Optics Communications 407 (2018) 327–332

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Simulating the spiking response of VCSEL-based optical spiking neuron

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ARTICLE INFO

Keywords:
Nonlinear optics
Devices
Vertical cavity surface emitting laser
Optical processing devices

ABSTRACT

Based on the Yamada model and rate equation model of vertical cavity surface emitting laser (VCSEL) with a saturable absorber (SA), we numerically simulate the spiking response of VCSEL–based optical spiking neuron under incoherent and coherent perturbations, respectively. First, we simply analyze the dynamics of the laser system based on the Yamada model. Then we discuss the dependence of spiking characteristics, including threshold, response time, response spike's amplitude and pulse-width, with the amplitude of perturbations, the driving current of gain and SA region for single optical pulse injection. Finally, we study the dependence of relative refractory period of VCSEL-based optical spiking neuron with different amplitudes of perturbations. Since VCSELs are ease of integration, it provides new opportunities for realization of large-scale and ultrafast neuromorphic computing systems.

1. Introduction

Neuromorphic engineering, developed by Carver Mead in the late 1980s [1], aims at emulating the neurons and synapses in human brain and mimicking the behavior of human brain, and it has a wide range of applications in the fields of machine learning, pattern recognition, adaptive control, etc. The Spiking Neural Networks (SNNs), touted to be the third generation of neural network models, are one of the most popular neural network models, and the SNNs employ spiking neurons as computational units which encode information in spike trains [2]. Recently, various hardware emulations on the neuromorphic computing have been developed in very-large-scale integration (VLSI) systems, including IBM's TrueNorth chip as part of DARPA's SyNAPSE program [3], Neurogrid system as part of Stanford's Brains in Silicon program [4], the Heidelberg HICANN chip as part of BrainScaleS project [5], etc. Microelectronic SNNs are both fast and highly interconnected, but they are subject to a fundamental bandwidth connection-density tradeoff, keeping their speed limited.

In contrast, photonics, characterized by its high speed, wide bandwidth, low power consumption and high parallelism, is an ideal way to realize ultrafast spiking-based information schemes. In the last six years, some bulky optical systems have been realized [6–9], which are difficult to implement large-scale optical SNNs. Using a single optical device which is excitable is a better way to implement large-scale SNNs. The definition of excitability in physiology is that a system is excitable if it is capable to generate a large-amplitude action potential when the input perturbation is strong enough, then it will return to its initial state. Excitability have been investigated in lasers with saturable absorber (SA) [10–15], lasers with optical injection [16–23] or optical feedback [24,25], silicon-on-insulator (SOI) microrings [26], semiconductor photonic-crystal nanolaser [27].

Compared with other realizations of spiking neurons, vertical cavity surface emitting lasers (VCSELs) exhibit attractive advantages, including low cost, low power energy consumption, low threshold currents and ease of integration. Various types of optical spiking neurons have been developed by using VCSELs based on Q-switching [14,15], polarization switching [17–22] and phase modulation [23]. And VCSEL with a SA shows rich features that can better mimic the spiking neuron.

In this paper, based on the Yamada model [28], we numerically simulate the spiking response of an optical spiking neuron consisting of a VCSEL with an intra-cavity SA with optical injection. We focused on the spiking response of the laser system with incoherent perturbations, which means the wavelength of the injected optical perturbations is different from the lasing wavelength, or coherent perturbations, which means the wavelength of the injected optical perturbations is the same as the lasing wavelength. In Section 2, we simply analyzed the excitability theory of the laser system based on the Yamada model. In Sections 3 and 4, we studied the spiking characteristics under incoherent and coherent perturbations, respectively.

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https://doi.org/10.1016/j.optcom.2017.09.066
Received 20 July 2017; Received in revised form 18 September 2017; Accepted 21 September 2017
Available online 5 October 2017
0030-4018/

2. Excitability theory

Laser with a SA can behave the third type optical excitability and can be described by the Yamada model as Eq. (1) [29,30].

$$\begin{aligned} \dot{G} &= \gamma_G (A - G - GI) \\ \dot{Q} &= \gamma_Q (B - Q - aQI) \\ \dot{I} &= \gamma_I (G - Q - 1) I \end{aligned} \tag{1}$$

where G is the gain, Q is the absorption, I is the laser intensity, A is the bias current of the gain, B is the level of absorption, a describes the differential absorption relative to the differential gain, γ_G and γ_Q are the relaxation rate of the gain and SA, respectively, γ_I is the reverse photon lifetime. γ_I is much larger than γ_G and γ_Q, so the Yamada model is a slow–fast system. The dynamics and bifurcations of this system were studied in Ref. [29].

In this paper, we study a laser system with spontaneous emission $\varepsilon f(G)$, which is very small and is not capable of exciting the system by itself. γ_Q and γ_G are both small, but γ_Q is much larger than γ_G. The dynamical system behaves some different characteristics compared with Ref. [29], which are much suitable to mimic the spiking neuron.

The curve $B(a-1) = 1$ approximates to separate (A, γ) plane in type 1 and type 2, as illustrated in Fig. 1(a) and (b), respectively. γ is γ_G or γ_Q. For $B(a - 1) < 1$, the (A, γ) plane is separated by a line T given by $A_T = B + 1$. If $A<A_T$ (region 1), $G \approx A$, $Q \approx B$, $I \approx 0$ is the only stable equilibrium, which is an attractor. If $A > A_T$ (region 9), $(A, B, 0)$ is unstable, and there is another stable equilibrium $(A/(1+I_+), B/(1+aI_+), I_+)$. For $B(a-1) > 1$, the (A, γ) plane is separated by a line T and a line S given by $A_S = \left(a - 1 + 2\sqrt{(a-1)B} + B\right)/a$. If $A < A_S$ (region 1), $(A, B, 0)$ is the only stable equilibrium. If $A_S < A < A_T$ (region 2), there are a stable equilibrium $(A, B, 0)$, and two unstable equilibriums $(A/(1 + I_\pm), B/(1 + aI_\pm), I_\pm)$. If $A > A_T$ (region 7 and 9), there are an unstable equilibrium $(A, B, 0)$, and a stable equilibrium $(A/(1 + I_+), B/(1 + aI_+), I_+)$. Where

$$I_\pm = \frac{aA - a - B - 1 \pm \sqrt{(aA - a - B - 1)^2 + 4a(A - B - 1)}}{2a}. \tag{2}$$

In region 7, the laser works as a passive mode-locked laser, which will output periodic spike trains. In region 9, the laser works as a solitary laser without SA which will output CW light. To mimic the spiking neuron, we only care about region 1 and 2. The sketch phase portraits of (G, I) plane of region 1 and 2 are shown in Fig. 2.

In regions 1 and 2, if we push the G above the threshold, which is near $G - Q - 1 > 0$, since γ_I is much larger than γ_G and γ_Q and the laser system exists spontaneous emission, the system will produce a single pulse and relax slowly back to the attractor $(A, B, 0)$.

In region 1, since γ_I and γ_Q are much larger than γ_G, if we push I above the equilibrium, I will increase fast, Q will decrease fast, and G will decrease slowly, which will make $G - Q - 1 > 0$, and I will continue increasing until $G - Q - 1 < 0$. If we push I above the threshold, the system will produce a single pulse. In region 2, if we push I above the stable manifold, the system will produce a single pulse [30].

Therefore, the laser system can be excitable by tuning G or I in regions 1 and 2, which also means it can behave excitability in both type 1 and type 2 of (A, γ) plane. In this paper, we focused on type 2 of (A, γ) plane, since it features all possible dynamics of the laser system. In the initial state, the laser is not lasing. When a sufficient high perturbation, which is incoherent or coherent, is injected into the laser, it can bring I or G above the lasing threshold, and a pulse is generated. G can be modulated by injecting incoherent perturbations θ_G, which is used for pumping the laser system, as shown in Eq. (3a), and I can be modulated by injecting coherent perturbations θ_I, as shown in Eq. (3b).

$$\dot{G} = \gamma_G (A - G - GI) + \theta_G \tag{3a}$$

$$\dot{I} = \gamma_I (G - Q - 1) I + \varepsilon f(G) + \theta_I. \tag{3b}$$

Table 1
The parameters of the simulation.

Parameters	Gain region	SA region
Cavity volume V	9.6×10^{-18} m^3	2.4×10^{-18} m^3
Confinement factor Γ	0.06	0.05
Carrier lifetime τ	1 ns	150 ps
Differential gain/loss g	2.9×10^{-12} m^3 s^{-1}	14.5×10^{-12} m^3 s^{-1}
Transparency carrier density n_0	1.1×10^{24} m^{-3}	0.89×10^{24} m^{-3}

The rate equation model of VCSELs for the total photon number N_{ph}, and the number of carriers in gain region n_a and in SA region n_s is described in Eq. (4) [13,14].

$$\begin{aligned} \dot{N}_{ph} &= \Gamma_a g_a (n_a - n_{0a}) N_{ph} + \Gamma_s g_s (n_s - n_{0s}) N_{ph} \\ &\quad - \frac{N_{ph} - \varphi_{ph}(t)}{\tau_{ph}} + V_a \beta B_r n_a^2 \\ \dot{n}_a &= -\Gamma_a g_a (n_a - n_{0a}) \frac{N_{ph} - \varphi_a(t)}{V_a} - \frac{n_a}{\tau_a} + \frac{I_a}{eV_a} \\ \dot{n}_s &= -\Gamma_s g_s (n_s - n_{0s}) \frac{N_{ph}}{V_s} - \frac{n_s}{\tau_s} + \frac{I_s}{eV_s} \end{aligned} \tag{4}$$

where e is the electron charge, I_a is the drive current of gain region, and I_s is the drive current of SA region, τ_{ph} is the photon lifetime, β is the spontaneous emission coupling factor, and B_r is the bimolecular recombination term. Other parameters are shown in Table 1. And The subscripts a and s identify the gain and SA region, respectively. $\varphi_a(t)$ represents the injected incoherent optical perturbations which only affects the carriers in the gain region and represents the optical pumping for VCSEL, and $\varphi_{ph}(t)$ represents the injected coherent optical perturbations which mainly affects the photon number in the cavity. For ease of understanding, Eq. (4) can be rewritten in dimensionless form as Eq. (1), as shown in Eq. (5).

$$\begin{aligned} G &= \tau_{ph}\Gamma_a g_a (n_a - n_{0a}), \quad Q = \tau_{ph}\Gamma_s g_s (n_{0s} - n_s) \\ I &= \frac{\tau_a \Gamma_a g_a}{Va} N_{ph}, \quad \tilde{t} = \frac{t}{\tau_{ph}}, \gamma_I = 1 \\ \gamma_G &= \frac{\tau_{ph}}{\tau_a}, \quad A = \tau_{ph}\tau_a \Gamma_a g_a \left(\frac{I_a}{eV_a} - \frac{n_{0a}}{\tau_a}\right) \\ \gamma_Q &= \frac{\tau_{ph}}{\tau_s}, \quad B = \tau_{ph}\tau_s \Gamma_s g_s \left(\frac{n_{0s}}{\tau_s} - \frac{I_s}{eV_s}\right) \\ a &= \frac{\tau_s \Gamma_s g_s V_a}{\tau_a \Gamma_a g_a V_s}, \quad \varepsilon f(G) = \tau_{ph}\tau_a \Gamma_a g_a \beta B_r n_a^2 \\ \theta_G(t) &= \frac{\tau_{ph}\Gamma_a g_a G \varphi_a(t)}{V_a}, \quad \theta_I(t) = \frac{\tau_a \Gamma_a g_a \varphi_I(t)}{V_a}. \end{aligned} \tag{5}$$

The output power can approximate to Eq. (6) [14].

$$P_{out} \approx \frac{\eta_c \Gamma_a}{\tau_{ph}} \frac{hc}{\lambda} N_{ph} \tag{6}$$

where η_c is the output power coupling coefficient, c is the speed of light, λ is the lasing wavelength of VCSEL, and h is the plank constant.

3. Incoherent perturbations

A 1550 nm VCSEL with an intra-cavity SA was considered in this paper, and the device parameters are shown in Table 1 [13,14]. And $\tau_{ph} = 4.8$ ps, $\beta = 1\times10^{-4}$, $B_r = 10\times10^{-16}$ m^3 s^{-1}, $\eta_c = 0.4$. Then we know that $a = 2.5$, which is fixed in this paper, and the laser system works in type II of (A, γ) plane. In this section, we considered the incoherent perturbations with the wavelength of 980 nm.

3.1. Single pulse injection

To begin with, we discuss the spiking response on the amplitude of input perturbation with a single pulse. First, we set the drive current of gain and SA region as $I_a = 8.5$ mA, $I_s = 0$ mA, so $A = 3.7032$, $B = 3.0972$, $A_S = 3.5632$, $A_T = 4.0972$. Therefore, the laser system works in region 2 of (A, γ) plane. The input pulse's full width at half maximum (FWHM) $t_{fwhm} = 20$ ps, which is shorter than the relaxing time of gain region and SA region, and it was injected at $t = 1$ ns. Fig. 3 illustrates the output of the VCSEL. When the amplitude of input pulse is less than 162.21 μW, no spike is generated. When the amplitude is greater than 162.21 μW, one spike is generated quickly. As the amplitude