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Controlled single- and multiple-pulse excitability in VCSELs for novel spiking photonic neurons

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Abstract: Excitability in VCSELs under parallel- and orthogonally-polarized optical injection is investigated numerically. Controlled single- and multiple-pulse excitability is found for the two polarizations offering prospects for novel VCSEL-based ultrafast spiking photonic neurons.

1. Introduction

Neurons compute information in the brain by firing spikes when stimulated, a behaviour known as excitability [1]. Interestingly, Semiconductor Lasers may also exhibit excitability but several orders of magnitude faster than neurons (up to 9) [2] thus opening new routes for photonic neuron models [3]. Amongst SLs, Vertical Cavity Surface Emitting Lasers (VCSELs) offer important advantages, i.e. reduced costs, lower energy consumption, ease to integrate in 2D arrays, etc. showing therefore great potential for interconnected photonic neurons. Recently, the use of VCSELs for the optical emulation of neuronal features has attracted attention and neuronal responses such as phasic and tonic spiking have been reported [3]. Furthermore, firing of sub-ns self-generated [4] and controllable [5] excitable spikes have also been recently observed in VCSELs. In this work, we investigate numerically the excitability in VCSELs under parallel- and orthogonally-polarized optical injection. Controlled firing of sub-ns single, multiple and bursts of excitable spikes is obtained in both cases. These results offer great potential for novel uses of VCSELs as spiking photonic neurons for use in novel non-traditional information processing paradigms.

2. Theory

The well-known Spin Flip Model (SFM) [6-7] is used to investigate the excitability in VCSELs. Realistic parameter values modeling commercially available 1550nm VCSELs were chosen by fitting measurements of the VCSEL power and relaxation oscillation frequency with its bias current, and stability map under parallel polarized optical injection [7]. Their values are as follows: photon decay rate $\kappa=125\ \mathrm{ns}^{-1}$, electron recombination rate $\gamma=0.67\ \mathrm{ns}^{-1}$, birefringence rate $\gamma_p=109$ rad/ns, spin relaxation rate $\gamma_s=1000\ \mathrm{ns}^{-1}$, linewidth enhancement factor $\alpha=2.2$, gain anisotropy or dichroism rate $\gamma_a=1.5\mathrm{ns}^{-1}$. Also, the device was biased at 1.5 times threshold.

3. Results

Fig. 1(a) shows the calculated time traces for the two linear polarizations of the VCSEL, referred to as orthogonal (x-LP) and parallel (y-LP), with the device subject to orthogonally- (middle plot) and parallel-polarized (lower plot) optical injection. In both cases a frequency detuning (frequency difference between the injected signal and the VCSEL's polarization mode) equal to $\Delta f=-4.5$ GHz was set. An injection strength K (the injection power/the power of solitary laser) equal to -8.5 dB sufficient to achieve stable injection locking, was set in the two cases. The upper plot in fig. 1(a) shows the injected signal which has a perturbation (in the form of a power drop) at t=25 ns with a duration of $d_p=0.5$ ns and a strength K_p (the reduction in K) equal to 1.4 dB. Fig. 1(a) shows that single-pulse excitability is found in both polarizations: a single spike is fired in the orthogonal (I_x, blue) and parallel (I_y, red) polarization intensities when the VCSEL is subject to orthogonal and parallel polarized optical injection, respectively. A time delay is also observed between the perturbation's arrival and the pulse's firing. The temporal maps in Figs. 1(b) and 1(c) show the effect of the perturbation's strength K_p (fig. 1(b)) and duration d_p (fig. 1(c)). Figs. 1(b) and 1(c) plot in both cases superimposed time-series of I_x when the VCSEL is subject to orthogonally-polarized injection. The red colour in the maps indicates a steady-state value of I_x whilst yellow indicates the existence of a spike (see color bar coding). Fig. 1(b) plots results when the perturbation strength K_p is varied from 0 to 10.45 dB; the injection strength, initial frequency detuning and perturbation's time width were fixed equal to K=-8.5 dB, $\Delta f=-4.5$ GHz and $d_p=0.5$ ns, respectively. Fig. 1(b) clearly shows the existence of a threshold level above which an excitable spike is fired. This threshold for excitability is also a feature observed in biological neurons and allows the effective control of the spike firing activity by acting on the incoming perturbations' strength [1]. Also, a transition from single to multiple excitable spike-firing dynamics is obtained as K_p is increased. Fig. 1(c) shows the effect of the perturbation duration, d_p. In this map, fixed values of K=-8.5 dB, $\Delta f=4.5$ GHz and perturbation pulse's strength $K_p=1.4$dB are used whilst d_p is varied from 0 to 3ns. Initially, a single spike is obtained; however increasing d_p triggers the firing of additional spikes and therefore a transition from single- to multiple-excitable spiking

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behavior is produced. In addition, fig. 2 shows the possibility to obtain different spiking patterns for the same input perturbation (shown in fig. 1(a)) depending on the initial conditions. Fig. 2 shows that for the two polarizations, orthogonal (blue) and parallel (red), a single-spike or bursts of two or three spikes (bursting) are obtained just by slightly varying the injection strength and detuning. These rich varieties of controllable response observed in a VCSEL are very similar to the phasic spiking, tonic spiking and bursting dynamics occurring in biological neurons [1], but 9 orders of magnitude faster.

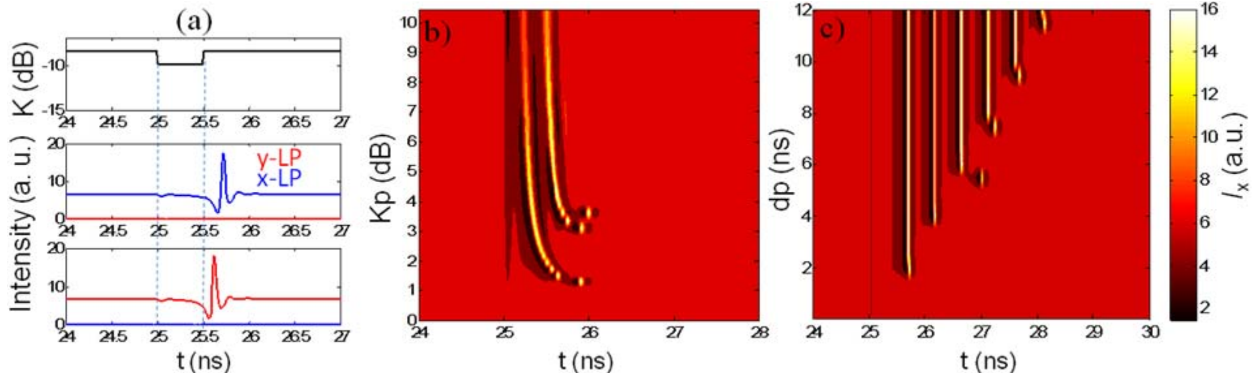

Fig. 1. (a) Time series for the: injected signal (top, in black) and the VCSEL's intensities under orthogonally- (middle plot) and parallel polarized injection (lower plot); (b & c) Temporal maps of the VCSEL's x-LP mode under orthogonally polarized injection for different perturbation's strength (c) and time duration (d).

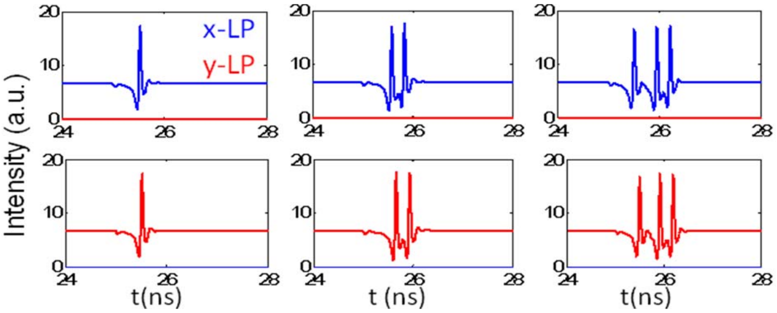

Fig. 2. VCSEL's output intensities under: (upper panel) orthogonal injection with (K(dB),Δf(GHz)) equal to (-8.1,-4.84), (-8.02,-4.82) and (8.01,-4.84); (lower panel) parallel injection with (K(dB),Δf(GHz)) equal to (-8.01,-4.84), (-7.8,-4.8) and (-8.1,-4.84);

4. Conclusions

We have investigated numerically the excitability in VCSELs under parallel- and orthogonally-polarized optical injection. Different dynamics including the firing of single, multiple and bursts of spikes are found in both polarizations. These features show strong similarities with the excitable properties of biological neurons but several orders of magnitude faster (up to 9). These results, combined with the particular advantages of VCSELs, offer promise for novel photonic neurons for non-conventional information processing paradigms.

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