Lossless Monolithically Integrated Photonic InP Neuron for All-Optical Computation

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Abstract: We demonstrate a monolithically integrated SOA-based photonic neuron, including both the weighted addition and a wavelength converter with tunable laser as nonlinear function, allowing for lossless computation of 8 Giga operation/s with an 89% accuracy. © 2020 The Authors

1. Introduction

The demand for high-speed and huge data processing has escalated to a point that brain-inspired computing architectures have been suggested and exploited to offer powerful computing engines via micro-electronics [1]. However, their implementation via electronics makes possible only slow timescale real-time operations [2]. Sophisticated photonic integrated circuits promise high switching speeds and high communication bandwidth via dense interconnectivity, which suits very well the need for brain-inspired information processing [2]. Computational architectures based on the interconnectivity of multiple neurons are called *artificial neural networks*, where the base model of an artificial neuron is mainly composed of two functions: a weighted addition (linear) function and a non-linear function. Recently, photonic integrated approaches have been proposed to realize the linear [3-5] and non-linear [6] functions, but so far these implementations have relied on hybrid integration schemes [3], external input lasers [6] and the involvement of power-consuming O/E/O conversions [4], hindering the realization of a scalable photonic neural network. All-optical neural network implementation, based on all-optical neurons, is expected to offer a route to scalability, however so far no demonstration of a full all-optical integrated neuron with continue input data sequences has been reported yet.

In this paper, we demonstrate for the first time a complete photonic neuron that is monolithically integrated on an InP SOA (semiconductor optical amplifier)-based single chip. Both the weighted addition and a non-linear function are co-integrated. Moreover, the additional co-integration of a tunable laser allows for an on-chip optimization of the non-linear function. The InP photonic integrated neuron explores the wavelength domain, allows for lossless data processing, opening the way to a scalable all-optical photonic neural network architecture.

2. The InP photonic integrated neuron

A feed-forward neural network consists of a network of concatenated layers of neurons, where information travels from the left to the right side. The conceived all-optical deep neural network architecture is showed in Fig. 1a. Each neuron (as in the grey box) receives at its input a number of different wavelength signals and it gives as output a signal coded into yet another wavelength. The output of this neuron, together with the outputs at the other neurons of the same layer, are then sent to the next layer of neurons for further processing, and so on and so forth.

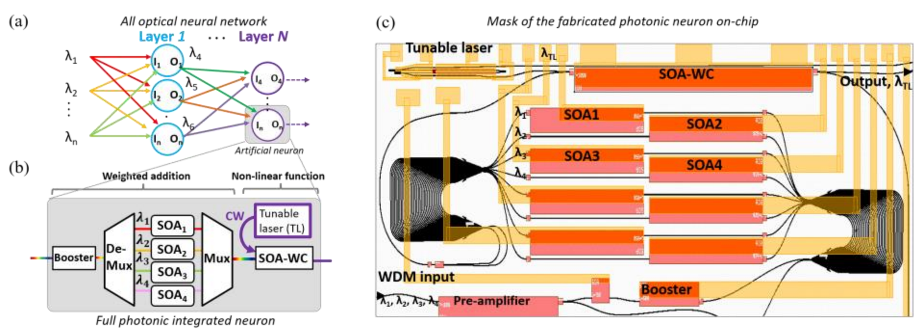

Fig. 1 (a) Representation of the all-optical deep neural network, with white circles being the neurons. (b) Scheme of the implemented monolithically integrated neuron. (c) Mask details of the chip. WC=wavelength converter. CW= continuous wave.

In this experiment, the full photonic integrated neuron is realized by using a combination of arrayed waveguide gratings (AWGs) and semiconductor optical amplifiers (SOAs) technology. Fig. 1b shows the schematic of the implemented photonic neuron. The neuron processes N wavelength division multiplexed (WDM) signals. After pre-amplification, the signals enter a de-multiplexer (De-MUX) which allows access to the individual channels. These are weighted by using the gain variation of multiple SOAs, then a multiplexer (MUX) combines back all the wavelength signals. The weighted WDM signals undergo the SOA-based wavelength converter (SOA-WC), which is employed as optical activation function. The tunable laser is co-integrated in the photonic chip. The SOA-WC converts all-optically the multi-wavelength signal total power into one single wavelength, which represents the neuron output. Although in this first demonstration the SOA-WC provides an inverted signal at its output, an SOA-MZI scheme can be used in the future as non-inverted WC [6]. Fig. 1c illustrates the mask details of the complete on-chip integrated neuron which includes the weighted addition circuitry and the SOA-WC. The weighting SOAs are 950 μm long. The 1×8 AWGs, for De-MUX and MUX, are designed with free spectral range (FSR) of 2.4 nm. The WC is based on cross-gain modulation [7], with a 2 mm long SOA and a tunable coupled-cavity laser (TL). The TL, centered at 1549.0 nm, provides 0 dBm optical power [8]. The chip employs a combination of SOAs at its input side to increase the SOA linear range. The broadband operation of the SOA enables the weighting of any wavelength in the C-band. The 4.6×2 mm^2 fabricated photonic integrated chip (PIC) has been processed via an InGaAsP/InP multi-project wafer run.

3. Experimental Setup and Results

The experimental set up to assess the operation of the monolithically integrated photonic neuron and a micrograph image of the chip are shown in Fig. 2a. Four input data at λ_1=1544.0 nm, λ_2=1546.0 nm, λ_3=1551.0 nm and λ_4=1554.0 nm are multiplexed and modulated by an optical modulator driven by an NRZ PRBS signal produced by an arbitrary waveform generator at 2 Gb/s. The modulated WDM signals are amplified by an EDFA, de-correlated and synchronized by using varied-length fibers and tunable time delays. After polarization controllers, the WDM signal is then input to the PIC port 1 via a lensed fiber. The neuron optical output is filtered by a 0.4 nm bandpass filter, centered at the tunable laser central wavelength and detected by an AC coupled PD, and a Digital Phosphor Oscilloscope, where the time traces are digitized and recorded. The input SOA and the WC SOA currents are set at 90 mA and 120 mA, respectively. For this first demonstration, 4 SOAs (Fig. 1c) are biased with different currents controlled via a multi-current controller, in order to assign the gain value which acts as a *weight factor* to the corresponding input data. But eight inputs are also possible.

The characterization of the all-optical photonic integrated neuron is carried out by calculating the normalized root mean square error (NRMSE), i.e. processing accuracy. The lower the NRMSE, the better the accuracy. Firstly, we operate the neuron with one input signal (Fig. 2b) to optimize the wavelength converter operation as an integrator and non-linear function. Fig. 2c shows the output of the photonic neuron after the SOA-WC: The measured output (blue line) is well matching to the expected inverted signal (red line), with an NRMSE of 0.13 (87% of accuracy). This experimental accuracy can be improved by increasing the optical input power budget and removing un-necessary sources of noise, but it is already comparable to the accuracy of a digital computer with 64-bit resolution in neural network implementation.

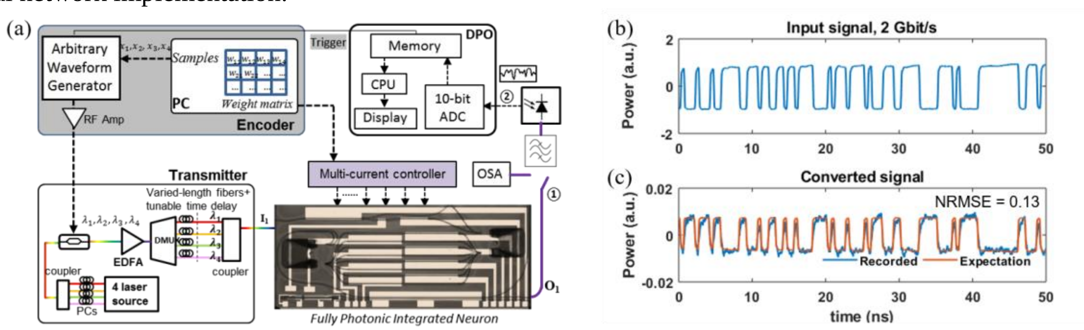

Fig. 2 (a) Experimental setup for the assessment of the photonic integrated neuron. (b) Single input channel. (c) Measured (blue) and expected (red) neuron output. An error of 0.13 is calculated.

The input power of the modulated optical data (probe signal) to the wavelength converter is critical for the cross-gain modulation, therefore an input optical power optimization procedure is investigated, by tuning current of booster SOA with a 26 mA range. Fig. 3a shows the error variation obtained while tuning the injection current at the booster SOA. While there are two regions where the final accuracy is visibly degraded, we can also distinguish an optimal operational regime where the NRMSE reaches its minimum. Fig. 4b shows the measured output signal (blue line) and the expected signal (red line) when the injection current of the booster SOA is set to 7 mA, 11 mA and 20 mA, resulting in an error of 0.15, 0.13, 0.19, respectively. The lower peak-to-peak values obtained for low current values (Fig. 3b (i)), i.e. lower probe optical powers, are caused by the low carrier-to-noise ratio. At higher power level (Fig. 3b (iii)), an increase in the probe optical power increases its contribution to the gain saturation effect, thereby reducing the conversion efficiency. The optimized current is found to be 11 mA (Fig. 3b (ii)). Once the optimal input power to the wavelength converter is found, we tested the full photonic neuron operation with 4 WDM input data shown in Fig. 3c (total input power of -6.5 dBm). Fig. 3d illustrates the optical spectrum at the chip output, where the peaks from left to right are at wavelength λ_1, λ_2, λ_{TL}, λ_3 and λ_4, (total unfiltered output power of -4.1 dBm) for a net on-chip gain of 11.4 dB. The different peak powers of each wavelength signal are due to the different weights assigned to each individual WDM signal. The measured photonic neuron output after being filtered and after the O/E conversion is shown in Fig. 3e (blue line). The expected results are also reported (red line) in order to estimate the accuracy of the fully integrated photonic neuron. The calculated NRMSE of the neuron for 4 channel input is 0.11 (89% accuracy).

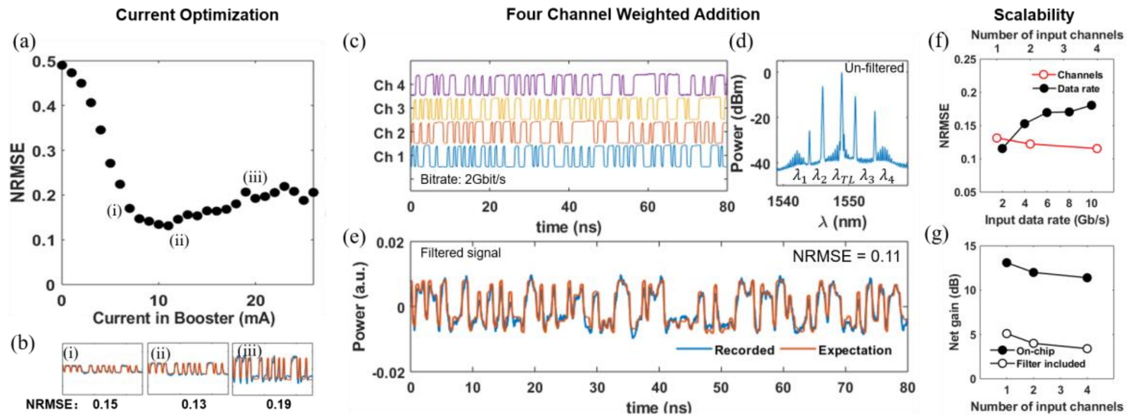

Fig. 3 Current Optimization: (a) NRMSE vs. Current in the booster. (b) Time traces at injection currents of: (i) 7mA, (ii) 11mA and (iii) 20 mA. Weighted Addition: (c) The four input channels. (d) Un-filtered output spectrum. (e) Filtered and detected time traces. Scalability: (f) Error evolution versus the input data-rate (filled circles) and versus the number of input channels (empty circles). (g) Net on-chip gain (filled circles), and if the external filter was co-integrated (empty circles) as a function of the number of input channels.

The error becomes slightly smaller as the total input signal power is increased, as the associated signal to noise ratio (SNR) is also improved. Furthermore, we measure the response of the optical neuron when increasing the input signal data rate. In Fig 3f the error gradually increases from 0.11 to 0.18 with the increase of the four input channel data rate from 2 Gb/s up to 10 Gb/s (filled symbols). This trend is in line with the carrier dynamics of both the booster SOA and WC SOA. Fig. 3f also includes the error variation (empty circles) when 1, 2 and 4 channels are input to the optical neuron. Fig. 3g depicts the net on-chip gain (filled circles), and if the external filter was co-integrated (empty circles), as a function of the number of input channels. The net on-chip gain is calculated considering 11 dB fiber-to-chip total coupling losses. Both the final accuracy and the on-chip gain improve while increasing the number of input channels. A higher number of input channels has offered a higher probe optical power to the wavelength converter, resulting in improved conversion efficiency for the used current settings.

4. Conclusion

An all-optical photonic integrated neuron with co-integrated wavelength converter and tunable laser as non-linear function is demonstrated with 4 inputs, resulting in a best-case accuracy of 89%. The achieved lossless neuron operation suggests that a scalable all-optical neural network is possible, based on the co-integration of optical amplifiers and cross-gain modulation effect. The level of accuracy achieved for Gb/s rate level, allowing for 2 orders of magnitude more algebraic operations per energy unit than in a conventional digital processor, suggests the possibility to address in the near future faster time-scale real-time applications.

5. Acknowledgments

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6. References

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