Temporal Dynamics of An Integrated Laser Neuron

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***Abstract*—Temporal dynamics plays an important role in spike processing. We experimentally demonstrate various biologically-inspired processing tasks in a laser neuron in a photonic integrated circuit platform. Our system provides a platform for gigahertz signal processing and computing.**

I. Introduction

Spike processing is a communication framework used by our brains. This technique, also known as pulse position modulation, is based on coding information in the timing between short, delta-function-like pulses. It has been shown to be very power efficient [1]. Neuromorphic photonic processing systems, in particular, have the potential to exhibit orders of magnitude improvements in bandwidth, latency, and energy efficiency over existing approaches [2]. To process signal at high speeds and high temporal precision, we must introduce two key components of a spike processing framework, the refractory dynamics and temporal integration.

Temporal integration, the ability to correlate different pulses in time (i.e., coincidence detection), is a critical task for nonlinear processors that use a spike processing framework. For example, the functionality of the Leaky Integrate-and-Fire neuron (LIF neuron) [3] is based on a response to large perturbations, closely spaced in time. When the two non-excitable input pulses are close enough in time, they will be integrated and their sum can exceed the excitability threshold and generate a spike. The generation of a spiking event indicates there is coincidence of input signals.

In a LIF neuron, the refractory period is the time duration following a first firing spike in which the system cannot be excited again. It is also a necessary condition of the excitability. The refractory dynamics governs the spike firing rate. An integrated photonic system can be a strong candidate of high speed processor since the the refractory period can be in nanon second time scale [4].

Here, we study spike processing properties that arise from the dynamics of our laser system, including temporal integration and a refractory period. This device is unique in that it is instantiated in a photonic integrated circuit platform, and uses an O/E/O driving principle based on a receiverless link between a photodetector and laser [5]. We demonstrate the ability to perform GHz firing rate and to detect a coincident event with less than 1 ns precision.

II. Device and Experimental Setup

We designed a device fabricated in a standard indium phosphide photonic integrated circuits (PIC) platform by the Heinrich Hertz Institute through JePPIX consortium. The composite structure (Fig. 1(a)) of the device consists of a high-speed balanced photodetector pair, a two-section distributed feedback laser (DFB), and a connecting wire printed on a standard metalization layer (Fig. 1).

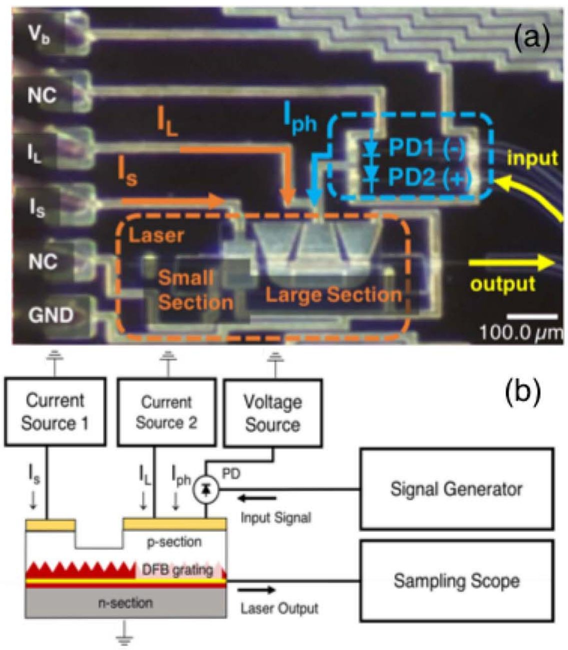

Fig. 1. (a) Figure of the integrated photonic neuron. The chip is an indium phosphide based device fabricated by the Heinrich Hertz Institute. V_b: Bias for PD2, NC: Not connected to any source in the experiment, I_L: current flowing into large section of DFB, I_S: current flowing into small section of DFB, GND: Ground. (b) The schematic figure of experimental setup.

In this experiment, we only used one photodetector (PD2 in Fig. 1(a)) to provide excitatory dynamics to the system. The two sections of DFB lasers connect to the metal pads on the edge of the chip, and can be pumped up by two independent current sources I_L, I_S, which can adjust the internal cavity parameters and lasing threshold. The photodetector (PD2) can be reverse biased by applying voltage (V_b) to the metal pad connected to it. The input optical signals are sent to the photodetector (PD2) through on-chip waveguide, and the photocurrent I_{ph} generated by PD2 provides excitatory perturbation to the large section of DFB laser. To generate the input signals, we used a continuous-wave DFB laser source followed by a high speed Mach-Zehnder modulator, and utilized a high speed pulse pattern generator and sampling scope connected to a synchronized clock source to measure the laser output. The

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schematic figure of experimental setup is shown in Fig. 1(b).

III. Temporal Dynamics

A. Coincidence Detection

Taking advantages of the property of temporal integration, we send two non-excitable input pulses to the system. If they are far from one another, then there is no output pulse response, but if two input pulses are close enough, then the system can fire a spike. This phenomenon can be exploited to detect coincident pulses. In the inset (i) of Fig. 2, the two input pulses (blue curve) are separated by $0.65\,\mathrm{ns}$, and the distinguishable spike output (red curve) can be generated. Note that the output pulse is only generated after receiving second input pulse. In the inset (ii) of Fig. 2, the temporal separation of two input pulses is $5.41\,\mathrm{ns}$, and the system undergoes a subthreshold oscillation. The data points shown in Fig. 2 are the maximal peak power of the output signal. Our system can perform the coincidence detection with the precision less than $1\,\mathrm{ns}$. Furthermore, due to the wide optical bandwidth of a photodetector, we can detect the signals with different wavelengths or from different channels.

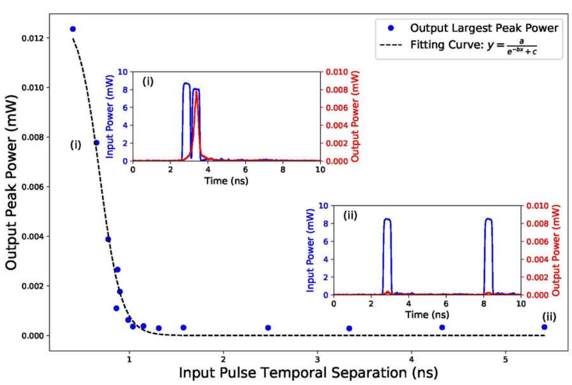

Fig. 2. The blue dots are the peak power of output spike when sending two non-excitable input pulses fitted by the sigmoid function: $y = \frac{a}{e^{-bx}+c}$ shown as black dashed curve in the figure. The optimized fitting parameters are $a = 5.12$, $b = -8.73$,, and $c = 394.54$. In the insets, the blue curve is the input signal, and the red curve is the output response. They correspond to the axis on the left and right respectively.

B. Refractory Period

To analyze the refractory dynamics of our system, we generate two input pulses strong enough excite a spike output independently, and send them to PD2 (excitatory photodetector) with different temporal separation. When the second input pulse is within the refractory period of the system, the second spike output cannot be fully excited. Specifically, one can make distinction between absolute and relative refractory period. In the absolute refractory period, there is no second spike as shown in the inset (i) of Fig. 3 (input temporal separation = $0.288\,\mathrm{ns}$). However, in the relative refractory period, the second pulse response can be generated which has been shown in the inset (ii) of Fig. 3 (input temporal separation = $0.388\,\mathrm{ns}$). When the temporal separation of two input pulses is large enough (greater than $0.5\,\mathrm{ns}$), the neuron will fire two spikes with identical peak power as the inset (iii) of Fig. 3 shows. The difference between first and second peak power decreases exponentially as the temporal separation of input pulses increases. And the system can have a maximal firing rate of $1/(0.5\,\mathrm{ns})$= 2 GHz. It is worth noting that our system behaves similarly and have same order of refractory period as in Selmi, F. *et al.* [4], but with a different photonic neuron architecture, and a different mechanism to excite the system.

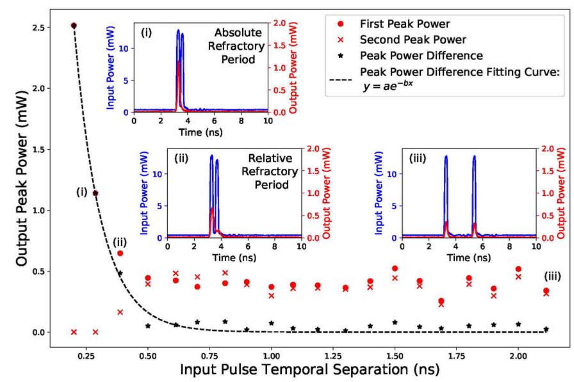

Fig. 3. The red dots represent the peak power of the first spike, and the red crosses represent the peak power of the second spike. The black stars are the difference of first and second peak power, which are fitted by a exponential delaying function: $y = ae^{-bx}$ shown as black dashed curve in the figure. The optimized fitting parameters are $a = 15.80$, and $b = 9.18$. In the insets, the blue curve is the input signal, and the red curve is the output pulse response. The inset (i), (ii), and (iii) show the condition that the system is inside the absolute refractory period, relative refractory period, and outside the refractory period respectively.

IV. Conclusion

We have explored two key spike processing properties, coincidence detection and a refractory period, in an integrated laser neuron on a photonic integrated circuit platform. We have shown that the device can process signals at high speeds (GHz) and high temporal precision (ns), far outpacing even the fastest spiking approaches in neuromorphic electronics by many orders of magnitude [6]. Its compatibility with photonic integrated circuit platforms and its use of a photodetector-driving principle make it amenable to system integration with passive networking protocols [7]. This component may serve as an important nonlinear neuromorphic processor in future on-chip photonic processing systems.

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