Neuromorphic Object Edge Detection with Artifical Photonic Spiking VCSEL-Neurons

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***Abstract*— Fast spiking Vertical Cavity Surface Emitting Laser neurons are used to reveal neuromorphic object edge information in digital images. Input integration and thresholding are used in tandem with convolution to create a photonic spiking node with high prospects for convolutional neural networks and computer vision.**

I. Introduction

With the ever-growing appeal of artificial intelligence (AI), there is a significant interest in realizing computing systems capable of performing complex tasks such as image recognition and feature extraction. This functionality, coined as computer vision, aims towards processing systems that recognize and understand images as humans do. One of the essential steps in computer vision is obtaining edge information, which can be revealed by scanning kernel operators (masks) across the source [1]. Using a large number of parallel nodes in a convolutional neural network (CNN), edge information can be generated and compared, allowing the CNN to identify distinctive features and achieve a successful recognition [2]. Traditionally, CNNs have been realized using electronics, but due to the challenges imposed at near-fundamental limits, CNNs are advancing into faster photonic technologies such as silicon weighting banks [3] and interferometers [4]. Simultaneously, new semiconductor laser systems are appearing under the guise of neuromorphic photonic devices as candidates for neural network nodes. Vertical-cavity surface-emitting lasers (VCSELs) are one of the devices that have shown the ability to demonstrate many of the key neuronal characteristics required for artificial neural networks such as CNNs (interconnectivity, fast sub-ns operation, thresholding [5]). Furthermore, these cheap and compact devices have recently demonstrated a basic pattern recognition task, operating as a leaky integrate-and-fire (LIF) neuron targeting 4-bit patterns [6].

Using these devices, we will show the first experimental implementation of a LIF VCSEL-neuron for spiking image edge detection. Utilizing time-multiplexing and optical injection, we trigger fast (~1ns long) neuronal spikes for target features (edges), revealing the desired object information. We believe these results have high prospects for the development of novel photonic CNNs using VCSEL-based photonic neurons towards AI systems capable of complex image recognition tasks at speeds much faster than traditional electronic systems.

II. Experimental Results

Figure 1 shows the image convolution process and experimental setup used to detect edge information in black (1) and white (-1) source images. Source images are multiplied by a 2x2 kernel operator, which is scanned along each row of the image pixel-by-pixel. The product of kernel and source produces four values. These are encoded using 830 ps-long positive and negative pulses depending on their specific values. The resulting four pulses are time-multiplexed into a return-to-zero (RZ) signal for their injection into the VCSEL-Neuron. The pixel duration is selected to match the speed of the dynamical responses in the VCSEL-Neuron. When source and kernel have a strong correlation (the target edge feature), the input signal has up to 4 positive time-multiplexed input pulses within 0.7 ns. The input signal is then optically encoded and injected into the LIF VCSEL-neuron.

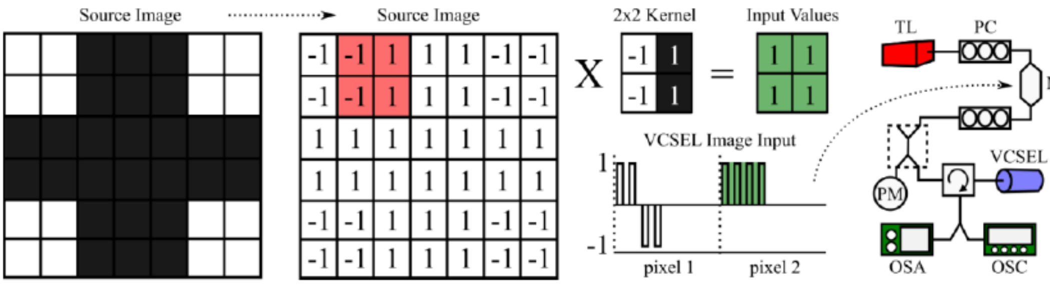

Figure 1 | A description of the image convolution process used to generate the VCSEL image input and the experimental arrangement used to trigger spiking dynamics. TL – tunable laser, MZ – Mack Zehnder, PM – Power meter.

Figures 2a-b plot schematic diagrams of the 28x28 pixel source image (a cross pattern), and the corresponding input signal optically encoded and injected into the VCSEL-Neuron when Kernel 1 (-1 1; -1 1) is applied. Kernel 1 targets vertical edge features that transition from white to black pixels. A pixel duration of 3.0 ns/pixel was selected to ensure that the system could trigger a spiking response for all pixels. Figure 2c plots the VCSEL-

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neuron's spiking response to the input generated in Fig. 2b. This shows that the VCSEL-Neuron, initially stably-locked to the external injection, produces a constant output until the encoded input pulses enter the device. When the target feature (vertical edge) produces 4 positive input pulses (green highlight) the system responds by firing a fast spiking response. The integration of these multiple positive input pulses results in a larger total input energy than other non-target features, allowing the spiking threshold to be adjusted for the triggering of target features only. Figure 3a plots the extended time series of this result as a temporal map, revealing spike activation for all the target white-to-black vertical edges. Figure 3b plots the VCSEL-neuron's response when Kernel 2 is applied. The spiking response of the VCSEL-Neuron reveals the detection of vertical edges transitioning from black-to-white pixels, as desired. Figure 3c shows the combined results of Kernels 1/2, which successfully detects all the vertical edge features in the source image. During the conference, we will expand upon these results by demonstrating kernel operators for horizontal and diagonal edge features, as well as detection of multiple edge features at once, acting on the spiking activation threshold of the VCSEL-Neuron.

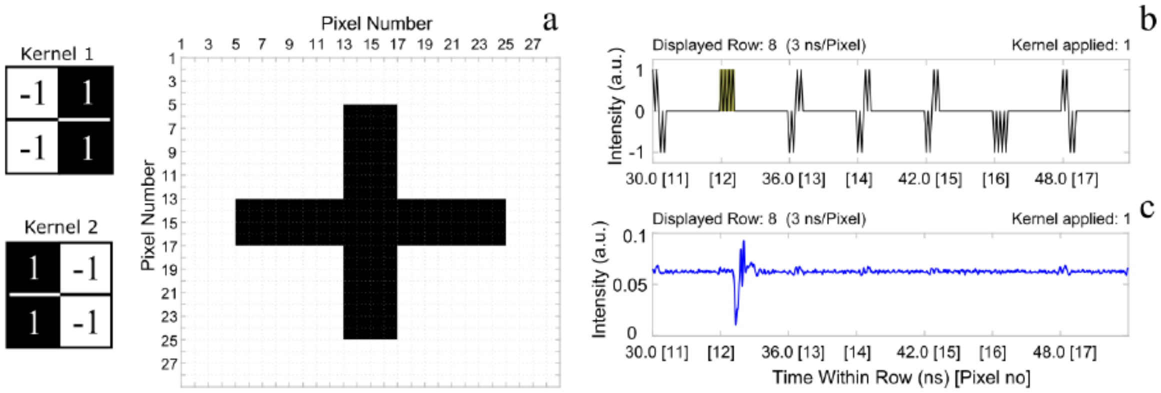

Figure 2 | The 28x28 pixel source 'cross-pattern' image and Kernels 1 and 2 (a). Encoded input signal after applying Kernel 1 (b). VCSEL-neuron's response (c). (b-c) show time series for pixel numbers 11-17 in row 8 of the source image.

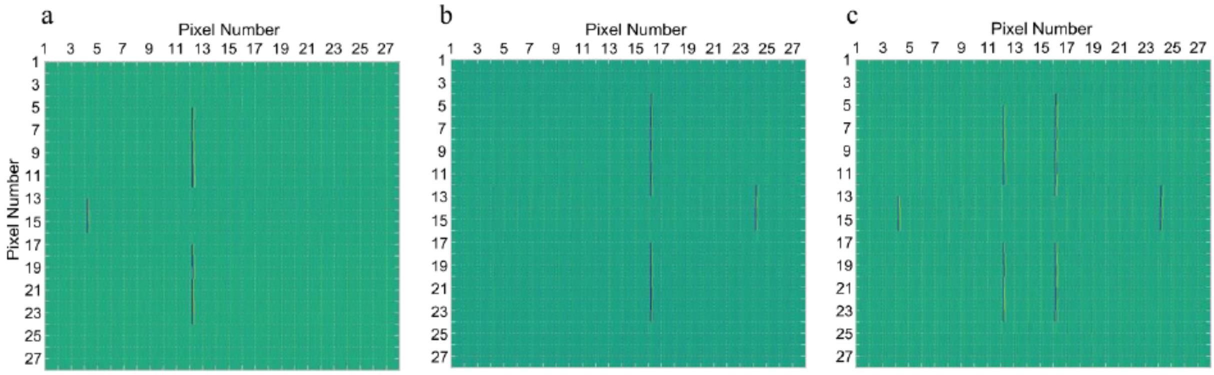

Figure 3 | Temporal maps revealing successful spike activations when Kernel 1 (a), Kernel 2 (b) and both Kernels 1 & 2 (c) are used to detect the vertical edge features in the source image. The intensity colour map plots spike troughs (peaks) as dark blue (yellow). Dimensionality is 1 less than the source image as no buffer was applied during kernel operation.

III. Conclusion

We demonstrate experimentally image edge detection using a single spiking photonic VCSEL-neuron able to perform the integration and thresholding steps of a traditional image convolution task. Using this technique, we gain information about different edges in black and white images using a fast (GHz rate) optical spiking representation. These results demonstrate the potential VCSEL-based photonic neurons have as nodes in larger artificial convolutional neural networks towards neuromorphic photonic realizations of computer vision and artificial intelligence systems.

References

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