Robertson, Joshua and Wade, Ewan and Hurtado, Antonio (2018) Electrically-controlled spiking regimes in vertical-cavity surface emitting lasers. In: 31st Annual Conference of the IEEE Photonics Society. IEEE, Piscataway, NJ. ISBN 9781538653586 , http://dx.doi.org/10.1109/IPCon.2018.8527111

Electrically-controlled spiking regimes in vertical-cavity surface emitting lasers

Joshua Robertson, Ewan Wade
and Antonio Hurtado
Institute of Photonics
University of Strathclyde
Glasgow, UK
antonio.hurtado@strath.ac.uk

Abstract – Electrically-controlled, tuneable and repeatable neuron-like spiking regimes are generated in an optically-injected 1300 nm Vertical-Cavity Surface-Emitting Laser at sub-nanosecond speeds (>7 orders of magnitude faster than neurons). These results offer great prospects for compact and ultrafast photonic neuronal models for future neuromorphic computing platforms.

I. INTRODUCTION

With a fast approaching bottleneck in microprocessor performance and power consumption [1], researchers scramble for high speed processing alternatives, in particular neuromorphic (or brain-inspired) systems. Many realizations, e.g. Neurogrid [2], make use of silicon and CMOS technology to electronically generate and communicate neuron-like spikes between 1000-1,000,000 electronic neuronal elements. However, approaches taking advantage of the unique properties of photonic technologies (e.g. very high bandwidths, reduced cross-talk), are emerging to create new ultrafast optical neuronal models. These have been based primarily in semiconductor lasers [3-8] but also on nonlinear photonic elements such as optical modulators [9]. These photonic neuronal models are capable of operating at speeds up to 8 orders of magnitude faster than the millisecond timescales of biological neurons and which are unreachable by traditional microelectronic processors. In particular, approaches for photonic neuronal models based on compact Vertical Cavity Surface Emitting Lasers (VCSELs), enabling ultrasmall footprint, easily incorporation into 2D/3D arrays and potentials for very large scale integration have attracted wide research interest in recent years [6-9]. Moreover, the low cost and reduced energy consumption of VCSELs added to their operation at telecommunication wavelengths set them up as ideal candidates for implementing future photonic neural networks. VCSELs have shown thresholding dynamics similar to the potential threshold of spiking cortical neurons as well as other neuronal behaviors such as tonic and phasic spiking [5]. Furthermore, controllable activation [6] and inhibition [7] of spiking dynamics in VCSELs by means of external optical injection have been reported and the interconnection of two VCSEL-based spiking photonic neuronal models was demonstrated [8].

In this work we demonstrate experimentally for the first time the electrically-controlled generation of ultrafast spiking regimes in VCSELs. We show that encoding short temporal perturbations (down to sub-nanosecond scales) in the applied bias current of an optically-injected VCSEL we can trigger spiking responses from the device with controlled number of events (spike duration of ~100 ps) and sub-nanosecond inter-spiking intervals. These results therefore offer exciting prospects for ultrafast, cascadable and electrically-controlled photonic neuronal models with VCSELs operating at telecom wavelengths (1310 nm). The latter will enable the electrical integration of multiple photonic inputs from diverse sources and at different wavelengths to trigger controlled spiking responses that could be then be propagated to other VCSEL neuronal models in an interconnected network. These features are of great interest for future neuromorphic computing platforms beyond traditional microelectronic/CMOS technology.

II. EXPERIMENTAL RESULTS

Fig. 1 depicts the experimental setup used in this work to trigger electrically controlled spiking regimes in a VCSEL operating at the telecom wavelength of 1310nm. During the experiments the VCSEL's current and temperature were kept at 6.0 mA and 293 K respectively. The VCSEL was first subject to constant optical injection from a tunable laser (Master Laser, ML) to injection-lock its emission to that of the ML. In this situation, short temporal perturbations from a signal generator (SG), yielding positive amplitude pulses with controlled duration (t_d) and intensity (I_p), were added (via direct modulation) to the VCSEL's bias current using a Bias Tee. Hence, in this configuration, the VCSEL's output is initially constant, as it is injection-locked to the optically injected signal; then, the arrival of a perturbation, increasing for a short period of time (t_d) the VCSEL's current (by an amount I_p) brings the device out of equilibrium producing as a result a spiking dynamical response.

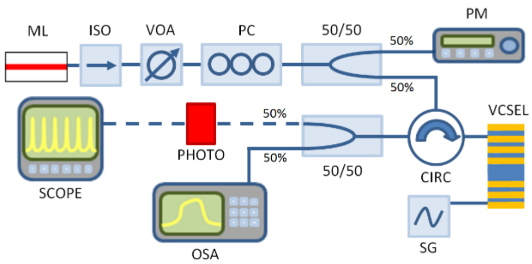

Figure 1 – Experimental setup. ML=Master Laser, ISO=Isolator, VOA=Variable Optical Attenuator, PC=Polarisation Controller, PM=Powermeter; CIRC=Circulator, OSA=Optical Spectrum Analyser; SG=Signal Generator, PHOTO=Photodetector.

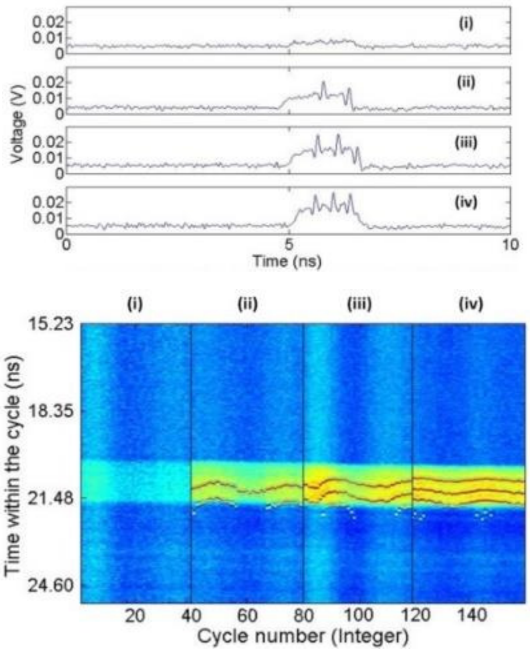

Figure 2 – Measured time series (top) and temporal map (bottom) at the VCSEL's output under the arrival of perturbations with constant t_d = 1.52 ns and increasing I_p of (i) 1.10 mA, (ii) 2.50 mA, (iii) 3.22 mA, (iv) 4.10 mA.

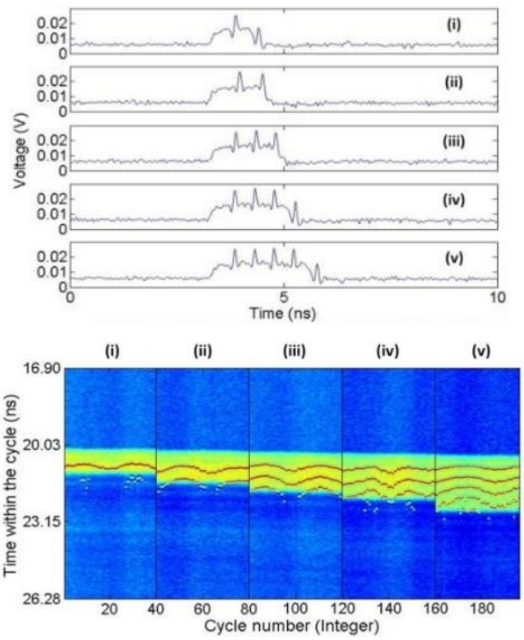

Figure 3 – Measured time series (top) and temporal maps (bottom) obtained at the VCSEL's output under the arrival of perturbations with constant I_p = 3.61 mA and varying t_d of (i) 1.07 ns, (ii) 1.34 ns, (iii) 1.65 ns, (iv) 1.90 ns, (v) 2.35 ns.

We have firstly investigated the effect of the perturbation's intensity I_p on the VCSEL spiking dynamics (see Fig. 1). To do so, perturbations with increasing strength from I_p = 1.10 mA to I_p = 4.10 mA were electrically-injected into the device. The perturbation's duration was kept constant at t_d = 1.52 ns. The time series in Fig. 1 -plots (i-iv)- reveal that the perturbation produces an increasing step in power at the VCSEL's output (due to the increase in bias current) during which spiking dynamics are obtained if a threshold in perturbation's intensity is exceeded. These spikes are ~100ps long and are fired with <1ns inter-spiking intervals. The temporal map included in fig. 1 below the time series merges in a single plot the VCSEL's response to 40 consecutive perturbations for each of the four cases analyzed in plots (i-iv). Blue/red color in the map indicates low/high intensity levels. This temporal map clearly demonstrates the repeatability of the spiking dynamics as these are consistently obtained for all incoming perturbations. Hence, like biological neurons a threshold in the value of perturbation's intensity needs to be exceeded before spiking dynamics are achieved. Also, increasing the perturbation's intensity results in the variation of the inter-spiking time interval, a feature also observed in biological neurons, and which is used to compute into the firing rate the strength of an incoming stimulus.

The effect of perturbation's duration t_d was also studied. Results of this analysis are shown in fig. 2, where t_d was increased from t_d = 1.07 ns to t_d = 2.35 ns and the perturbation's strength was set constant at I_p = 3.61 mA (above the threshold for the firing of spiking dynamics). The time series in fig. 2 -plots (i-v)- show that as t_d increases the number of generated spikes increases from 2 in (i) to 5 in (v). This behavior is analogous to the tonic spiking dynamics observed in biological neurons where spikes are fired continuously over the course of a stimulus with only short refractory periods between them. Hence, as in biological neurons, fully controllable spiking responses can be obtained with the VCSEL, just by varying the duration of t_d. The temporal map shown in fig. 2 also demonstrates the repeatability of the achieved tonic spiking responses over 40 consecutive incoming perturbations in each of the five cases investigated in fig. 2.

III. CONCLUSION

We demonstrate the generation of controlled spiking dynamics (>7 orders of magnitude faster than in neurons) in a 1310nm VCSEL in response to electrically-injected perturbations. These results offer great prospects for cheap, compact and highly interconnected photonic neuronal models for inclusion in future photonic neuronal networks for ultra-fast neuromorphic photonic processors beyond current electronic technologies.

REFERENCES

[1] Kim, N.S. et al., Computer. 36, 68-75 (2003).
[2] Benjamin, B.V et al., Proc. of IEEE. 102(5), 699-716 (2014).
[3] Coomans, W. et al., Phys. Rev. E Statistical, nonlinear and soft Matter Physics. 83(3), 036209 (2011).
[4] Vaerenbergh, T.V. et al., Optic. Expr. 21, 28922-28932 (2013).
[5] Hurtado, A. et al., Appl. Phys. Lett. 100, 1037013 (2012).
[6] Hurtado, A. et al., Appl. Phys. Lett. 107, 241103 (2015).
[7] Robertson, J. et al., Opt. Lett. 42, 1560-1563 (2017).
[8] Deng, T, et al., IEEE Quantum. Electron. 23, 1800408 (2017).
[9] Tait, A. et al., Scientific Reports. 7(1), 7430 (2017).

ACKNOWLEDGEMENTS

The authors acknowledge support from the US Office of Naval Research Global under grant ONRG - NICOP - N62909-18-1-2027.