

Ultrafast Emulation of Retinal Neuronal Circuits with Artificial VCSEL optical Neurons

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Abstract— Biological retinal neuronal circuits are emulated using a system of connected 1550 nm Vertical-Cavity Surface-Emitting Laser (VCSEL)-neurons. Spiking and non-spiking neuronal responses are reproduced at ultrafast speed (>7 orders of magnitude faster than neurons) with prospects for novel brain-inspired computing platforms and Artificial Intelligence.

I. INTRODUCTION

NEUROMORPHIC platforms aimed at reproducing the powerful computational capabilities of the brain are receiving increasing research interest for new paradigms in neuro-inspired computing and Artificial Intelligence. Whilst electronic circuitry techniques have been traditionally used [1], in recent years photonic approaches for neuromorphic systems have also emerged as these offer unique advantages, e.g. ultrafast speeds (up to 9 orders of magnitude faster than neurons), long communication links, wavelength multiplexing, large bandwidths, low crosstalk, etc. Amongst the diversity of photonic techniques for artificial neuronal models that have recently appeared, approaches based on different types of semiconductor lasers have dominated (see [2] for a review). In particular, neuromorphic photonic techniques based upon Vertical Cavity Surface Emitting Lasers (VCSELs) are undergoing increasing research interest given the important advantages that these devices offer (e.g. low footprint, reduced costs, ultrafast operation, easy incorporation into 2D/3D arrays, etc) [3] and the wide range of neuron-like dynamics they can exhibit [4-8]. Specifically, VCSELs have shown similar thresholding dynamics, phasic and tonic spiking regimes, spike bursting, etc., as biological neurons [4]. Moreover, VCSEL-based neuronal models (or VCSEL-Neurons) have been shown to exhibit both excitatory and inhibitory neuronal spiking responses [5-6] as well as the successful communication of spiking signals between interconnected VCSEL-Neurons [7-8].

In this work, we provide a first experimental demonstration of the ultrafast photonic emulation of biological neuronal circuits using systems of VCSEL-Neurons. As a first effort towards developing future brain-inspired spike processing

systems and neuronal circuit simulators, here we have focused on the emulation of basic neural circuitry in the human retina. Spiking and non-spiking responses of different neurons, e.g. Photoreceptors, Bipolar Cells (BCs) and Retinal Ganglion Cells (RGCs) are reproduced optically using interconnected VCSEL-Neurons and at ultrafast speeds. This work therefore provides a first demonstration of key processing features of interest to neuromorphic computing platforms and highlight the diversity and versatility of VCSEL-Neurons for use in future neuro-inspired processing networks.

II. EXPERIMENTAL RESULTS

Fig. 1(a) shows diagrams of the emulated retinal neuronal circuit and the non-spiking and spiking signals produced by the photoreceptors, BCs and the RGCs. BCs are non-spiking neurons connected to photoreceptors in the eye that fire different graded potentials dependent on the photoreceptor input. RGCs are spiking neurons synapsed to the BCs, that convert graded potentials into spike firing patterns that are transmitted to the brain (via the optic nerve). Two types of BCs and RGCs exist, creating circuits of opposite responses (ON and OFF-type). These yield different outputs under the presence or absence of incoming light stimuli [9-10]. Figs. 1(b) and 2 plot respectively the designed architecture and the setup developed in this work. These use three VCSEL-Neurons (M-, BC-, RGC-VCSELs) connected in series to emulate the different types of biological neurons forming the ON- and OFF-type BC+RGC retinal circuitry. Devices compatible with current optical communication networks operating at 1550 nm were used here with their wavelengths matched by tuning their operation temperature.

The first VCSEL (M-VCSEL) emulates the square potentials produced by photoreceptors in the eye in response to light stimuli. To do so, M-VCSEL is encoded with temporal perturbations (stimuli) of opposite signs, negative and positive for the ON- and OFF-type circuits, using a Mach-Zehnder amplitude modulator. The signals from M-VCSEL are launched into the second device, emulating a BC Neuron (BC-VCSEL), injection-locking its output to M-VCSELs' light. In this situation, stimuli from M-VCSEL, trigger the firing of square-like signals (graded potentials) by BC-VCSEL. These will be of opposite sign (negative or positive) depending on the circuit emulated (ON- or OFF-type). BC-VCSEL's signals arrive into the third device (RGC-VCSEL), emulating an RGC Neuron, injection-locking it to BC-VCSEL. In the ON-type circuit, the graded potentials from BC-VCSEL trigger a short transition from injection-locking to unlocking regimes, and the RGC-VCSEL fires as a result a controlled spiking pattern. On

the other hand, in the OFF-type circuit the positive graded potentials from BC-VCSEL cause a short transition from an unlocked (spiking) to an injection-locked (stable) regime producing a temporal window of spiking inhibition.

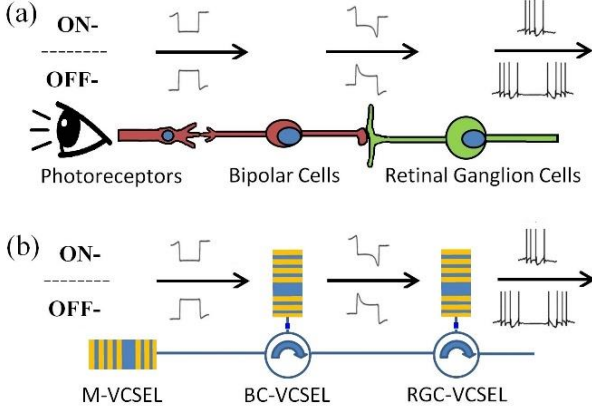


Fig. 1. (a) Schematic of the emulated retinal neuronal circuits formed by Photoreceptors, Bipolar Cells (BC) and Retinal Ganglion Cells (RGC). The signal conversion of the two different types of circuits is shown, ON- (top) and OFF- (bottom). (b) Diagram depicting the emulation of the neuronal circuits using three interconnected VCSEL-Neurons (M-/BC-/RGC-VCSELs).

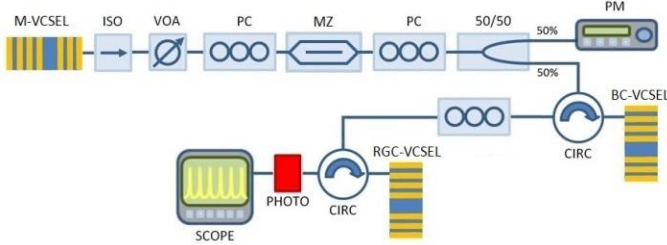


Fig. 2. Experimental Setup. M-, BC-, RGC-VCSEL: Master-, Bipolar Cell, Retinal Ganglion Cell-VCSEL, ISO: optical isolator, VOA: variable optical attenuator, PC: polarization controller, MZ: Mach-Zehnder amplitude modulator, PM: power meter, CIRC: optical circulator, PHOTO: photodetector, SCOPE: oscilloscope.

Figs. 3(a) and 3(b) respectively depict the outputs measured from each VCSEL-Neuron when operating in the ON- and OFF-type circuits. Fig. 3(a) shows that a 4.9ns-long (negative) stimuli encoded in M-VCSEL (Fig. 3(a,i), in black) triggers a (negative) graded potential at the output of BC-VCSEL (Fig. 3(a,ii), in red) analogous to the non-spiking response of a BC Neuron. When the RGC-VCSEL receives the graded potential from BC-VCSEL, it reacts by firing spikes continuously until the graded potential is removed (Fig. 3(a,iii), in blue). Similarly, Fig. 3(b) plots the measured time-series from the 3 VCSEL-Neurons in the OFF-type architecture when 5.18ns-long stimuli are encoded in M-VCSEL (Fig. 3(b,i), in black). The responses from M- and BC-VCSEL obtained here are opposite to those achieved in the ON-type circuit (Fig. 3(a)). The BC-VCSEL whose output (Fig. 3(b,ii), in red) produces a (positive) non-spiking graded potential triggers as well an opposite spiking response from RGC-VCSEL (Fig. 3(b,iii), in blue). The latter reacts producing a temporal window of spiking inhibition for the duration of the graded potentials from BC-

VCSEL. Importantly, the spiking responses produced at the output of both the ON- and OFF-type circuits were consistently produced across 60 consecutive stimulations as shown in the temporal maps of Figs. 3(a,iv) and 3(b,iv).

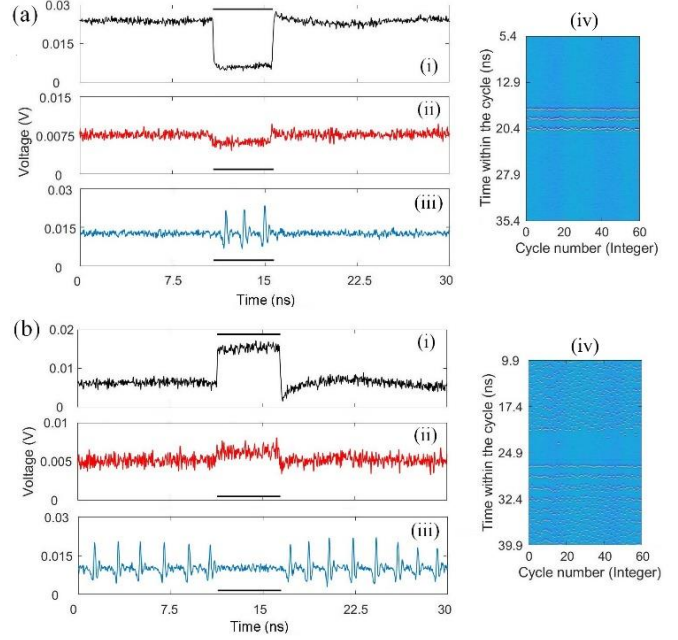


Fig. 3. Emulation of (a) ON- and (b) OFF-type retinal circuits with VCSEL-Neurons. Time-series from M-VCSEL ((i), black) BC-VCSEL ((ii), red) and RGC-VCSEL ((iii), blue) are plotted. The maps at the right hand side, plot the combined response at the output of the ON- (a,iv) and the OFF-type (b,iv) circuits under the arrival of 60 consecutive stimuli.

III. CONCLUSION

We emulate neural circuitry in the retina using a system of VCSEL-Neurons operating at the important telecom wavelength of 1550 nm. We demonstrate that the biological signals from different types of neurons (BCs and RGCs) can be optically reproduced but at much faster (sub-ns/ns) timescales, >7 orders of magnitude faster than the millisecond response times of neurons. These results hold great promise for new compact, inexpensive neuromorphic photonic systems for future to brain-inspired computing platforms, neural circuit simulators and Artificial Intelligence systems.

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