Are the Spikes Emitted by a Semiconductor Laser with Feedback Similar to Neuronal Spikes?

C. Quintero-Quiroz[1], T. Sorrentino[1,2], A. Aragoneses[1,3], M. C. Torrent[1], and C. Masoller[1]

[1]*Departament de Física, Universitat Politècnica de Catalunya, Colom 11, Terrassa 08222, Barcelona, Spain*

[2]*Departamento de Ciencias Exatas e Naturais, Universidade Federal Rural do Semi-Arido, Av. Francisco Mota 572, 59625-900 Mossoro, RN, Brazil*

[3]*Department of Physics and Astronomy, Carleton College, One N. College st., 55057, Northfield, MN, USA*

e-mail: cristina.masoller@upc.edu

ABSTRACT

We study experimentally a semiconductor laser operating in a feedback-induced regime known as low frequency fluctuations (LFFs), in which the laser emits a spiking output that resembles the spikes of biological neurons. We analyze the response to a weak periodic signal that is directly applied to the laser pump current, as a function of the frequency of the signal, and discuss the observations in relation to the response of sensory neurons.

Keywords: semiconductor lasers, optical feedback, current modulation, chaos, excitability, photonic neurons.

1. INTRODUCTION

In semiconductor laser the effects of optical feedback have attracted attention for more than three decades for being important both for applications and basic research [1]. For applications optical feedback can be either detrimental or beneficial. In optical communications and information processing systems the performance of semiconductor lasers is substantially degraded by fed back light from external reflectors such optical disk surfaces and fibre connectors. On the other hand, external cavities using a frequency selective reflector, usually a diffraction grating, reduce the linewidth, enhance frequency stability and allow the continuous tuning of the laser wavelength over several nanometres. Interferometric applications of optical feedback have also been developed, allowing measurements of displacement, distance, vibration and velocity [2].

From a basic research point of view, semiconductor lasers with optical feedback provide an excellent benchmark for studies of optical nonlinear dynamics and chaos. Following the dynamical classification of lasers by Arecchi *et al*. [3], semiconductor lasers are class B lasers, and their dynamical behaviour is determined by the evolution in time of two variables, the carrier and photon densities. Class B lasers can oscillate, but cannot present chaotic dynamics by themselves. However, the number of degrees of freedom increases when an external perturbation is applied, such optical feedback or current modulation, and then the laser can display a chaotic output. Since optical feedback is a time-delayed perturbation (due to the finite photon round trip time in the external cavity) the re-injection of the 'past state' in the system's present state renders the system infinite dimensional and, thus, opens the door to high-dimensional chaos. This feedback-induced generation of high-dimensional chaos, regarded as fundamental research in the past decades, has found many practical applications (see [4] for a recent review).

Optical feedback induces different dynamical regimes, depending on several parameters. Regarding the length of the external cavity, two regimes are in general distinguished: the short cavity regime, if the feedback delay time is shorter than the relaxation oscillations period and the long cavity regime, if the delay time is much longer than the relaxation oscillations period. In the long cavity regime, when varying the feedback strength, five regimes have been identified [5]. If the feedback strength is very small, the linewidth of the laser may become narrow depending on the phase of the re-injected light (regime I). For increasing feedback (regime II) external modes play a role giving rise to mode hopping. For even higher feedback (regime III) mode hopping is suppressed and the laser oscillates with a very narrow linewidth. For moderated feedback (regime IV) the relaxation oscillations become undamped and the linewidth of the laser is highly broadened. For even stronger feedback (regime V) the laser oscillates once again with narrow linewidth, but in a mode of the compose cavity.

The third parameter that strongly affects the dynamics of semiconductor lasers with optical feedback is the injection current. In the long cavity regime and under moderate feedback, Besnard *et al*. [6] and Heil *et al*. [7] proposed a classification, which distinguishes three regimes (see Fig. 1): at low pump current the laser intensity displays noisy fluctuations (stationary regime), at higher pump current it displays abrupt, apparently random dropouts (low-frequency fluctuations, LFF regime) and at even higher pump current, it displays very fast and irregular oscillations (coherence collapse, CC regime). The gradual transition from noisy fluctuations to LFFs and then to the CC regime, as the pump current is increased, was recently studied in [8] by using different nonlinear time-series analysis tools.

Here we focus in the LFF dynamics, characterized by intensity dropouts that are followed by a slow, step-like recovery of the intensity. The time duration of the recovery "steps" is the external cavity round trip time. The dynamics has been referred to as low-frequency fluctuations because the average frequency of the dropouts (several MHz) is much slower than the characteristic frequencies of the system: the frequency of the relaxation oscillations (a few GHz) and the external cavity frequency (hundreds of MHz). It has been shown that the dropouts are actually the envelope of fast (tens of picoseconds) pulses [9] that, due to the limited bandwidth of the detection system used in our experiments, cannot be observed.

We are interested in the LFF regime because the spiking output resembles the spikes of biological neurons. Thus, in this regime semiconductor lasers have potential to act as ultra-fast photonic neurons [10], which can be building blocks of novel information processing systems, inspired in the way biological neurons process information. In order to use the laser in the LFF regime as a basic information processing unit, it is crucial to understand how the information is encoded in the output sequence of optical spikes. Here we analyze the response to a weak periodic signal that is directly applied to the laser pump current. We study experimentally the statistical properties of the emitted optical spikes, as a function of the input frequency, and discuss the observations in relation to the response of sensory neurons. Despite the fact the dynamics of the laser with optical feedback is high-dimensional, while the dynamics of single sensory neurons is typically low-dimensional, remarkable similarities between them are found, due to excitability.

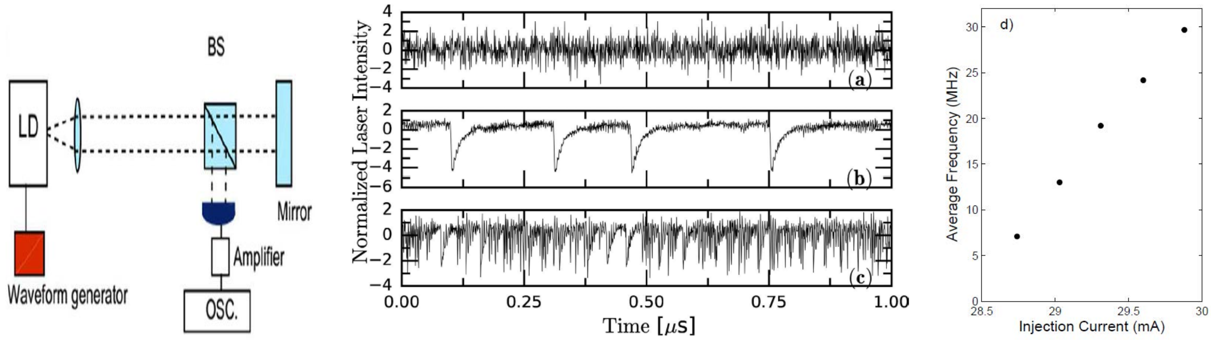

Figure 1. Left: Experimental setup: LD stands for laser diode, BS for beam-splitter and OSC for oscilloscope. Right: Typical intensity time-series, normalized to zero mean and unit variance: (a) noisy fluctuations, (b) dropouts in the LFF regime and (c) fast fluctuations in the coherence collapse regime. The laser pump current, normalized to the threshold current of the solitary laser is I/Ith = 0.95, 1.02 and 1.20, respectively. The horizontal axis is the same in the three panels [8], (d) during the transition to coherence collapse the frequency of the dropouts increases linearly with the injection current.

2. EXPERIMENTAL SETUP

The experimental setup is schematically shown in Fig. 1. A semiconductor laser emitting at 650 nm (Sony SLD1137VS) was used; the external cavity was 70 cm (giving a feedback time delay of 4.7 ns). The laser temperature and current were stabilized with an accuracy of 0.01 °C and 0.01 mA, respectively, using a combi controller (Thorlabs ITC501). A 50/50 beam-splitter in the external cavity sends light to the detection branch consisting of a photodetector (Thorlabs DET210) connected to an amplifier (FEMTO HSA-Y-2-40) and a 1 GHz oscilloscope (Agilent Technologies Infiniium DSO9104A). A neutral density filter in the external cavity allows controlling the feedback power. The DC pump current was 29.10 mA, the laser was operated at 19.00 °C and a threshold reduction due to feedback of 7% was observed.

Through a bias-tee in the laser mount, the pump current was modulated with a sinusoidal signal provided by a waveform generator (Agilent 33250A), with frequency varying from 1 to 50 MHz in steps of 1 MHz, and a peak-to-peak amplitude varying from 0.8% to 2% of the dc value, in steps of 0.4%. For these modulation amplitudes the laser current was always above the solitary threshold. The experiment is controlled by a LabVIEW program that acquires the intensity time series, detects the optical spikes (i.e., the intensity dropouts), and calculates the inter-spike-intervals (ISIs) until 40,000 ISIs are recorded. Then, the program changes the modulation frequency and/or amplitude, waits a few seconds to let transients die away, and the process is repeated.

3. RESULTS

Figure 2 displays the intensity time series, the probability distribution functions (PDFs) of the inter-spike intervals, T_i (ISIs), and the return maps, i.e., the plot of one interval vs. the next (T_i vs. T_{i+1}), for four modulation frequencies and a weak modulation amplitude (0.8% of the pump current dc value). As it has been reported in the literature [11, 12, 13], current modulation entrains the dropouts which tend to occur at the same phase of the drive cycle, and the ISIs are multiples of the modulation period, $T_{\mathrm{mod}} = 1/f_{\mathrm{mod}}$. For increasing modulation frequency, the ISIs become progressively higher multiples of T_{mod}, as seen in the PDF that presents a strong peak at an increasing large integer number of T_{mod}. However, we note in the right panel of Fig. 2 that the actual value of the mean inter-spike interval tends to decrease (non-monotonically) with f_{mod}, i.e., the spikes become faster with increasing modulation frequency.

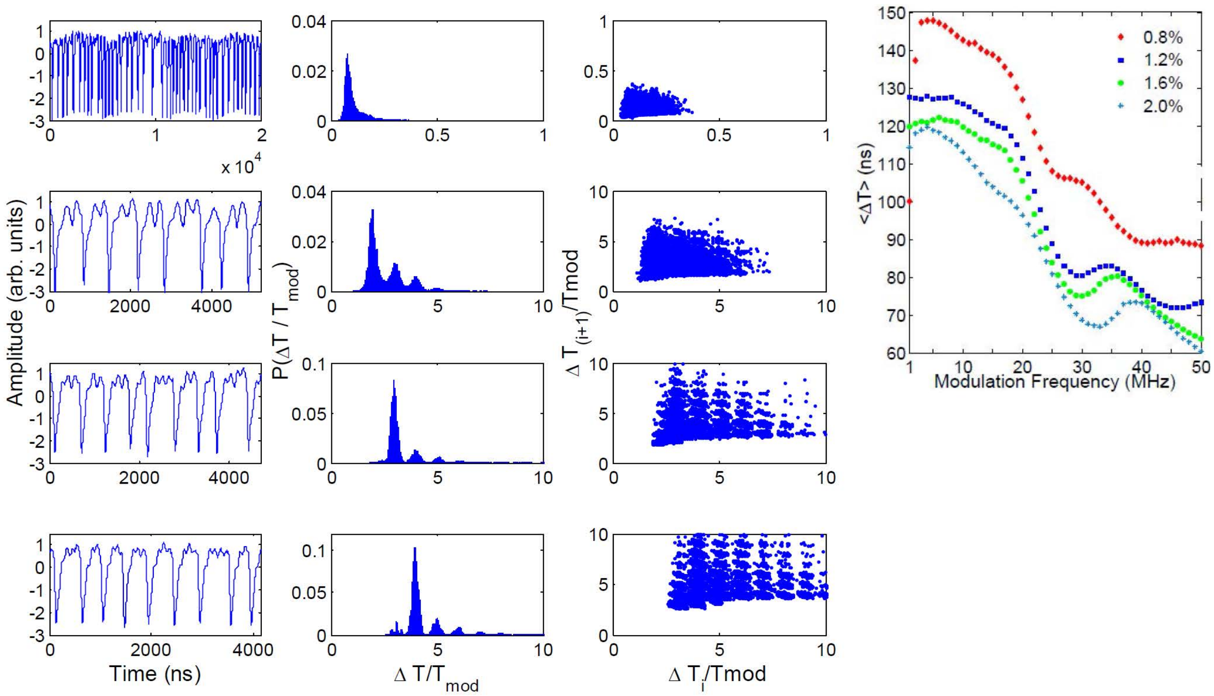

Figure 2. Time-traces of the laser output intensity, probability distribution functions (PDFs) of the inter-spike intervals (ISIs), and return maps (plot of one interval, T_i vs the next interval, T_{i+1}, in units of the modulation period, T_{mod}) for increasing modulation frequency, from top to bottom: 1 GHz, 22 GHz, 36 GHz and 50 MHz. The modulation amplitude is 0.8% of the pump current dc value. The right panel displays the mean inter-spike interval vs. the modulation period for four values of the modulation amplitude (in units of the pump current dc value) and it can be noticed that the mean ISI tends to decrease, but not monotonically.

The return maps (third column of Fig. 2) display a clustered structure, with “islands” that correspond to the well-defined peaks observed in the PDFs, also in good agreement with previous reports [11, 12, 13]. The return maps are almost symmetric, suggesting that consecutive ISIs are uncorrelated (i.e., $T_i > T_{i+1}$ and $T_i < T_{i+1}$ are equally probable); however, in [14] we have shown, by using a symbolic method of time-series analysis, the presence of correlations in the ISI sequence, which depend on the frequency of the external modulation.

4. DISCUSION AND CONCLUSIONS

Entrainment dynamics due to external weak periodic forcing has been observed in biological neurons, and very similar ISI distributions have been reported. For example, in [15] an experimental ISI PDF was analysed from a single auditory nerve fibre of a squirrel monkey with a sinusoidal low sound-pressure-level stimulus applied at the ear, and an analytical two-state model was developed, which explained the main features of the PDF as due to the firing-reset mechanism of neurons. More recently [16], temporal ISI correlations detected in the LFF dynamics were interpreted in terms of a minimal model (a modified circle map) which has also been used to explain ISI correlations in sensory neurons (electroreceptors) of paddlefish [17]. A detailed comparison is in progress and will be reported elsewhere.

To summarize, we have studied experimentally the dynamics of a semiconductor laser with optical feedback, in the regime of low-frequency-fluctuations (LFF), and analysed the properties of the inter-spike-intervals (ISIs) when a weak periodic modulation is applied to the laser pump current. We have found the expected entrainment to the external signal, characterized by an ISI probability distribution function (PDF) which has peaks at integer values of the modulation period. As the modulation frequency increases, the strongest peak in the PDF occurs at an integer number of the modulation period which increases with the modulation frequency.

ACKNOWLEDGEMENTS

This work was supported in part by Spanish MINECO (FIS2015-66503-C3-2-P) and ITN NETT (FP7 289146). C. M. also acknowledges partial support from ICREA ACADEMIA.

REFERENCES

[1] J. Ohtsubo: *Semiconductor Lasers: Stability, Instability and Chaos*, New York: Springer-Verlag, 2012.
[2] S. Donati: Developing self-mixing interferometry for instrumentation and measurements, *Laser and Photonics Reviews*, vol. 6, no. 3, pp. 393–417, 2012.

[3] F. T. Arecchi, G. L. Lippi, G. P. Puccioni, and J. R. Tredicce: Deterministic chaos in laser with injected signal, *Optic Communications*, vol. 51, pp. 308–314, 1984.
[4] M. Sciamanna and K. A. Shore: Physics and applications of laser diode chaos, *Nature Photonics*, vol. 9, pp. 151–162, 2015.
[5] R. Tkach and A. Chraplyvy: Line broadening and mode splitting due to weak feedback in single frequency 1.5 µm lasers, *Electronics Letters*, vol. 21, pp. 1081–1083, 1985.
[6] P. Besnard, B. Meziane, and G. M. Stephan: Feedback phenomena in a semiconductor laser induced by distant reflectors, *IEEE Journal of Quantum Electronics*, vol. 29, pp. 1271–1284, 1993.
[7] T. Heil, I. Fischer, and W. Elsässer: Coexistence of low-frequency fluctuations and stable emission on a single high-gain mode in semiconductor lasers with external optical feedback, *Physical Review A*, vol. 58, pp. R2672–R2675, 1998.
[8] C. Quintero-Quiroz, J. Tiana-Alsina, J. Romà, M. C. Torrent, and C. Masoller: Quantitative identification of dynamical transitions in a semiconductor laser with optical feedback, *Scientific Reports*, 6:37510, 2016.
[9] I. Fischer, G. van Tartwijk, A. M. Levine, W. Elsasser, E. Gobel, and D. Lenstra: Fast pulsing and chaotic itinerancy with a drift in the coherence collapse of semiconductor lasers, *Physical Review Letters*, vol. 76, pp. 220–223, 1996.
[10] P. R. Prucnal, B. J. Shastri, T. F. de Lima, M. A. Nahmias, and A. N. Tait: Recent progress in semiconductor excitable lasers for photonic spike processing, *Advances in Optics and Photonics* , vol. 8, pp. 228-299, 2016.
[11] M. Giudici, C. Green, G. Giacomelli, U. Nespolo, and J. R. Tredicce: Andronov bifurcation and excitability in semiconductor lasers with optical feedback, *Physical Review E*, vol. 55, pp. 6414–6418, 1997.
[12] D.W. Sukow and D. J. Gauthier: Entraining power-dropout events in an external-cavity semiconductor laser using weak modulation of the injection current, *IEEE Journal of Quantum Electronics*, vol. 36, pp. 175–183, 2000.
[13] A. Aragoneses, T. Sorrentino, S. Perrone, D. J. Gauthier, M. C. Torrent, and C. Masoller: Experimental and numerical study of the symbolic dynamics of a modulated external cavity semiconductor laser, *Optics Express*, vol. 22, pp. 4705–4713, 2014.
[14] T. Sorrentino, C. Quintero-Quiroz, A. Aragoneses, M. C. Torrent, and C. Masoller: Effects of periodic forcing on the temporally correlated spikes of a semiconductor laser with feedback, *Optics Express*, vol. 23, pp. 5571–5581, 2015.
[15] A. Longtin, A. Bulsara, and F. Moss: Time-interval sequences in bistable systems and the noise-induced transmission of information by sensory neurons, *Physical Review Letters*, vol. 67, pp. 656-659, 1991.
[16] A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent, and C. Masoller: Unveiling the complex organization of recurrent patterns in spiking dynamical systems, *Scientific Reports*, vol. 4, p. 4696, 2014.
[17] A. B. Neiman and D. F. Russell: Models of stochastic biperiodic oscillations and extended serial correlations in electroreceptors of paddlefish, *Physical Review E*, vol. 71, 061915, 2005.