# Optical neuron using polarisation switching in a 1550nm-VCSEL

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**Abstract:** We report a new approach to mimic basic functionalities of a neuron using a 1550 nm Vertical Cavity Surface Emitting Laser (VCSEL) which is based on the polarisation switching (PS) that can be induced in these devices when subject to polarised optical injection. Positive and negative all-optical threshold operations are demonstrated experimentally using external optical injection into the two orthogonal polarizations of the fundamental transverse mode. The polarisation of the light emitted by the device is used to determine the state of the VCSEL-Neuron, active (orthogonal) or inactive (parallel). This approach forms a new way to reproduce optically the response of a neuron to an excitatory and an inhibitory stimulus.



**OCIS codes:** (140.7260) Vertical cavity surface emitting lasers; (230.5440) Polarization-selective devices; (130.4815) Optical switching devices; (200.4700) Optical neural systems.

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## 1. Introduction

The use of lasers to mimic the behaviour of the neuron has been investigated both theoretically and experimentally over the last decade [1–8]. Various theoretical approaches have been used to simulate different neuron models [9], including the Wilson-Cowan [2], Hodgkin-Huxley [4], and FitzHugh-Nagumo [7,8] models. Experimentally it is already known that some basic functionalities of a neuron can be performed with an edge-emitting laser (slave laser, SL) by using optical injection from another laser (master laser, ML) as well as external optical feedback [1]. The authors of [1] reported all-optical threshold operation due to injection locking when a SL is subject to simultaneous optical injection from two MLs. External optical feedback was used to select two of the longitudinal modes of the slave laser, and the signals from the master laser were matched to these two modes. With this technique, positive and negative all-optical threshold operations were demonstrated, interpreted as the response of a neuron to excitatory or inhibitory stimuli. However such systems are very demanding in terms of frequency control making them difficult to scale in practice.

Here we report a novel method to mimic neural behaviour based on the polarisation properties of VCSELs. We demonstrate that the neural response to excitatory and inhibitory stimuli can be reproduced experimentally with a 1550 nm VCSEL (SL) subject to double optical injection (two MLs) using parallel and orthogonal polarisation. Under these conditions we can induce polarisation switching (PS) [10–14], where the polarisation of the light emitted by the VCSEL determines the state of the VCSEL-Neuron, active (orthogonal) or inactive (parallel). Moreover the mode structure of the solitary VCSEL [10–15], with a parallel polarised dominant mode and an orthogonally-polarised subsidiary mode, aligns with that needed to perform the optical neuron operation [1], thus obviating the need for longitudinal mode selection through external optical feedback.

There are many specific advantages of using VCSELs in comparison to edge-emitting devices, including low manufacturing cost, high-coupling efficiency to optical fibres, single-mode operation, low operating power, potential for scaling into 2D and 3D arrays, etc [16]. Additionally and in common with neural cells which are profusely interconnected in the brain yielding very effective information processing, VCSELs offer the prospect of high degrees of interconnection with very low cross-talk, operating at very high speed. Hence, conceived in its simplest form, the VCSEL could be equated to an individual optical neuron which benefits from a much faster operational speed than that of actual neural cells. These early results offer exciting prospects for optical neural emulation as well as for novel uses of VCSELs in optical signal processing applications for optical neural networks, optical computing and for optical switching/routing in optical networks.

The major advantage of using an approach based on optically-injected lasers is that there is now a substantial body of literature indicating that their behaviour is very well described by theory based on rate equations, to such an extent that the theory has a predictive capability not matched by comparative studies for other complex systems. Hence, it is speculated that this approach of using semiconductor lasers, VCSELs in particular, for neural behaviour emulation could lead to the development of laser-neuron models which could in turn make important contributions in disparate fields such as laser physics and neuroscience. In conclusion, we believe that the speculative approach reported in this work opens new and exciting possibilities and therefore merits further study.

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## 2. Spectral properties of 1550 nm VCSEL

A commercially available quantum-well 1550 nm VCSEL was used in the experiments [15]. Figure 1(a) depicts the L-I curve of the device measured at 298 K, indicating a threshold current ($I_{th}$) of approximately 2 mA. Figure 1(b) shows that the spectrum of the device exhibits two modes which correspond to the two orthogonal polarisations of the fundamental transverse mode. A Side Mode Suppression Ratio (SMSR) in excess of 35 dB was measured, and similar spectra were observed for all biases above threshold. The lasing mode is located at 1543 nm whereas the suppressed subsidiary mode is shifted approximately 0.47 nm (57 GHz) to the long wavelength side. Throughout this work we associate "parallel polarisation" ("orthogonal polarisation") with the polarisation of the lasing (subsidiary) mode of the VCSEL.

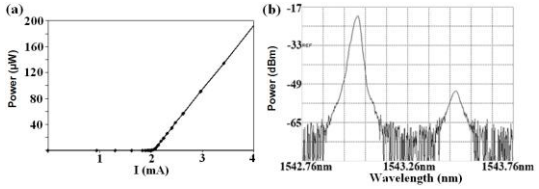


Fig. 1. (a) L-I Curve and (b) optical spectrum of the 1550 nm VCSEL measured at 298 K.

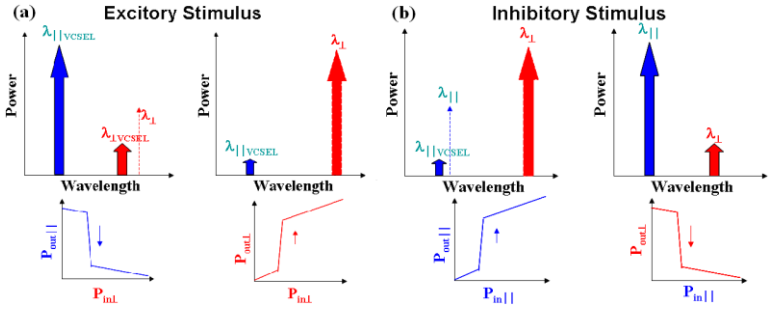


Fig. 2. Operation principle of the VCSEL-Neuron under (a) an excitatory and (b) an inhibitory stimulus.

## 3. Operational principle

Before describing the experimental results we consider operational principles of a VCSEL neuron under polarised optical injection. The two modes corresponding to the two orthogonal polarisations of the fundamental transverse mode are represented schematically in the upper left plot of Fig. 2(a) by blue and red arrows. Without optical injection, the lasing mode of the VCSEL emits light with parallel polarisation whereas the subsidiary orthogonal polarised mode is suppressed. This situation is directly equivalent to a non-active neuron. The arrival of an excitatory stimulus is reproduced with the external injection of an orthogonally-polarised optical signal [marked with a dashed red thin arrow at $\lambda_{\perp}$ in Fig. 2(a)] into the orthogonally polarised mode of the VCSEL ($\lambda_{\perp VCSEL}$). If this orthogonally-polarised signal is powerful enough, PS is induced [10–14]. In this situation, the parallel polarised lasing mode is suppressed, the orthogonal polarisation mode is activated and thus the polarisation of the light at the output of the VCSEL switches from parallel to orthogonal [as shown graphically in the upper right plot of Fig. 2(a)]. This behaviour is equivalent to an excited or active neuron. Figure 2(a) also shows schematically in its lower part the all-optical threshold functions attained for the parallel (switching from high to low output state) and the orthogonal (switching from low to high output state) polarised modes of the VCSEL which are used to obtain neural-like performance.

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The response of the VCSEL-Neuron to an inhibitory stimulus is shown schematically in Fig. 2(b). Here, initially the optical neuron has already been activated and consequently the VCSEL emits orthogonally-polarised light, as indicated in the upper left plot of the figure. The arrival of an inhibitory stimulus is now reproduced with the injection of a second optical signal with parallel polarisation into the parallel polarised mode of the VCSEL ($\lambda_{||}$). If the optical power of this signal exceeds a particular threshold level reverse PS is induced. This will reactivate the parallel polarisation mode of the VCSEL and will suppress the orthogonal polarisation mode. As a result, the VCSEL-Neuron will return to its non-active state characterized by the emission of parallel polarised light. Finally, Fig. 2(b) also shows schematically the nonlinear threshold functions for the parallel (switching from low to high output state) and the orthogonal (switching from high to low output state) mode of the VCSEL resulting from the external injection of a second parallel polarised optical signal.

## 4. Experimental setup

Figure 3 shows the experimental setup used in this work. The two external optical signals that will correspond respectively to the excitatory and the inhibitory stimuli are generated by two tuneable laser sources. An optical isolator is included at the output of each tuneable laser to avoid backward reflections that might lead to spurious results. The polarisation of the tuneable lasers is controlled by use of two fibre polarisation controllers and configured to be alternatively orthogonal or parallel to that emitted by the solitary VCSEL depending on the particular case (excitatory or inhibitory stimulus). A variable optical attenuator is included to control the optical power of one of the tuneable lasers. An 85/15 fibre directional coupler is included in the setup to combine the light coming from both laser sources into a single optical path. One of the outputs of the coupler is connected to a power meter to monitor the optical input power, whereas the second branch is injected into the VCSEL (optical neuron) via a three-port circulator. Finally, the reflective output of the VCSEL is analyzed using an optical spectrum analyser (OSA) and an optical polarimeter.

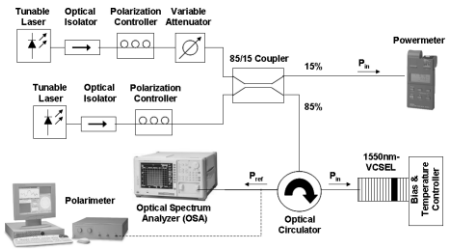


Fig. 3. Experimental setup.

## 5. Experimental results

### *5.1. Excitatory stimuli*

Figures 4(a)–4(c) show three different sets of experimentally measured input/output power relationships for the parallel and the orthogonal polarisations of the VCSEL-Neuron. The VCSEL was biased with a constant current of $1.5 \times I_{th}$ and three different initial detunings ($\lambda_{\perp}$-$\lambda_{\perp VCSEL}$) were configured, namely 0 nm [Fig. 4(a)], 0.02 nm [Fig. 4(b)] and 0.034 nm [Fig. 4(c)], between the wavelength of the external signal and the resonant wavelength of the orthogonal polarisation mode of the device. Without external injection the parallel polarisation mode of the VCSEL dominates and therefore the neuron is inactive. Under increasing external optical injection using an orthogonally polarised signal the power of the parallel (orthogonal) polarisation decreases (increases) linearly. This trend continues until the optical power of the orthogonally-polarised injected signal exceeds a threshold level, when PS is produced. The output power of the parallel polarisation is suppressed and the orthogonal

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polarisation dominates at the output of the device. This turns the VCSEL-Neuron into its active state. In addition it is important to note that once PS is induced further increments of the injected optical power are not translated into a significant increase of the power of the orthogonal polarisation at the output of the VCSEL. This limiting behaviour is in fact the same as that exhibited by a neuron cell. It is also noteworthy that the laser behaviour was reproducible, the states after switching were measured to be stable and that the characteristic all-optical threshold operation determining the response of the optical neuron to an excitatory stimulus is achieved for very low input power requirements of only a few μWatts.

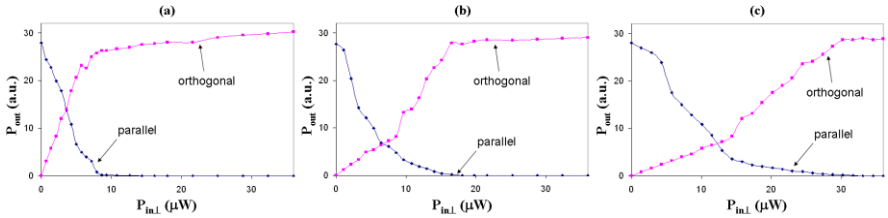


Fig. 4. Response of the VCSEL-Neuron to an excitatory stimulus (orthogonally-polarised signal). Three different detunings ($\lambda_{\perp}$-$\lambda_{\perp VCSEL}$) are set: (a) 0 nm, (b) 0.02 nm and (c) 0.034 nm.

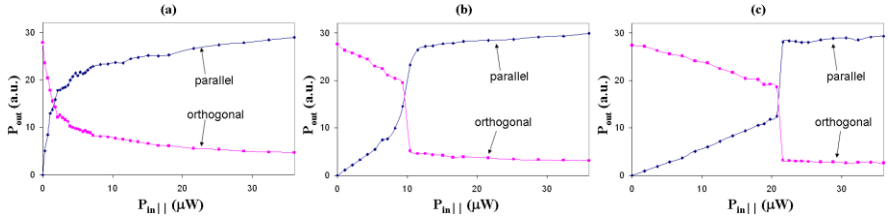


Fig. 5. Response of the VCSEL-Neuron to an inhibitory stimulus (parallel polarised signal). Three different detunings ($\lambda_{||}$-$\lambda_{||VCSEL}$) are set: (a) 0.01 nm, (b) 0.026 nm and (c) 0.034 nm. Initially the VCSEL-Neuron is under the influence of an excitatory stimulus with power of $P_{in\perp}$ = 15 μW and detuning of $\lambda_{\perp}$-$\lambda_{\perp VCSEL}$ = 0 nm.

### *5.2. Inhibitory stimuli*

In this case, the VCSEL-Neuron is initially active as it is under the influence of an excitatory stimulus. If the VCSEL receives now an additional inhibitory stimulus it will be deactivated, returning to the initial non-excited state. This situation is demonstrated in our experiments by simultaneous injection of two polarised optical signals into the device. The first signal has orthogonal polarisation corresponding to the excitatory stimulus and is configured with enough optical power to produce PS from parallel to orthogonal polarisation (active neuron). The second optical signal used to induce an inhibitory stimulus has parallel polarisation and is injected into the parallel polarisation mode of the VCSEL.

We show this in Figs. 5(a)–5(c) where there are three different sets of input/output power relationships for the parallel and the orthogonal polarisation outputs of the VCSEL-Neuron under the influence of an inhibitory stimulus. The orthogonally-polarised optical signal is injected at the resonant wavelength of the orthogonal polarisation mode of the device ($\lambda_{\perp}$-$\lambda_{\perp VCSEL}$ = 0 nm) with a constant optical power of 15 μW. The parallel polarized signal is injected into the long-wavelength side of the parallel polarisation mode of the VCSEL with initial wavelength detunings ($\lambda_{//}$-$\lambda_{//VCSEL}$) of 0.01 nm [Fig. 5(a)], 0.026 nm [Fig. 5(b)] and 0.034 nm [Fig. 5(c)] and its optical power is increased from 0 to 36 μW. As seen in Figs. 5(a)–5(c), initially the orthogonally-polarised signal produces PS at the output of the VCSEL where the orthogonal polarisation dominates (active neuron). A parallel polarised optical signal (inhibitory stimulus) is then injected, and once this exceeds a certain threshold "reverse" PS from orthogonal to parallel polarisation is produced, the influence of the excitatory stimulus is negated and the neuron is de-activated. Again, low input power

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requirements (of a few μWatts) as well as reproducible and stable laser behaviour was measured for the switching determining the response of the optical neuron to inhibitory stimuli.

*5.3. Polarisation analysis*

The measured Poincare sphere is shown in Fig. 6(a) which illustrates the evolution of the polarisation state of the light at the output of the VCSEL-Neuron under the influence of an excitatory stimulus. As seen in Fig. 6(a), initially without optical injection, the parallel polarisation mode of the free-running VCSEL dominates. Therefore the initial polarisation state as measured at the output of the device is parallel, and is represented on the Poincare Sphere as linear horizontal polarisation by the red star on Fig. 6(a). After the arrival of the excitatory stimulus, reproduced here by the injection of an orthogonally-polarised signal with an initial detuning ($\lambda_{\perp}$-$\lambda_{\perp VCSEL}$) of 0.02 nm, the polarisation at the output of the VCSEL switches from parallel to orthogonal. This is marked on the Poincare sphere by the change from linear horizontal to linear vertical polarisation [final blue star on Fig. 6(a)]. The measured "arch" around the Poincare sphere of Fig. 6(a) shows the trajectory followed by the polarisation of the light emitted by the VCSEL-Neuron, from linear horizontal or parallel (red) to linear vertical or orthogonal (blue) as the power of the excitatory stimulus is increased gradually.

In contrast Fig. 6(b) illustrates the reverse situation; that is when an initially excited VCSEL-Neuron, already under the influence of an excitatory stimulus, subsequently receives an inhibitory stimulus. The initial excitatory stimulus is configured here by an orthogonally-polarised signal with a power of 15 μW and an initial detuning of $\lambda_{\perp}$-$\lambda_{\perp VCSEL}$ = 0 nm. To this is added the inhibitory stimulus by the injection of a parallel polarised signal with a detuning of $\lambda_{//}$-$\lambda_{//VCSEL}$ = 0.02 nm and an optical power varying from 0 to 36 μW. In this second case, the polarisation at the VCSEL output is initially linear vertical or orthogonal (blue) and switches to linear horizontal or parallel (red) after the arrival of the inhibitory stimulus. Figure 6(b) also shows the trajectory followed by the polarisation at the output of the VCSEL-Neuron as the power of the inhibitory stimulus is increased from 0 to 36 μW.

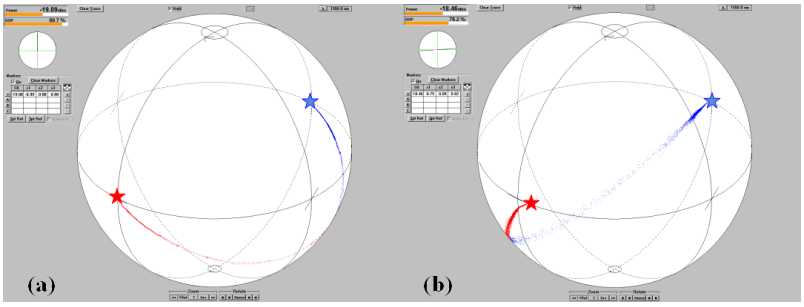


Fig. 6. Evolution of the polarisation state at the output of the VCSEL optical neuron under the arrival of (a) an excitatory and (b) an inhibitory stimulus.

## 6. Conclusions

We demonstrate experimentally a new approach to optically mimic some basic functionalities of a neuron cell using a 1550 nm VCSEL. The technique is based on use of PS effects that can be induced in the two orthogonal polarisations of the fundamental transverse mode of VCSELs under single and/or double polarised optical injection. Polarised optical injection into the VCSEL-Neuron is associated with distinct types of external stimuli; in particular orthogonal (parallel) polarised injection is associated with an excitatory (inhibitory) stimulus. Positive and negative all-optical threshold operation with low input power requirement is demonstrated experimentally. Moreover the different emitted polarization states 'activated' in

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the VCSEL are equated with an active (orthogonal polarisation) or an inactive (parallel polarisation) neuron. These early results offer exciting prospects for optical neural emulation and merit further study for their potential use in novel architectures of optical computing, optical neural networks as well as for switching/routing applications in optical networks.

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