Asynchronous spiking photonic neuron for lightwave neuromorphic signal processing

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We developed an asynchronous spiking photonic neuron that forms the basic building block for hybrid analog/digital lightwave neuromorphic processing. Our approach enables completely asynchronous spiking in response to input signals while maximizing the throughput relative to synchronous approaches. Asynchronous operation is achieved by generating the spike source for the photonic neuron through four-wave mixing. This hybrid analog/digital photonic neuron has an electro-absorption modulator as the temporal integration unit for analog processing, while the digital processing portion employs optical thresholding in a highly Ge-doped nonlinear loop mirror.

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Neuromorphic signal processing aims to marry physiological principles of biological neurons with engineering that not only helps in studying biological neural circuits, but also opens up a wide range of applications such as adaptive control, learning, perception, motion control, sensory processing, and autonomous robots. The leaky integrate-and-fire (LIF) neuron [1] is one of the most accurate models used by neuroscientists to describe the functionality of biological neurons. The basic structure of a LIF neuron consists of a dendritic tree that collects, weights, and delays spiking signals from other neurons, a soma that temporally integrates the signals, and an axon hillock that performs thresholding. Information in a LIF neuron is represented by the analog timing of spikes, so the bandwidth of the system is used efficiently. These digital spikes can be thresholded and restored by each neuron, which can then be cascaded and are immune to noise. Thus, neurons using spike processing to exploit both the bandwidth efficiency of analog signal processing and the scalability of digital logic.

With the photonic realization of spiking neurons, lightwave-neuromorphic signal processing harnesses the high-switching speed and wide communication bandwidth of optics. Recently, the optical realization of a spiking neuron based on the LIF neuron model [2] and a small neuromorphic circuit modeled after the tail-flip escape response in crayfish [3], were demonstrated. The photonic neuron in the above optical circuits required a sampling pulse train with fixed sampling rate as a spike source that limited the photonic neuron to respond synchronously resulting in quantization error in timing.

In this paper we demonstrate a photonic spiking neuron that asynchronously processes the supply and demand of information [4]. The photonic neuron (Fig. 1) resembles the biological neuron using photonics components and consists of an electro-absorption modulator (EAM)-based temporal integrator, a four-wave mixing (FWM)-based asynchronous spike source generator, and a Ge-doped nonlinear optical loop mirror [5] as an ultra fast thresholder. With asynchronous response, the capacity of the neural output is not limited by the synchronous sampling rate but by the pulse width, which is less than 10 ps in our demonstration.

In our spiking photonic neuron, temporal integration is achieved through cross-absorption modulation in a multiple quantum-well EAM. Based on the quantum confined stark effect, the absorption in the EAM is larger under a negative voltage bias, thus the input optical signal is absorbed and generates carriers. The optically generated carriers shift the absorption spectrum edge to the shorter wavelength side [6]. The shift in spectrum allows the spike source to pass through the EAM even under strong negative voltage bias. Since the carrier escape time is finite, the carrier density and transmittance decreases gradually over time, which happens shortly after the input signal exits the EAM. Therefore, any input signal that comes within the EAM recovery window will be integrated. The output intensity of the spike source reflects the strength of the temporally integrated input signals.

In our spiking neuron, a spike source is used to provide spikes for the neuron in response to the input stimulus. Since a spiking neuron spikes only if the temporally integrated input signals are strong enough to exceed the threshold, a spike is needed to be present at the input spike source only if there is an input signal present at that particular temporal position. The spike source in our asynchronous spiking photonic neuron is generated by making a copy of the input signal to another wavelength through FWM, allowing the photonic neuron to spike

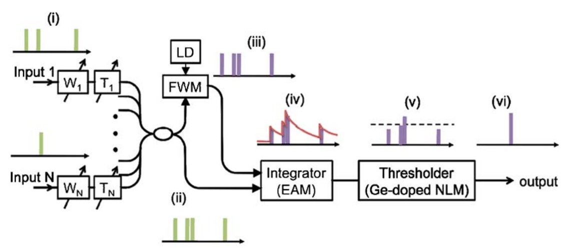

Fig. 1. (Color online) Illustration of an asynchronous spiking photonics neuron. W_1–W_N, variable weight; T_1–T_N, variable time delay; FWM, four-wave mixing; LD, laser diode; EAM, electro-absorption modulator; Ge-doped NLM, optical thresholder.

asynchronously. Figure 1 illustrates the asynchronous spiking photonic neuron. The input signals (i) at 1550.12 nm are weighted and delayed according to the signal processing function that the photonic neuron is performing, and they are combined using an optical coupler (ii). A small portion of the combined signal is tapped for the generation of spike source through FWM. A CW optical signal from a distributed-feedback laser diode at 1547.21 nm is used as the pump for FWM, while a 60 m photonic crystal fiber with nonlinear coefficient of 11/W · km is used as the nonlinear medium. FWM occurs only when the pump light and the input signal co-exist, such that new wavelength components are generated, having the same pattern as the input signals. An optical bandpass filter with bandwidth 0.5 nm is used to filter the newly generated wavelength at 1544.3 nm and is used as the spike source (iii). Both the combined input signal and the spike source are launched to the EAM based photonic neuron. The input signals are temporally integrated in the EAM and the integrated output is represented by the intensity of the spike source at the output (iv). The output spike from the EAM is then passed to a highly Ge-doped nonlinear loop mirror (Ge-NLM) for optical thresholding (v). The highly Ge-doped nonlinear loop mirror removes any undesired weak spikes and equalizes the amplitude of the strong desired spikes (vi).

The integration of a signal at the EAM is based on the finite cross-absorption modulation recovery time of a negatively-biased EAM. To measure the recovery time, a strong optical pump at 4.6 dBm is used, while a weaker probe pulse is temporally scanned from about 50 ps before the launching of the pump pulse to 550 ps after launching to sample the effect. Both the pump and probe pulses have pulse widths of ~5 ps. Figure 2(a) shows the measured recovery time of an EAM at different voltage biases, where the larger the bias (the more negative), the shorter the recovery time. Due to the finite recovery time of the EAM, the transmittance of the EAM gradually decreases over time after the influence of an optical pulse. Therefore, by placing multiple control pulses within the recovery interval, the EAM integrates them. The recovery time of the EAM also depends on the optical pump power, Figure 2(b) shows the change in recovery time as a function of the optical pump power. To study the integration effect in an EAM, two strong-input optical pulses of about the same power (4 dBm) are used, while a weaker optical probe pulse at −2 dBm is used to measure the effect. The separation of the two pump pulses is variable, while the probe signal is temporally scanned over 600 ps. Shown in Fig. 2(c) is the output probe signal power after integration, when the EAM is biased at −2.5 V. The black cross data points represent the output with just one input pulse. When the second pump pulse is placed 100 ps after the first pump pulse (outside the integration window, the EAM completely recovers), no integration is observed, as shown by red square data points. As the second pump pulse moves closer to the first pump pulse, time-sensitive integration is observed, resulting in a different integrated power depending on the temporal separation between the two pump pulses.

After studying the integration behavior of the EAM-based temporal integrator, a more complex signal is used to verify the performance of temporal integration in a

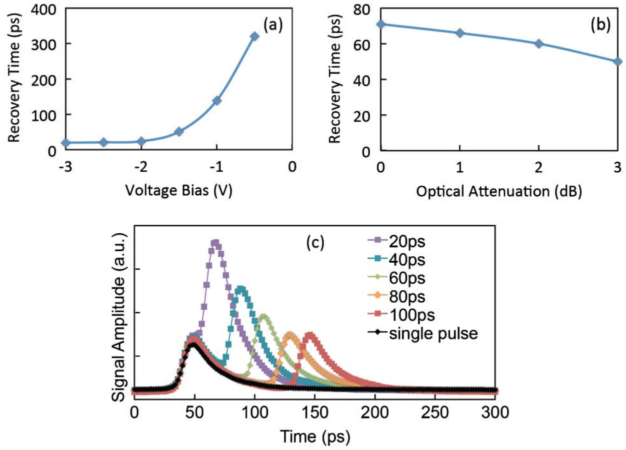

Fig. 2. (Color online) (a) Measured absorption recovery time as a function of EAM bias voltage. (b) Measured absorption recovery time as a function of optical pump-pulse attenuation. (c) Integration response of the EAM with different temporal separation of the pump pulses.

photonic neuron, as shown in Fig. 3(a), measured using a photoreceiver at 30 GHz. To measure the dynamic change in the EAM, we use the same probe scanning approach as describe above. There are a couple of features that are worth noticing, as indicated by (i)–(iv). The integrated output with long integration time (EAM biased at −1 V) and short integration time (EAM biased at −2.5 V) are shown in Figs. 3(b) and 3(c), respectively. The dotted lines are used as a reference to compare the integration behavior of the two cases. Feature (i) consists of two pulses that are very close together (<10 ps). The integrated output in both cases shows that a strong integrated signal results. For (ii), the three pulses are of medium separation, thus they can only be integrated and result in a strong intensity if the integrator has a longer integration window [Fig. 3(b)]. For (iii), the first two pulses are very close together, while the third pulse is a bit further apart. Thus, the first and second pulses are integrated in both Figs. 3(b) and 3(c) and give a relatively strong output (above the dotted reference line). In the −1 V bias case, since it has a longer integration time,

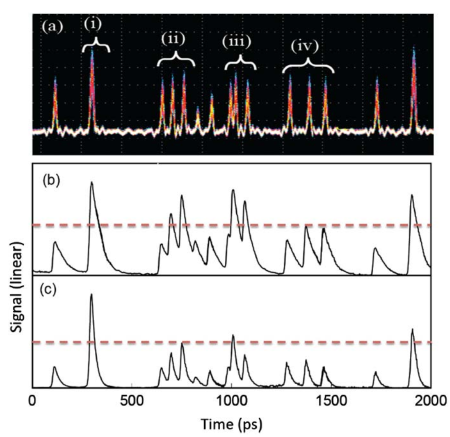

Fig. 3. (Color online) Time-sensitive signal integration in EAM: (a) input signal, (b) integrated output with long integration window, and (c) integrated output with short integration window.

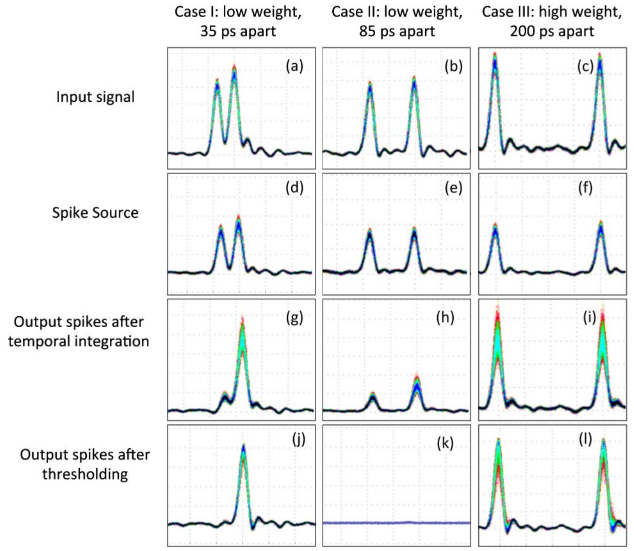

Fig. 4. (Color online) Experimental results of input, spike source, and output pulses in three different cases with different time intervals and weight values.

the third pulse also is integrated and results in a strong output. For (iv), the three pulses are further apart and none of the two cases has a long enough integration time to obtain significant integration. Therefore, the output pulses are below the reference line for both cases. From Fig. 3 we experimentally study the dynamics of signal integration in a photonic neuron, and the integration can be configured to have different integration responses to the input signal.

To demonstrate asynchronous spiking of the photonic neuron, FWM in a 60 m photonic crystal fiber is used for the generation of spike source. The signal pulse width is ∼9 ps, while the average power of the signal and the pump light are 14 dBm and 21.6 dBm, respectively. The optical pump spikes and input signal spikes are offset by ∼5 ps to obtain the maximum cross-absorption modulation effect. The photonic neuron is set to have an integration window of 50 ps. We study the performance of the photonic neuron in three cases where the time interval and the weights of the inputs are different, as shown in Fig. 4. The three cases we studied are: case I, where two input signals are 35 ps apart with average power of 7.8 dBm; case II, where two input signals are 85 ps apart with average power of 7.8 dBm; and case III, where two input signal sare 200 ps apart with average power of 9.8 dBm. The oscilloscope traces of the inputs for all three cases are shown in Figs. 4(a)–4(c), respectively. Under FWM, the spike sources for each of the cases are generated [Figs. 4(d)–4(f)], and they all have the same pattern as the corresponding input signals. In case I (left column), the two input signals have a temporal separation that is within the integration window of the photonic neuron. Due to the low-input signal power, the first input pulse only saturates the absorption of the EAM slightly, thus, only a small portion of the first sampling pulse can pass through the EAM. Since the second input pulse arrives before the EAM recovers, and further saturates the EAM, a larger transmittance of the second pulse in the spike source is observed [Fig. 4(g)]. The output spike is then passed to the thresholder such that the first weak output spike is removed and amplitude noise of the second output spike is suppressed. As shown in Fig. 4(j), the final output consists of only one spike that is triggered immediately after the second input spike. In case II, (middle column), input pulses are the same as in case I, but are now further apart from each other, i.e. outside the integration window. After the absorption in the EAM is slightly saturated by the first pulse, the EAM recovers back to its high absorption level before the stimulation from the second pulse. Thus the second pulse induces a similar amount of absorption as the first pulse, resulting in two weak spikes at the EAM output [Fig. 4(h)]. Since both the weak output spikes are below the threshold of the thresholder, both are eliminated at the thresholder [Fig. 4(k)]. In case III (right column), the two input pulses are much further apart but have larger weights. Both the first and second input pulses strongly saturate the absorption of the EAM resulting in two, strong output spikes from the photonic neuron. The two output spikes are above the threshold level of the thresholder, and both of them come out from the thresholder [Fig. 4(l)].

In this paper we demonstrate the optical implementation of an asynchronous spiking neuron. The approach uses an electro-absorption modulator as the temporal integrator due to its finite recovery time and a highly Ge-doped nonlinear fiber loop mirror as the thresholder. Asynchronous spiking is achieved by generating the spike source through FWM. The photonic neuron operates on picosecond-width pulses and provides completely asynchronous response that eliminates quantization error in spike timing and maximizes the output bandwidth.

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