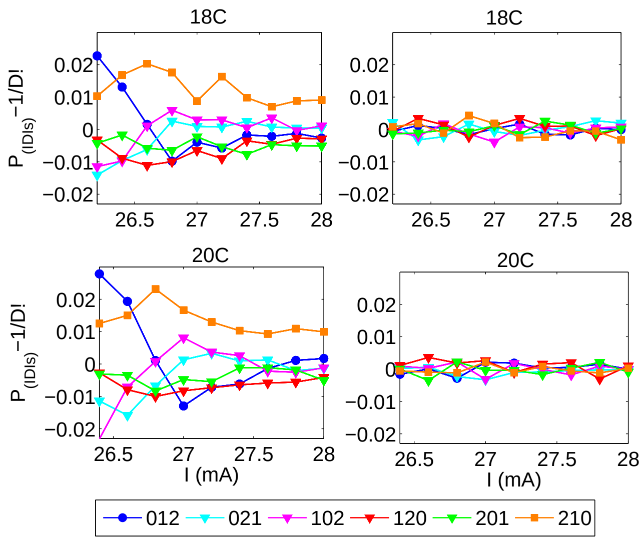

Figure 3: Ordinal patterns probabilities for the IDIs series, P_{IDIs}, for the original data (left column) and for the surrogated data (right column) when the pump current varies while the temperature is kept constant at 18 C (top row) and at 20 C (bottom row). As 1/D! has been subtracted to the probabilities, in the vertical axis the zero corresponds to equally probable OPs.

data. In these plots we subtracted $1/D!$ and thus positive values correspond to more probable words and negative values correspond to less probable words.

With the OPs calculated from the original data one can observe a behavior different from a purely stochastic dynamics (as is observed with surrogated data). For low pump currents the signatures of determinism are higher. Here the difference between the most probable word and the less likely one is larger than for higher pump currents, although for high pump currents the probabilities still remain different from the fully random case.

The results are robust to temperature variations as they are observed at two temperature values. Comparing the top and bottom panels in Fig. 3 one can observe that the tendency of the words probabilities is the same. For low pump currents the words '012' and '210' are the most probable ones but, as the pump current increases, '012' decreases sharply and '210' remains as the most probable one. At lower pump currents (not shown) increasing the temperature while keeping the pump current constant has a similar effect as decreasing the pump current while keeping the temperature constant: in both cases, the '012' becomes the most probable OP.

To further analyze the underlying structure of the sequence of power dropouts we select a threshold, ΔT_{th}, that separates the IDIs into bursts of consecutive short intervals (refereed to as BIs) that are sep-

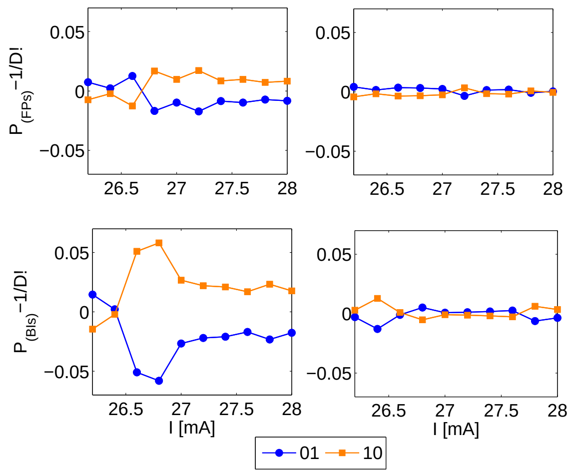

Figure 4: Probabilities of the $D = 2$ OPs formed with consecutive Fixed Point intervals (top row) and Bursts Intervals (bottom row) for the original data (left column) and the surrogated data (right column). The laser pump current is varied while the temperature is fixed at T=18 C.

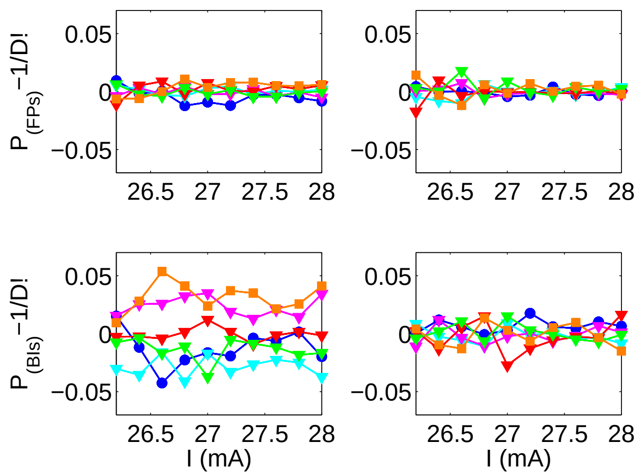

Figure 5: As Fig. 4 but for $D = 3$ OPs.

arated by longer IDIs that are assumed to correspond to stable, fixed point emission (referred to as FPs, see Fig. 2b). While the system is in the fixed point in the phase space, it emits a nearly constant output power, but, due to the influence of noise, when it escapes it develops a burst of LFFs (a series of consecutive short BIs) until it finds and returns to the fixed point, where it stays (long FP) until it escapes again due to the noise. There can be a single dropout before returning to the FP or a burst of consecutive short dropouts.

This classification transforms the IDI sequence into BIs and FPs sequences. These new sequences have less events than the IDIs series but still high enough to perform a robust statistical ordinal analysis. An adequate selection of the threshold, ΔT_{th}, is crucial in order to obtain two sequences with significantly different statistics. We found that this occurs when the threshold ΔT_{th} is the most probable IDI value. With this choice, the probability distribution function of the FPs (the IDIs longer than ΔT_{th}) is an exponentially decaying distribution, which is consistent with noise-induced escape times.

With this choice of ΔT_{th}, as can be observed in Figs. 4 and 5, the probabilities of the OPs formed with consecutive FPs appear almost random for all pump currents, as it is expected for noise-induced escapes. On the contrary, the probabilities of the OPs formed with consecutive BIs are more deterministic. They are also more deterministic than the IDIs OPs (i.e., without splitting the IDI sequence in two), as the stochastic contribution of the FPs has been removed. Notice that the vertical axes in Fig. 5 go from -0.07 to 0.07 while those in Fig. 3 go from -0.02 to 0.03. The signature of more deterministic behavior is found for intermediate pump currents. These observations are robust to small variations of the threshold ΔT_{th} around the most probable IDI value.

5. Conclusions

Ordinal time-series analysis has been found to be a useful methodology for the study of the stochastic dynamics of a semiconductor laser with time-delayed optical feedback. We have shown that it allows to distinguish signatures of determinism and stochasticity in the sequence of intensity dropout events.

The analysis suggests the existence of an underlying structure in the IDI sequence. For adequate values of the threshold, ΔT_{th}, that was used to separate the IDIs into the two categories (BIs and FPs), the differences in the statistics of the OPs formed by consecutive BIs and by consecutive FPs allow to interpret the full sequence of LFF dropouts as composed by bursts of short dropouts with a deterministic underlying dynamics, that are separated by longer time-intervals that finish with dropouts that are associated to noise-induced fixed-point escapes. This structure is observed with both, $D = 2$ and $D = 3$ OPs.

With this methodology one can in principle discriminate which dropouts correspond to stochastic escapes from a stable state and which to a deterministic transient back to the stable state. However, the selection of the threshold that separates the IDIs into these two categories is quite arbitrary and naturally there will be short FP intervals that are wrongly classified as BIs, and longer deterministic intervals that are wrongly classified as FPs. Nevertheless, we found significant differences in statistics of the OPs formed by these two groups of IDIs that suggest that different physical mechanisms are at the origin of the dropouts in the two categories.

The ordinal method proposed here can be applied to other stochastic time-delayed systems, as it can be used to distinguish signatures of noise-induced dynamics from deterministic, high-dimensional delay-induced dynamics.

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