Autaptic Circuits of Integrated Laser Neurons

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Abstract: The presence of autapses in neural networks enables complex temporal dynamics and information storage. We experimentally demonstrated feedback dynamics in an integrated laser neuron, which provides a proof-of-principle demonstration of cascadability and stable recurrent memory.

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1. Introduction

An autapse is a synapse that connect the output of a neuron back to itself. Autapses play a significant role in neuronal information processing [1]. A positive-feedback loop of a neuron results in a stabilized spike train, which can be used as a memory unit [2]. The autaptic circuit is the simplest example of a recurrent neural network, which is widely used in natural language processing and temporal pattern recognition [3]. Here, we demonstrate a photonic autaptic circuit with an integrated excitable laser [4] while studying its feedback dynamics.

2. Device and Experimental Setup

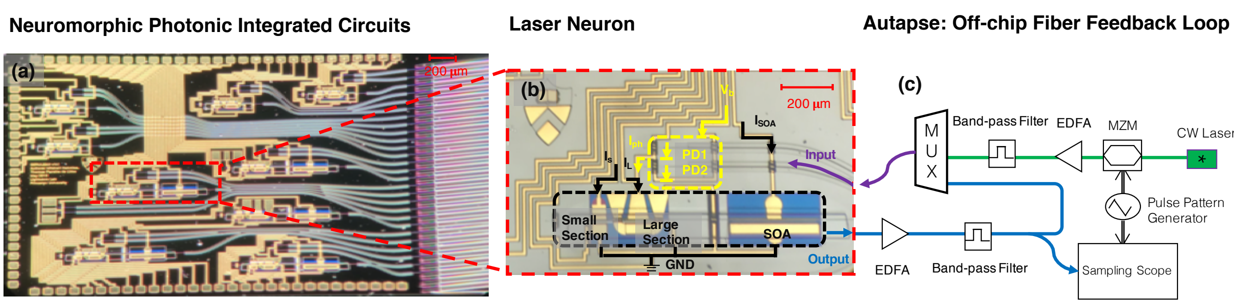

Fig. 1: (a) Neuromorphic photonic integrated circuits with 9 laser neurons. In this experiment, we focus on the laser neuron highlighted inside the dashed box. (b) Micrograph of the laser neuron unit (two-section DFB laser, described in ref. [4]). I_L: current flowing into large section of DFB (provide gain of laser), I_S: current flowing into small section of DFB (adjust absorption level of laser), V_b: bias for PD2, I_{SOA}: pump current for SOA, GND: ground for the circuit, I_{ph}: the photocurrent generated by PD2 provides excitatory perturbation to laser. (c) Experimental setup of the autaptic circuit using off-chip fiber-based devices.

We designed an array of laser neurons in a standard indium phosphide (InP) photonic integrated circuits (PIC) platform by the Heinrich Hertz Institute (HHI) through the JePPIX consortium. In this experiment, we used the laser neuron highlighted in Fig. 1(a). This laser neuron consists of a high-speed balanced photodetector (PD) pair, a two-section distributed feedback laser (DFB), and a semiconductor optical amplifier (SOA) on the output port as shown in Fig. 1(b). For the positive-feedback experiment, we only used the bottom photodetector (PD2 in Fig. 1(b)) to provide excitatory dynamics to the system. The details of the working principle of the laser neuron is described in [4, 5]. The autaptic circuit is constructed by a feedback loop connecting laser output back to its input, in addition to an external periodic input pulse train. In Fig. 1(c), the output signal (in blue) is amplified by erbium-doped fiber amplifier (EDFA), and passed through a bandpass filter to improve the signal-to-noise ratio, then fed back to an input port of the neuron. The periodic external input pulse train (in green) in Fig. 1(c)) is generated by modulating a continuous-wave laser with a high speed Mach-Zehnder modulator (MZM), and programmed through a high speed pulse pattern generator. Finally, the external input and feedback output are multiplexed and sent to the input port of the neuron.

3. Results

We performed two experiments to test the characteristics of an autapse of an integrated laser neuron. In the first experiment, we showed the self-sustained spike train can be generated (Fig. 2(a–h)). In order to stabilize the pulse train in time such that we can collect it by the sampling scope, the condition $T = n\tau$ is required, where $n \in \mathbb{N}$, and τ is the delay time of feedback loop. In Fig. 2(b), (d), (f), (h), each spike in a period is separated by $\tau \approx 249$ ns, which indicates that it is triggered by the feedback perturbation rather than external input pulses. The result of self-sustained spike train demonstrates that the information of the neuron is cascadable and can be processed in the network. This *cascadability* is an important and necessary condition of a neuron to form of a network system. In the second experiment, we tested the effect of feedback strength of the autaptic circuit by appling different pump currents of the EDFA connected to the output signal. As shown in Fig. 2(j–l), when the strength is not strong enough, the output spikes may not possess enough strength to trigger another excitation. From this experiment, we also noticed that the main spike amplitude of Fig. 2(j–l), which is caused by the external input, is smaller than the spike amplitude of Fig. 2(m). This result indicates that the spike amplitude will be enhenced when the feedback pulse is coincident with the external input pulse.

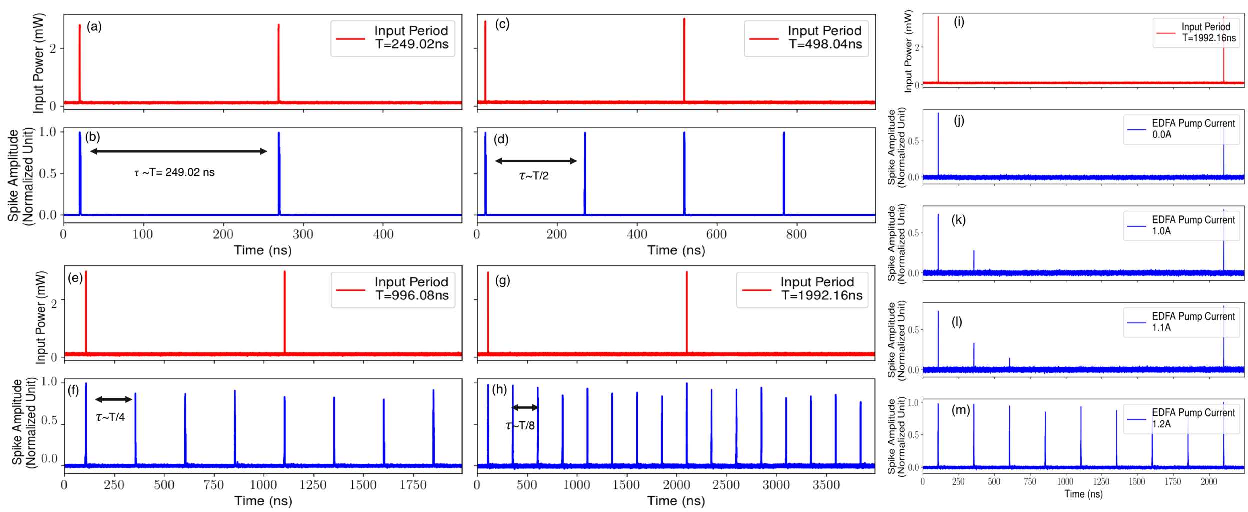

Fig. 2: Experiment 1. (a)-(f): Demonstration of self-sustained spike output when input pulse period is integer multiple of feedback loop delay time. (a), (c), (e), (g) are the input pulses with period = τ, 2τ, 4τ, 8τ and (b), (d), (f), (h) are corresponding output of them respectively. Experiment 2. (i)-(m): Feedback dynamics for different feedback strengths. (i) is the input pulse with period = 1992.16 ns = 8τ, (j)-(m) are the corresponding outputs for different the EDFA pump currents. The output amplitude is normalized to the largest spike of each experiment.

4. Conclusion

We demonstrated feedback dynamics of an integrated laser neuron with an autaptic connection. The self-sustained spikes can be generated by the feedback loop. This experiment demonstrates the cascadability of the laser neuron. When the feedback connection is strong enough, the spike train persisted permanently in the feedback loop of the neuron, otherwise it quickly degraded as shown in Fig. 2(j–l). With the demonstration of cascadability, this integrated laser neuron provides a promising platform for large-scale neural networks and a memory unit of neuromorphic photonic circuits.

References

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