(Invited Paper)

PHOTONIC NEURONS FOR TERAHERTZ PULSE PROCESSING

Mable P. Fok[1*], David Rosenbluth[2], Konstantin Kravtsov[1] and Paul R. Prucnal[1]

[1]Princeton University, Princeton, New Jersey 08544, USA
[2]Lockheed Martin Advanced Technologies Laboratory, Cherry Hill, New Jersey 08002, USA
*Corresponding author: mfok@princeton.edu

Keywords: Lightwave neuromorphic signal processing, Optical neural systems, Semiconductor optical amplifier, Ge-doped nonlinear fiber.

Abstract

We developed a hybrid analog/digital computational primitive that elegantly implements the functionality of an integrate-and-fire neuron using a Ge-doped non-linear optical fiber and off-the-shelf semiconductor devices. Spike processing devices for optical computational system have the potential to be scalable, computationally powerful, and have high operation bandwidth. They open up a range of optical processing applications for which electronic processing is too slow. In this paper, we demonstrate the feasibility of implementing simple photonic neuromorphic circuits, including the auditory localization algorithm of the barn owl, which is useful for LIDAR localization, and the crayfish tail-flip escape response.

1 Introduction

Technologies for real-time signal processing have received considerable attention due to their processing power for numerous applications. Neuromorphic engineering provides the capability of performing practical computing and signal processing based on the biophysical model of neuronal computation. For example, using analog VLSI technology, small, low-power front end sensors have been developed to mimic the functionality of the retina and the cochlea. However, the speed of analog VLSI is just too slow for many real-time signal processing applications.

In this paper, we present an optical hybrid analog-digital computational primitive that implements the functionality of an integrate-and-fire neuron. Our lightwave neuromorphic approach [1] is made up of a novel type of Ge-doped highly nonlinear optical fiber and an off-the-shelf semiconductor device. Utilizing this hybrid analog-digital processing primitive, processing algorithms can be implemented that are too complex for existing optical technologies and have a much higher bandwidth compared with existing electronic technologies. The spiking neuron comprises a small set of basic operations (delay, weighting, spatial summation, temporal integration, and thresholding), and is capable of performing a variety of computations, depending on how its parameters (e.g., delays, weights, integration time constant, threshold) are configured. An optical computational system based on spike processing devices has the potential to be scalable, computationally powerful, and have high bandwidth. It opens up a range of optical processing applications for which electronic processing is too slow.

2 Spike Processing in a Neuron and Its Optical Implementation

Our approach based on the standard leaky-integrate-and-fire (LIF) model of a neuron that operates as follows [2]: The neuron has N inputs that are a continuous time series, consisting either of spikes or continuous analog values representing voltages. After each input is independently weighted and delayed, they are spatially summed (summed point-wise). The resulting single time-series is then temporally integrated using an exponentially decaying impulse response function. If the integrated signal exceeds a threshold, then the neuron outputs a spike. After the spike, there is a short refractory period during which no other spikes can be issued. The output of the neuron consists of a continuous time-series of spikes.

To mimic the LIF neuron optically, we utilize a semiconductor optical amplifier (SOA) and a Ge-doped nonlinear fiber based thresholder as the key elements. The functional architecture of the integrate-and-fire device consists of three processing blocks as shown in Figure 1: (i) passive weighting, delay, and summation of inputs; (ii) temporal integration; and (iii) thresholding. We found an exact correspondence between the equations governing SOA carrier density and the equations governing leaky integration in LIF neuron models [3], which justifies the use of an SOA as the embodiment of the leaky integrator in the computational primitive.

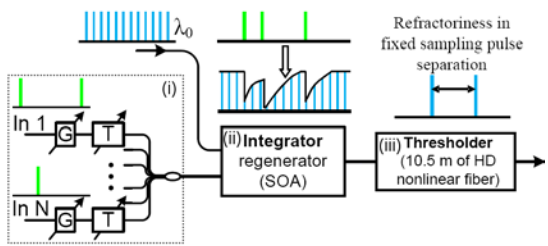

Fig. 1. Block diagram of the photonic neuron. G: gain; T: time delay; SOA semiconductor optical amplifier: HD nonlinear fiber: highly Ge-doped nonlinear fiber. The three processing are (i) passive weighting, delay, and summation of inputs; (ii) temporal integration; and (iii) thresholding.

The exponential recovery behavior of the SOA provides the integration characteristic that a neuron requires. The carrier density of an SOA decreases when an optical pulse is launched into it. In the presence of a pumping current, the carrier density recovers exponentially. When a second optical pulse is launched into the SOA before the carrier density completely recovers, it further decreases the carrier density, resulting in a temporal integration of the effects of both input pulses. The change in SOA carrier density is converted into pulse intensity through gain sampling. Figure 2(a) shows a series of optical pulses that are launched into the SOA, while Figure 2(b) shows the change in carrier density, represented by the intensity of the sampling pulses.

(a)

(b)

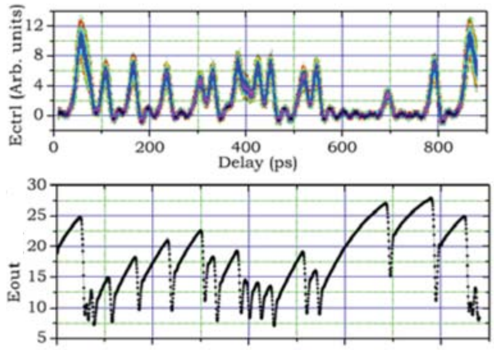

Fig. 2. The measured SOA response to excitation by multiple pulses. (a) Oscilloscope trace of the control pulse sequence; (b) Sampled SOA gain dynamics The SOA recovery time (integration time constant) is 180 ps.

For thresholding, a loop mirror incorporating a short piece of Ge-doped nonlinear fiber is utilized [4]. The optical thresholder has a cubic transfer function which saturates at high powers. The thresholder amplitude-discriminates the input signal and the neuron fires when the input power exceeds a certain threshold. The optical thresholder removes the undesired weak spikes while equalizing the strong spikes that can be used as a control for a second-stage neuron.

3 Lightwave Neuromorphic Circuits

With small-scale lightwave neuromorphic circuits, we demonstrated several important neuronal behaviors, including the auditory localization algorithm of the barn owl, useful for LIDAR localization, and the crayfish tail-flip escape response, useful for feature recognition.

3.1 Auditory localization algorithm of the barn owl

A simple diagram of the auditory localization algorithm is shown in Figure 3(a). The time difference between the signals arriving the owl's left sensor and right sensor is different for object 1 (t_{1a}-t_{1b}) and object 2 (t_{2a}-t_{2b}), governed by the position of the object. Therefore, the neuron can be configured to respond to a certain object location only by adjusting the weight and delay of the neuron inputs. The neuron spikes only if the weighted and delayed signals are strong enough and arrive within the integration window. Figure 3(b) shows the corresponding SOA based integrator response when the two weighted and delayed signals are too far apart. The stimulated signal cannot pass through the thresholder and therefore no spike is obtained. When the two inputs are close enough, the carrier density reaches the threshold and leads to a spike, as shown in Figure 3(c). This algorithm is useful for LIDAR localization.

(a)

(b)

(c)

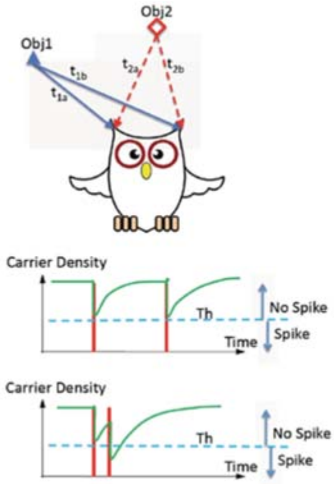

Fig. 3. (a) Schematic illustration of the auditory localization algorithm of the barn owl. (b) SOA carrier density - when two signals are far apart (no spike). (c) SOA carrier density - when two signals are close (spike).

3.2 Tail-flip escape response of the crayfish

Crayfish escape from a predator by means of a rapid escape response. The corresponding neuron circuit is configured to respond to appropriately abrupt stimuli but not respond to stimuli from normal water flow. Since this is a life-or-death decision to the crayfish, the response has to be executed quickly and accurately. A potential military application of lightwave neuromorphic signal processing based on escape response could be for pilot ejection from aircraft under serious attack. By means of compact optical devices, the latency can be as low as 500 ps.

Acknowledgements

The authors gratefully acknowledge the generous support of the Lockheed Martin Advanced Technology Laboratory through their IRAD program, as well as the Lockheed Martin Corporation through their Corporate University Research Program.

References

[1] M. P. Fok, D. Rosenbluth, K. Kravtsov, and P. R. Prucnal, "Lightwave Neuromorphic Signal Processing" in Press, IEEE Signal Processing Magazine, November 2010.

[2] W. Maass and C. M. Bishop, eds., Pulsed Neural Networks (The MIT Press, 1999).

[3] D. Rosenbluth, K. Kravtsov, M. P. Fok, and P. R. Prucnal, "A High Performance Photonic Pulse Processing Device," Optics Express, vol. 17, iss. 25, pp. 22767–22772, December 2009.

[4] K. Kravtsov, P. R. Prucnal, and M. M. Bubnov, "Simple nonlinear interferometer-based all-optical thresholder and its applications for optical CDMA," Opt. Express 15, 13114 (2007).