Noise-induced excitable pulses in a two-section semiconductor laser: a first-passage time analysis

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Abstract: *A two-section semiconductor laser can exhibit excitability for certain parameter settings. When used as a photonic spiking neuron, it is relevant to investigate its sensitivity to noise due to, e.g., spontaneous emission. Under excitable conditions, the system emits irregularly timed noise-triggered pulses. Their statistics is analysed in terms of a first-passage time distribution for the fluctuating intensity to reach the threshold for excitable response. Two analytic approximations valid for short and long times, respectively, are derived which very well explain measured pulse-repetition time distributions. This provides physical insight into the noise-triggered spiking mechanism.*

1. Introduction

The principles of a biological spiking neural network (SNN) can be transferred to integrated photonics due to the spiking capabilities of semiconductor lasers [1]. Integrated photonic SNNs benefit from high switching speed, high communication bandwidth, low crosstalk [2] and temporal characteristics governed by ultra-fast carrier dynamics [3]. This results in the operation of an optical neuron orders of magnitude faster than its biological counterpart. These semiconductor lasers can be the building block in an all-optical SNN on a photonic integrated circuit (PIC).

One successful realization of a photonic spiking neuron is by using an integrated two-section Fabry–Pérot-type (FP) semiconductor laser, where one section operates as the gain and the other as saturable absorber. This configuration is known to exhibit, apart from self-pulsations and CW operation, a form of excitability when operating near, but below threshold [4]. Under excitable conditions, the laser emits a short optical pulse when triggered by an optical input pulse of sufficiently large energy and thus can operate as an artificial neuron. Such a trigger can also be caused by a sufficiently large positive intensity fluctuation due to spontaneous-emission noise. As this "spontaneous" emission of output pulses can be a source of errors on the one hand, but also a marker for identifying excitability, it is relevant to investigate this phenomenon in more detail, which is the purpose of the present study.

2. Device under Study and Observations

The gain and saturable absorber integrated laser was fabricated in a commercially available active–passive multi-project wafer (MPW) InP integration platform [5]. The device basically consists of two electrically isolated semiconductor optical amplifiers (SOAs), one for the gain and the other for the saturable absorption, between two mirrors. The output of the laser is coupled to the edge of the chip, where the emitted light is collected using lensed fibres. A schematic overview of the measurement set up is shown in Figure 1; a description is given in [6].

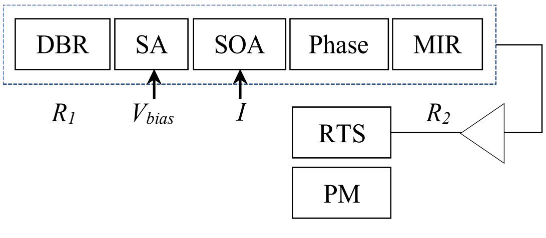

Figure 1: Schematic overview of the measurement setup. DBR: distributed Bragg reflector, SA: saturable absorber, SOA: semiconductor optical amplifier, MIR: multimode interference reflector, RTS: real time scope, PM: power meter.

The absorber SA is reversely biased with a voltage V_{bias}, while the SOA is biased with a direct current I to raise the effective gain very near, but below the lasing threshold. For the settings of Fig. 2 the laser is just below threshold and the relatively large intensity fluctuations have a probability to trigger the apparently excitable laser system. In Fig. 2(a,b) two examples of measured spontaneously emitted intensity pulses are shown.

3. Theory

We are interested in the time T it takes for the intensity, initially at I_1, to hit the excitability threshold value $I_C > I_0$ for the first time, where I_0 is the most probable intensity, $I_0 \approx < I >$. When this happens, a response pulse will be emitted by the laser. It then takes one refractory period T_{refr} before the laser is ready for the next excitation. This first-passage time (FPT) T, obviously is a stochastic quantity itself and thus given by a distribution, the first-passage-time density (FPTD) $P_{first}(T; I_1, I_C)$ for the intensity to diffuse from I_1 to I_C. The pulse-timing distribution is then equal to $P_{tim}(T; I_1, I_C) = 0$ when $0 < T < T_{refr}$ and $P_{tim}(T; I_1, I_C) = P_{first}(T - T_{refr}; I_1, I_C)$ for $T < T_{refr}$.

In [7] we have derived 2 explicit analytic asymptotic expressions for the FPTD:

$$P_{first}(T; I_0, I_C) = e^{-\left(1+\frac{T}{T_{I_0,I_C}}\right)} \frac{I_{Bessel,1}\left(2\sqrt{\frac{T}{T_{I_0,I_C}}}\right)}{\sqrt{T_{I_0,I_C} T}}, \qquad (T \text{ large}), \qquad (1)$$

$$P_{first}(T; I_{\text{i}}, I_C) = \frac{(I_C - I_{\text{i}})}{\sqrt{4\pi \mathcal{D} T^3}} e^{-\frac{(I_C - I_{\text{i}})^2}{4\mathcal{D}T}}, \qquad (T \text{ short}), \qquad (2)$$

with I_{i} the initial intensity, $\mathcal{D} = 2R_s I_0$ the diffusion coefficient, T_{I_0,I_C} a characteristic time related to the first passage from I_0 to I_C, and $I_{Bessel,1}$ the modified Bessel function of the first kind.

4. Results

The asymptotic short-time and long-time approximations are indicated in Fig. 2(c) and explain well the measured pulse-repetition time distribution. This supports the idea that excitable pulses are triggered by the relatively large spontaneous-emission intensity noise. The understanding of the influence of spontaneous-emission noise is important for reliable operation of an excitable two-section semiconductor laser when used as a photonic spiking neuron and it can be helpful for exploring the mechanism of stochastic spiking found in biological neurons. Identification of the region of spontaneously emitted pulses can also serve as a marker for the parameter domain setting for excitability.

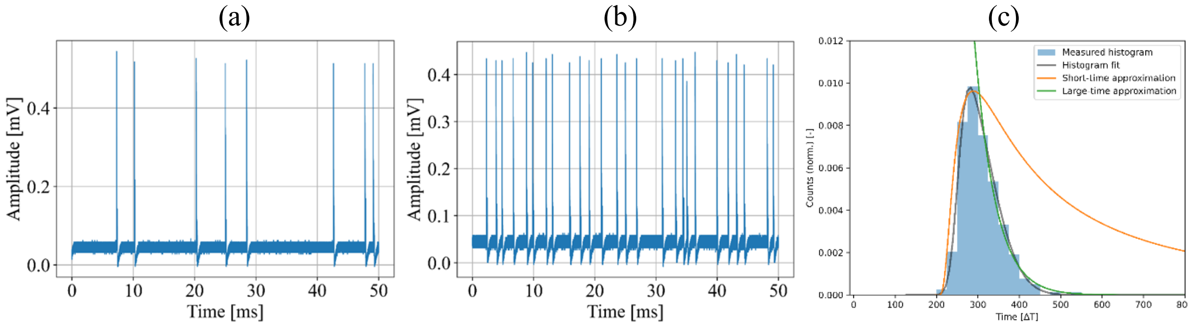

Figure 2: Time trace when the absorber is reversely biased at voltage $V_{bias} = 0.727V$ (a) and $V_{bias} = 0.730V$ (b), while the SOA is directly biased with current $I = 50.11mA$ in both cases. In (c) a histogram of 313 measured consecutive pulse timing events is shown for a SOA current of $50.12mA$ and $V_{bias} = 1.38V$; the black line is a fit based on the skewnorm.fit() function in Python, the yellow curve is the large-time approximation (1), and the green curve is the short-time approximation (2). The parameters used for the approximations in (c) are $T_{I_0,I_C} = 33.3$, $I_C = 6.1$.

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