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Citation: *Appl. Phys. Lett.* **100**, 103703 (2012); doi: 10.1063/1.3692726

View online: <http://dx.doi.org/10.1063/1.3692726>

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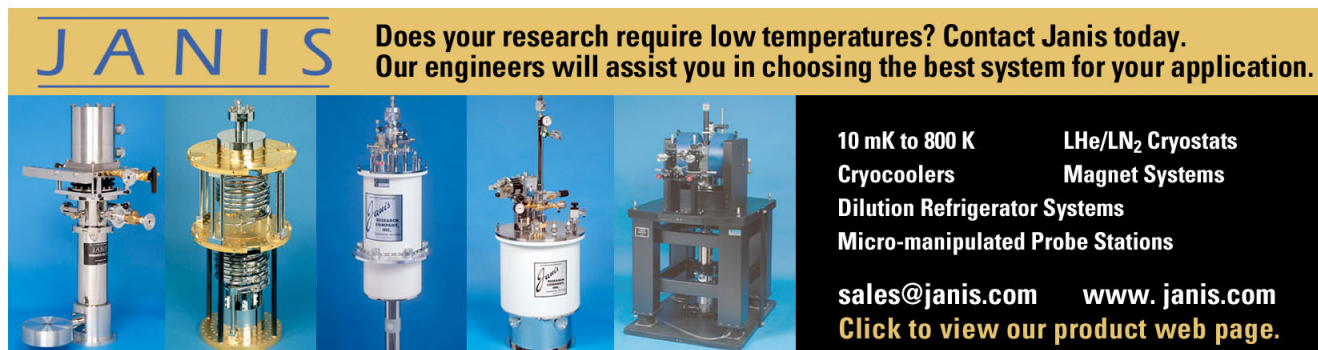
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Investigation of vertical cavity surface emitting laser dynamics for neuromorphic photonic systems

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(Received 18 November 2011; accepted 20 February 2012; published online 7 March 2012)

We report an approach based upon vertical cavity surface emitting lasers (VCSELs) to reproduce optically different behaviors exhibited by biological neurons but on a much faster timescale. The technique proposed is based on the polarization switching and nonlinear dynamics induced in a single VCSEL under polarized optical injection. The particular attributes of VCSELs and the simple experimental configuration used in this work offer prospects of fast, reconfigurable processing elements with excellent fan-out and scaling potentials for use in future computational paradigms and artificial neural networks. © 2012 American Institute of Physics.

[<http://dx.doi.org/10.1063/1.3692726>]

Neuromorphic research aims to explore solutions to complex computational problems inspired by sophisticated models of the human brain.¹ Models of cortical neurons are required to exhibit a variety of complex features such as spiking² if they are to be of use in the development of artificial neural networks. Very large scale integration (VLSI) implementation of these features has been studied for decades.³ Previous work has shown that analogue VLSI circuitry using only 14 metal-oxide semiconductor field-effect (MOS-FETs) demonstrated the spiking and bursting behaviour of a cortical neuron.⁴ This operated on a timescale which was 10^5 times faster than a biological neuron, offering the exciting prospect of ultrafast neural computations. Recently, optical approaches have also emerged^{5–11} as it is widely recognised that these offer even faster timescales (up to 10^9 times⁹). However, these are often complex and scaling sufficiently to permit the demonstration of network characteristics is challenging.

Semiconductor lasers can exhibit a range of characteristics similar to those observed in neuronal systems, including excitability^{12–14} and complex nonlinear dynamics.¹⁵ The majority of biological neurons are excitable systems and respond by firing spikes when stimulated (for a review see, for instance, Refs. 2, 16 and 17 and references therein). This may take the form of a single spike occurring just upon the arrival of a stimulus or may involve a train of spikes emitted for the whole duration of the stimulus. These behaviours are usually referred to as phasic and tonic spiking, respectively. Very recently, a theoretical study has analysed the excitability properties of semiconductor ring lasers for use as optical spiking neurons.¹⁰ Here, we report an approach based upon vertical cavity surface emitting lasers (VCSELs).^{11,18,19} This utilizes an alternative physical mechanism, namely, the polarization switching (PS) and nonlinear dynamics induced in these devices when subject to polarised optical injection. These laser nonlinear dynamics which have been described for various kinds of semiconductor lasers can be attributed to well known carrier-photon coupling and associated dynamics in the optical

injection locking processes.¹⁵ We demonstrate experimentally that a variety of neuronal features can be emulated using a single device and on a much faster time-scale than biological neurons. Additional interesting features of our approach include low input power requirements, controllability and reproducibility of results, and an ability to modify the response function. Moreover, VCSELs offer high fan-in/fan-out with very low crosstalk and ease of integration into 2D arrays.²⁰ These attributes offer a promising research direction for fast, versatile, and reconfigurable computational elements with excellent scaling prospects for uses in computing and artificial neural networks.

Fig. 1 shows the experimental arrangement. An all-optical fiber setup was developed to inject polarized light from a tunable laser into a commercial 1550 nm-VCSEL; the latter forms the VCSEL-neuron. The laser had a threshold current (I_{th}) of 1.6 mA at 298 K and oscillated in its fundamental transverse mode. The operation of the VCSEL-neuron is based on its response to orthogonally polarized optical injection which induces phenomena such as PS,¹⁸ injection locking, and nonlinear dynamics.¹⁹ Figs. 2(a) and 2(b) illustrate PS in association with injection locking. Fig. 2(a) plots the spectrum of the solitary device showing two modes corresponding to the two orthogonal polarizations of the fundamental transverse mode. We associate “parallel (orthogonal) polarization” with the polarization of the lasing (subsidiary) mode of the VCSEL. Fig. 2(b) shows the spectrum of the device under orthogonally polarized injection into its orthogonal mode; here, the parallel mode is suppressed as the orthogonal mode locks to the external signal, and PS occurs with emission in the orthogonal polarization.¹⁸ Throughout this work, we associate the solitary mode of the device with the inactive state of the VCSEL-neuron and the arrival of an external stimulus is emulated with the injection of an orthogonally polarized time-varying signal. We report an experimental study of the simultaneous temporal dynamics of the two orthogonal polarizations (parallel and orthogonal) of the VCSEL-neuron.

Figs. 3 and 4 show the response of the VCSEL-neuron to different external stimuli (4 ns long). Initially, the VCSEL emits light with parallel polarization; the incoming stimulus induces PS, from parallel to orthogonal. A rich variety of

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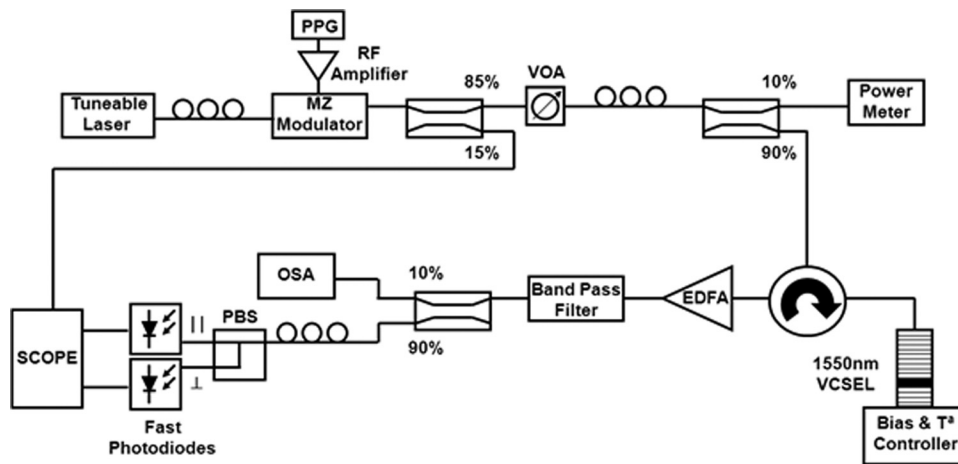


FIG. 1. Experimental setup. PPG, pulse pattern generator; VOA, variable optical attenuator; MZ, Mach Zehnder; RF, radio frequency; EDFA, erbium doped fibre amplifier; OSA, optical spectrum analyzer; PBS, polarization beam splitter.

nonlinear dynamic responses are generated for both polarization outputs in addition to PS. We first focus on the orthogonal polarization output which is dominant following the stimulus. Fig. 3(a) shows that a single abrupt spike is generated upon the arrival of the stimulus followed by a stable state for the remaining duration of the input. Fig. 4(a) shows in turn a different response where the external injection induces periodic oscillations or spikes at firing rates of \sim GHz (many orders of magnitude above that observed in biological neurons). These dynamics exhibit similarities with the phasic and tonic spiking behaviours exhibited by biological neurons.^{2,16,17} Furthermore, Figs. 3(b) and 4(b) reveal the occurrence of additional dynamics in the parallel polarized output similar to those occurring in neurons. These include first the appearance of a rebound spike at the end of the stimulus duration (Fig. 3(b)), behaviour observed for instance in thalamic interneurons.¹⁸ Finally, Fig. 4(b) shows the attainment of a small amplitude oscillatory behaviour, which is similar to the so-called sub-threshold oscillations² appearing in neu-

rons. We have also analysed the VCSEL-neuron response to increasingly strong stimuli. Fig. 5 plots the orthogonally polarized output for different injected powers. We observe oscillations similar to tonic spiking as seen in biological neurons where the oscillation frequency increases with optically injected power. Specifically, certain types of cortical neurons show increasing spiking rates with stronger stimuli,^{2,16} the firing rate being an indicator of the stimulus strength.

The VCSEL-neuron dynamics of Figs. 3 and 4 can be explained from the effects induced by polarised optical injection.^{19,21,22} Fig. 3 shows the case where PS appears associated with injection locking¹⁹ (this is a situation in which the orthogonal polarization mode of the VCSEL locks to the injected field and has constant output intensity with emission at the wavelength of the external signal¹⁵). The results show that the external signal switches the VCSELs output between two different stable states, the solitary and a locked state. Hence, constant power levels appear before and after the stimulus arrival/removal for both polarizations, and only a single spike is obtained as the system transits from one stable state to the other. This explains the phasic spiking behaviour (solitary to locked state transition), and the rebound spike (locked to solitary transition) appearing, respectively, for the orthogonal and parallel polarizations. Fig. 4 shows a different situation where PS is associated with a limit cycle dynamics characterised by the appearance of periodic oscillations in the VCSELs orthogonal polarized output.¹⁹ These oscillations can appear either as a result of the excitation of the device's relaxation oscillations or from the beating of the resonant mode of the VCSEL with the externally injected field, depending on the initial conditions configured for the externally injected signal (initial detuning and injection strength).¹⁵ This behaviour is similar to the tonic spiking dynamics observed in neurons. Additionally, for the case depicted in Fig. 4(b), the parallel polarization is significantly attenuated but not completely suppressed.^{19,21,22} In such cases, it has been demonstrated that the two polarized outputs of the VCSEL can both exhibit limit cycle dynamics.^{21,22} This is the case here where an attenuated periodic signal is also obtained in the parallel polarization, showing a similar behaviour to the sub-threshold oscillations of biological neurons. The behaviour in Fig. 5 arises due to the pushing movement of the VCSELs resonance to longer wavelengths as the injection power is increased. This increases the initial

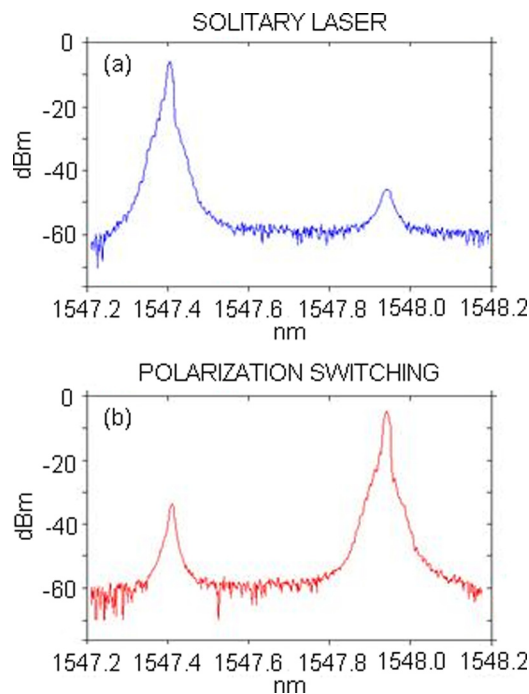


FIG. 2. (Color online) Optical spectrum of the VCSEL with and without orthogonally polarized optical injection producing PS and injection locking.

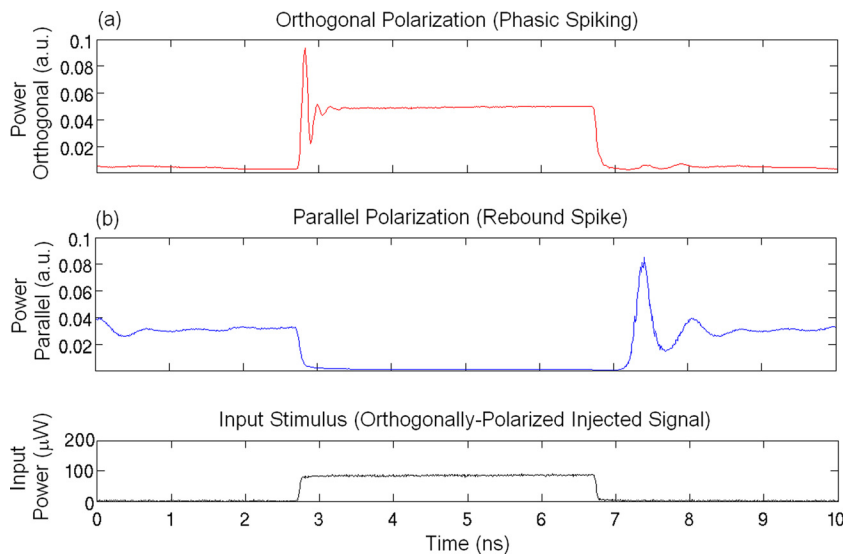


FIG. 3. (Color online) VCSEL-neuron's response to an external stimulus (4 ns long); the bias current and initial wavelength detuning are $I_{Bias} = 1.5I_{th}$ and $\Delta\lambda_{\perp} = 0$ nm. (a) Phasic spiking and (b) rebound spike behaviours are obtained for the (a) orthogonal (in red) and (b) parallel (in blue) polarization outputs. The lowest plot (in black) shows the injected signal.

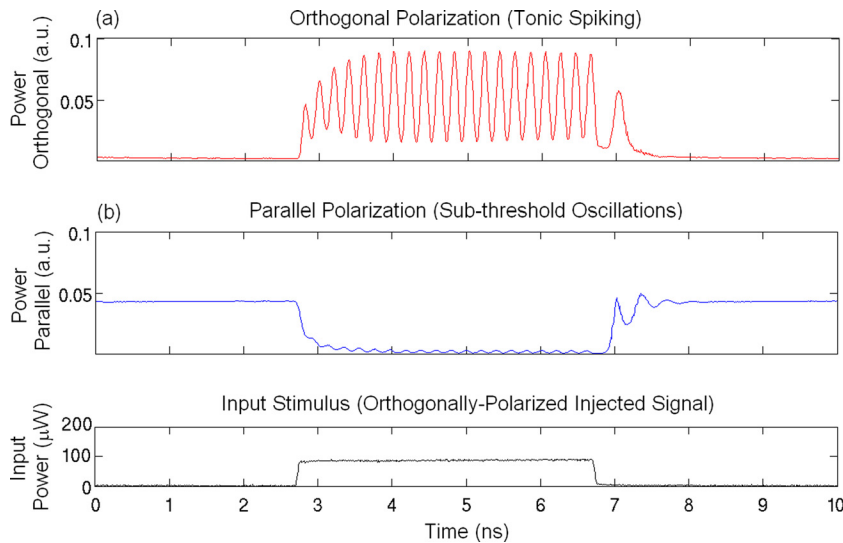


FIG. 4. (Color online) VCSEL-neuron's response to an external stimulus (4 ns long); the bias current and initial wavelength detuning are $I_{Bias} = 2.5I_{th}$ and $\Delta\lambda_{\perp} = -0.02$ nm. (a) Tonic spiking and (b) sub-threshold oscillations appear for the (a) orthogonal (in red) and (b) parallel (in blue) polarization outputs. The lowest plot (in black) shows the injected signal.

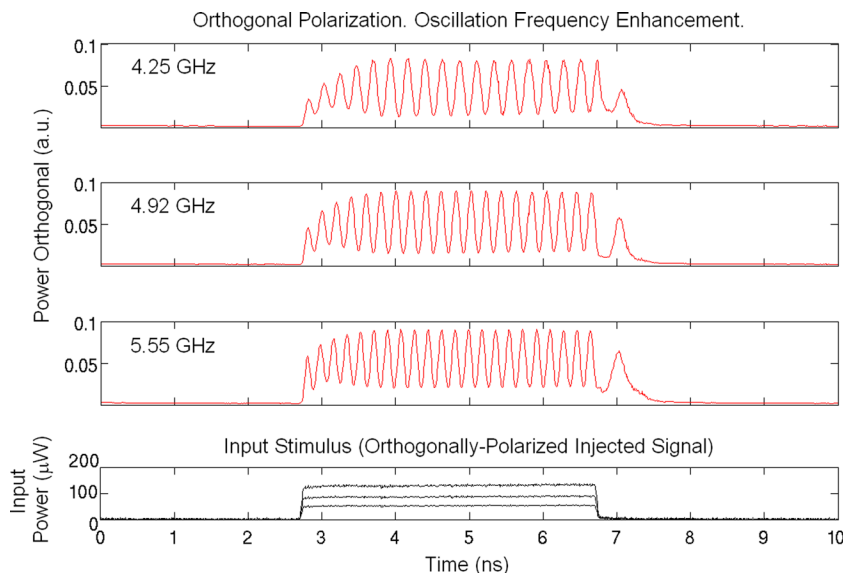


FIG. 5. (Color online) VCSEL-neuron's response to increasingly strong stimuli; the bias current and the initial wavelength detuning are $I_{Bias} = 2.5I_{th}$ and $\Delta\lambda_{\perp} = -0.02$ nm, respectively. The time evolution and strength of the input stimuli is shown in the lower plot (in black).

wavelength detuning which ultimately determines the oscillation frequency of the limit cycle dynamics. Finally, we should note that the results in Figs. 3–5 were obtained with the same device by simply adjusting three parameters: bias current, initial detuning, and injected power. Also, encouragingly, very low power requirements, from only 50 to 125 μW , were needed to induce the different behaviours at operation speeds of several GHz.

In conclusion, we have experimentally investigated a VCSEL-neuron which shows different computational features exhibited by biological neurons but on a much faster timescale. Our proposed technique is based upon the use of PS and nonlinear dynamics induced in optically injected VCSELs. We show that a single device can emulate various neuronal behaviours by controlling basic system parameters. There are many advantages of using VCSELs for such applications which include low operating power, an ability to modify the response function, and the potential for scaling into 2D and 3D arrays.²⁰ Additionally, in common with neural cells which are profusely interconnected in the brain, VCSELs offer the prospect of high fan-in/fan-out interconnection with very low cross talk.

This work has been funded in part by the European Commission under the Programme Marie Curie Intra-European Fellowships (Grant No. PIEF-GA-2007-219682) and the UK EPSRC (Project No. EP/G012458/1 and EP/E04610X/1). The authors would also like to thank Dr. Giorgos Zervas and Professor Dimitra Simeonidou for the loan of the oscilloscope and pulse pattern generator.

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