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Experimental study of the neuron-like dynamics of a semiconductor laser with optical feedback and current modulation

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ABSTRACT

Excitable lasers that mimic neuronal activity can be building blocks of ultra-fast neuro-inspired information processing systems, which can revolutionize the fields of optical signal processing, optical computing and artificial intelligence. To implement such photonic neurons, we must first identify low-cost and energy-efficient lasers whose excitable dynamics mimics neuronal dynamics. Here we conduct an experimental study of the dynamics of a diode laser with optical feedback from an external cavity. We focus on the response of the laser when is under weak periodic perturbations that are implemented via direct modulation of the laser pump current. We consider sinusoidal and pulsed waveforms. The dynamics of the laser intensity is compared with the dynamics of the membrane potential of a neuron, which is simulated with the FitzHugh-Nagumo (FHN) model. The analysis of the statistics of the time intervals between dropouts of the laser intensity (optical spikes) and of the time intervals between the neuron's action potentials (or spikes) unveils similarities, and also differences. The analysis of the spike rate reveals a variation with the amplitude and with the frequency of the external signal that is similar for both, the laser and the FHN neuron. Therefore, in terms of the spike rate, the laser response to a weak periodic signal mimics the response of a FHN neuron, and thus diode lasers with optical feedback can be used to implement photonic neurons. A drawback of this implementation is the length of the feedback cavity, which prevents on-chip integration.

Keywords: semiconductor lasers, diode lasers, optical feedback, excitable lasers, neuromorphic photonics

1. INTRODUCTION

Neuromorphic photonics is a research field that can revolutionize optical signal processing, optical computing and artificial intelligence.¹⁻⁴ Optical neural networks can potentially outperform (by orders of magnitude) electronic neural networks, both, in signal processing speed and in energy consumption. However, to implement such ultra-fast photonic neural networks we need to identify low-cost and energy-efficient excitable lasers whose output mimics neuronal activity. Diode lasers are good candidates because they are compact, inexpensive and efficient. Neuron-like excitability has been demonstrated when a diode laser is under optical injection from another laser,^{5,6} or under optical feedback from an external reflector.⁷⁻⁹

Here we consider a diode laser with optical feedback operating in the so-called low-frequency fluctuation (LFF) regime.¹⁰ In this regime, which occurs close to threshold with weak to moderate feedback levels, the laser intensity shows sudden dropouts, which are followed by gradual, stepwise recoveries. We refer to the intensity dropouts as optical spikes.

We analyze experimentally how the intensity spiking dynamics is affected by a weak periodic perturbation (a sinusoidal or a pulsed signal) that is directly applied to the laser pump current. We compare the laser spiking dynamics with that of a synthetic neuron that is simulated with the well-known FitzHugh-Nagumo (FHN) model.^{11,12} Long spike sequences are experimentally recorded, and they are also simulated numerically. The analysis of the statistical properties of the relative timing of the optical spikes and of the neuron spikes unveils similarities, but also some differences. On the other hand, the analysis of the laser spike rate reveals a variation

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Figure 1. Experimental setup. SL: semiconductor laser; BS: beam-splitter; M: mirror; L: lens; PD: photo-detector.

with the amplitude and with the frequency of the periodic signal that is similar to that shown by the FHN neuron. Therefore, in terms of the spike rate, the laser response to a weak periodic pump current perturbation mimics the response of a FHN neuron, and thus the laser could be used to implement a photonic neuron.

This paper is organized as follows. Section 2 describes the experimental setup, section 3 presents the FitzHugh-Nagumo (FHN) model, section 4 presents the comparison of the laser spikes and the simulated spikes, and section 5 presents a discussion of the results and the conclusions.

2. EXPERIMENTAL SETUP

The experimental setup is as described in 1. A semiconductor laser (685 nm Thorlabs HL6750MG with solitary threshold $I_{th,sol} = 26.62$ mA), has part of its output fed back to the laser by a mirror. The feedback produced a 7.2% threshold reduction ($I_{th,fed} = 24.7$ mA). The length of the external cavity is 70 cm, which gives a delay time of 5 ns. The laser temperature and current were stabilized with 0.01 C and 0.01 mA accuracy, respectively. A 90/10 beam-splitter in the external cavity sends light to a photodetector (Det10A/M), an amplifier (Femto HSA-Y-2-40), and a 1 GHz oscilloscope (Agilent DSO9104A). The laser is electrically pumped through a 500 MHz bias-tee that combines a constant dc current, $I_{dc} = 26$ mA, with a periodic signal from a function generator (Agilent 81150A). Sinusoidal and pulsed waveforms were used. The duration of the pulse was the shortest available: 5 ns with raising and falling times of 2.5 ns each. The modulation frequency was varied from 1 MHz to 80 MHz in 79 steps of 1 MHz each. The spike rate of the laser without modulation is 3.3 MHz.

The peak to peak modulation amplitude was varied from 0.19 to 0.631 mA in 7 steps of 0.063 mA. Therefore, the modulation amplitude, for the dc value of the pump current used during the experiment, 26 mA, represents a variation between 0.8% and 2.4% of the dc level.

A LabVIEW program was used to control the experiment and for each set of parameters, intensity time series with 10^7 data points were recorded with 2 GS/s sampling rate, which allowed to capture the intensity dynamics during 5 ms. Figures 2(a) and 2(b) (without and with modulation respectively) display a short time interval (2 μ s) during which typical abrupt drops of the intensity (referred to as spikes) can be seen. The spikes are irregular in the absence of current modulation, and become regular when the external signal modulates the laser current.

The intensity time series typically contains more than 10^4 spikes. The interspike intervals (ISIs) are $\Delta T_i = t_i - t_{i-1}$, where t_i are the spike times, which were detected using the following method. First, each time series is normalized to unit variance (the dc value is removed by the amplifier, so the time series has zero mean). Then, a spike is detected whenever the intensity drops below a threshold, equal to -1.5 in units of the standard deviation. To avoid detecting as spikes the fluctuations that occur during the recovery process, the intensity has to grow above the zero mean value, before another spike can be detected.

Figure 2. Example of the experimental intensity time series (solid line) and the signal that modulates the laser current (dashed line). In panel (a) no modulation is applied; in (b) and (c) the signal produces 1:1 and 2:1 locking respectively.

3. FITZHUGH-NAGUMO MODEL

The FitzHugh-Nagumo (FHN) model^{11,12} is a popular model of neuronal activity. The model equations are:

$$\epsilon \dot{u} = u - \frac{u^3}{3} - v + s(t) + \sqrt{2D}\xi(t), \quad (1)$$

$$\dot{v} = u + a, \quad (2)$$

where the two dimensionless variables u and v are a fast voltage-like variable and a slow recovery-like variable, also called activator and inhibitor variables, respectively; $s(t)$ represents an external input signal, and $\xi(t)$ represents Gaussian white noise of intensity D . a and ϵ are parameters that control the spiking activity of the neuron: for $|a| < 1$ without any perturbation ($D = s = 0$) the neuron fires periodic (tonic) spikes, while for $|a| > 1$ the neuron is in the excitable regime: if a small perturbation occurs (below a certain threshold) the neuron returns to the stable state after a small oscillation. On the contrary, if the perturbation is above the threshold, then, there is a large excursion in the phase space, which is known as action potential or spike. After the spike the neuron returns to the rest state and a refractory period follows during which another perturbation can not trigger another spike.

The input signal $s(t)$ is periodic, with sinusoidal or pulsed waveform. For a precise comparison the same signal that modulates the laser current is used; however, to trigger spikes the pulsed waveform is inverted, as shown in Fig. 2. In the FHN model the signal is included in the rate equation of the fast variable because of the biophysical mechanisms of spike generation (sufficiently large inputs change the neuron's membrane potential and generate electrical pulses, known as action potentials or spikes); in contrast, in the laser the signal is applied to the pump current, which is coupled to the intensity dynamics via the dynamics of the carriers.

The FHN equations were simulated with parameters in the excitable regime, $a = 1.05$, $\epsilon = 0.02$ and $D = 10^{-5}$. For these parameters the natural spike rate of the neuron (without the external signal) is 0.12 arb. units. The signal amplitude was varied between 0.03 and 0.07, and the signal frequency was varied from 0.02 to 1.2 arb. units. These values were found to give a good agreement with the empirical laser data.

Figure 3. Example of the simulated neuronal spikes ($u(t)$, solid line) and the modulating signal (dashed line). In panel (a) no modulation is applied; in panels (b) and (c) the signal produces no locking and 1:1 locking respectively.

4. COMPARISON OF EMPIRICAL AND SIMULATED SPIKE SEQUENCES

Figure 4 displays in color code the ISI distribution for the empirical laser ISIs (a,b) and for the simulated neuronal ISIs (c,d). The signal waveform is sinusoidal in panels (a), (c) and pulsed in panels (b), (d). The ISI values are normalized to the period of the signal, T_{mod} ; therefore, the plateaus seen for $ISI/T_{mod} = 1, 2, 3, \dots$ reveal the characteristic locking structure of periodically forced excitable systems. In the following, locking $n:1$ means that the laser, or the neuron, emits a spike every n cycles of the modulation.

For the laser ISIs, with sinusoidal modulation, Fig. 4(a), locking regions 2:1 and 3:1 are observed, located at ~ 30 MHz and ~ 50 MHz, respectively. With pulsed modulation, Fig. 4(b), at lower frequencies locking 1:1 is also seen [for 7 MHz the intensity time series was shown in Fig. 2(b)]. With both waveforms, at higher frequencies the laser is unable to lock and the ISI distribution is multi-modal. The waveform affects the laser ISI distribution mainly at low frequencies (below ~ 30 MHz).

For the neuron ISIs, with sinusoidal modulation, Fig. 4(c), locking regions 2:1, 3:1 and 4:1 are clearly observed as narrow plateaus. At low frequencies, there is a wider plateau that corresponds to noisy 1:1 locking. In contrast to the laser, even at high frequencies (not shown) the neuron ISIs show locking plateaus, multimodal peaks being observed only during the transitions between $n:1$ and $(n+1):1$ locking. With the pulsed waveform, Fig. 4(d), the locking is noisier, as revealed by wider plateaus, in comparison with the plateaus produced by the sinusoidal waveform.

The locking plateaus in the four panels of Fig. 4 reveal that at low frequencies the laser and the neuron ISI distributions agree qualitatively well for both, the sinusoidal and the pulsed waveforms, while at high frequencies the responses of the laser and the neuron are different.

Next, we characterize the laser and the neuron responses to the external signal by analyzing how the average spike rate (the inverse of the mean ISI) depends on the signal's amplitude and frequency. The results are presented in Fig. 5 that displays in color code the spike rate for sinusoidal [Figs. 5(a), (c)] and pulsed [Figs. 5(b), (d)] waveforms for the laser ISIs [Figs. 5(a), (b)] and for the neuron ISIs [Figs. 5(c), (d)].

For the laser, with the sinusoidal waveform, Fig. 5(a), locking 1:1 is not seen, but is produced by pulsed modulation (narrow region in panel b). At high frequencies the laser spike rate is similar for both waveforms.

Figure 4. Interspike interval (ISI) distribution as a function of the frequency of the signal for (a,b) the laser ISIs with a modulation amplitude of 0.62 mA (2.4% of I_{dc}), and for (c,d) the simulated neuronal ISIs with $a_{mod} = 0.07$. The modulation waveform is sinusoidal in (a), (c) and pulsed in (b), (d). In order to enhance the plot contrast, the color scale indicates the logarithmic of the number of ISIs (the white color stands for zero counts). The vertical axis displays the ISI normalized to the period of the signal.

For the neuron, the variation of the spike rate with the signal's amplitude and frequency is qualitatively similar to the laser, but locking 1:1 is seen with both waveforms. We note that for the lower amplitudes the locking regions are wider for the sinusoidal waveform than for the pulsed one. We also note that, for the lowest frequencies, the spike rate of the laser and the spike rate of the neuron are almost unaffected by the signal (blue regions at low frequencies in the four panels of Fig. 5).

5. DISCUSSION AND CONCLUSIONS

We have studied experimentally a semiconductor laser with optical feedback and current modulation operating in the low-frequency fluctuation (LFF) regime, and compared the intensity spiking dynamics with the dynamics of a FitzHugh-Nagumo (FHN) neuron, which is modulated with the same input signal that modulates the laser current (sinusoidal or pulsed). We have compared the distributions of inter-spike-intervals (ISIs) and found a good qualitative agreement at low modulation frequencies. We have also compared how the laser's spike rate and the neuron's spike rate depend on the amplitude and on the frequency of the signal, and found a qualitative good agreement. As future work, it would be interesting to compare the laser and neuron responses to aperiodic signals.

Our results suggest that, under appropriated conditions (when the laser operates in the LFF regime), a diode laser with optical feedback from an external cavity could act as a photonic neuron in neuromorphic systems that use spike rate coding for information processing. A drawback of this implementation is that the length of the external cavity prevents the laser integration in a chip.

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Figure 5. The average spike rate (i.e., the inverse of the mean ISI) in color code vs. the amplitude and the frequency of the signal, for (a,b) the laser ISIs and for (c,d) the neuron ISIs. The waveform is sinusoidal in (a), (c); pulsed in (b), (d).

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