# Large-Scale Photonic Integrated Cross-Connects for Optical Communication and Computation

**R. Stabile, N. Calabretta, B. Shi**
*Eindhoven University of Technology, Institute for Photonic Integration, 5600 MB Eindhoven, The Netherlands*
r.stabile@tue.nl

**Abstract:** An 8×8 InP cross-connect chip for optical switching within ROADMs is employed for demonstrating optical feed-forward neural networks for analog data processing. An all-optical approach is also explored for deeper optical neuromorphic computing on chip. © 2020 The Authors

## 1. Introduction

Massive volume of data demands wider capacity and higher speed information processing. The extraction of effective information from databases remains a challenge as it requires huge power and processing time. Artificial neural network architectures are being used in visual classification, audio recognition, astronomy information processing and many other applications, as it allows to extract information more efficiently, because of its inherent parallel computational scheme. Electronic neuromorphic computing is already being explored as an approach to suit these architectures and aims at reducing processing power consumption. However, the interconnection electronic bandwidth still limits computing speed to slow timescale operation [1].

Recently, neuromorphic approach has been applied to optical computing: In contrast to electronics, there is negligible energy overhead for moving light encoded information around, which enables unprecedented circuit interconnectivity and speed. Moreover, bit-rate agnostic photonics has the potential to enable higher bandwidth applications. Recently, a number of photonic accelerators have been proposed based on discrete optical components and micro-optics as well as on silicon photonic integrated devices [2]. In this work we address a different architecture which exploits Indium Phosphide based optical circuits, starting from the strong analogy between cross-connects for optical communications and cross-connectivity in the brain, as explained in the following. The huge amount of information traveling within an optical communication network needs to be switched through various points known as "nodes". Information arriving at a node will be forwarded on towards its final destination via the best possible path, which may be determined by factors like distance, cost and reliability of specific routes. Optical cross-connects are used to reconfigure the network dynamically and are particularly important for high-degree reconfigurable optical add-drop multiplexers (ROADMs). As a naïve analogy, the huge amount of information traveling in a brain needs to be processed through various nodes known as "neurons". Information arriving at a neuron will be forwarded on towards its final destination via interconnecting paths which brings in also information coming from other connections, for determining the final label probability.

In this paper, we exploit optical cross-connect circuits as optical neural networks on chip to investigate potential and performance. By setting the gain of the SOA as (trained) weighted factor to the WDM input, the cross-connect is not used anymore as a digital processor in a ROADMs, but as an analog engine with off-line nonlinear function. Feeding the layer output back to the optical input, and reconfiguring the on-chip weight matrix, a 3-layer photonic deep neural network (PDNN) is performed to demonstrate the Iris flower classification [3]. The demonstration of an all-optical lossless photonic integrated neuron, including the non-linear function, suggests that a scalable all-optical neural network is possible [4].

## 2. InP Optical Cross-Connect

Recently, we have proposed a new monolithic architecture for broadband photonic and wavelength selective cross-connection within one multiple-input, multiple-output, monolithic circuit and scaled this one to create the first InP 8×8×8λ monolithic cross-connect circuit [5]. Here, the combination of space and wavelength selection provides a radical step forward in switch integration complexity and an opportunity for considerably simplified optical engine control [6]. The selection functionalities in the space and wavelength domain are implemented simultaneously on a single chip, based on semiconductor optical amplifiers (SOAs) and array waveguide gratings (AWGs). Eight broadband inputs connect to an array of 1×8 broadband space selection switches. Wavelength domain selection is subsequently performed with an array of eight 8×8 gated cyclic routers. The on-chip fan-outs and fan-ins allow for the integration of 136 semiconductor optical amplifier gates within a total chip area of 14.6×6.7 mm$^2$ (see picture in Fig. 1). Circuit connectivity is evaluated for the full range of paths with optical and electronic connections for 84%

of the paths in this first prototype [7]. Good spectral uniformity for the cyclic routers allows for operation across a broad spectral range. Data routing studies are performed for a representative range of paths to show optical signal to noise ratios of greater than 30 dB/0.1 nm, after 3 SOA stages, suggesting that 3 layer-based optical neural networks can be feasible using this technology. Dynamically reconfigurable routing is also demonstrated with switching rise and fall times of 3.8 and 3.2 ns respectively: SOA-based technology allows to co-integrate fast optoelectronic devices for potential in real-time training, provided that the memory issue is addressed. The ultimate performance for the space and wavelength select cross-connect is determined by crosstalk, losses and path bandwidth. The −19 dB crosstalk level observed is primarily due to imperfect wavelength channel discrimination in the cyclic routers. Higher precision lithography tools are expected to improve crosstalk performance further and also to enable lower-loss designs. The losses inherent to the broadcast and select architecture, namely 18 dB from the six 3 dB splitter/combiners, are compensated by the on-chip gain in the current circuit. Much of the remaining loss may be removed through component optimization and a maturing fabrication technology.

## 3. Photonic Feed-Forward Neural Network on Chip

The 8×8 InP SOA-based cross-connect chip in Fig. 1a is capable of providing space connectivity of up to 8 neurons, and multi-wavelength connectivity of up to 64 channels, eight multiplexed channels (a WDM signal) per input. Here the SOA technology is exploited in combination with the AWG technology for multiple reasons: The optical amplifiers are employed for setting the weight matrix and providing on-chip gain for scalability, while the AWGs are used to filter out the out-of-band noise built up by cascading multiple stages of SOAs, in order to increase the weight resolution. The chip broadcasts the WDM signals to eight neurons belonging to the same layer and de-multiplexes it via an array of eight AWGs. Each neuron consists of eight (different channels) inputs, eight SOAs (one per channel) and an 8:1 MMI (multimode interferometer) based combiner.

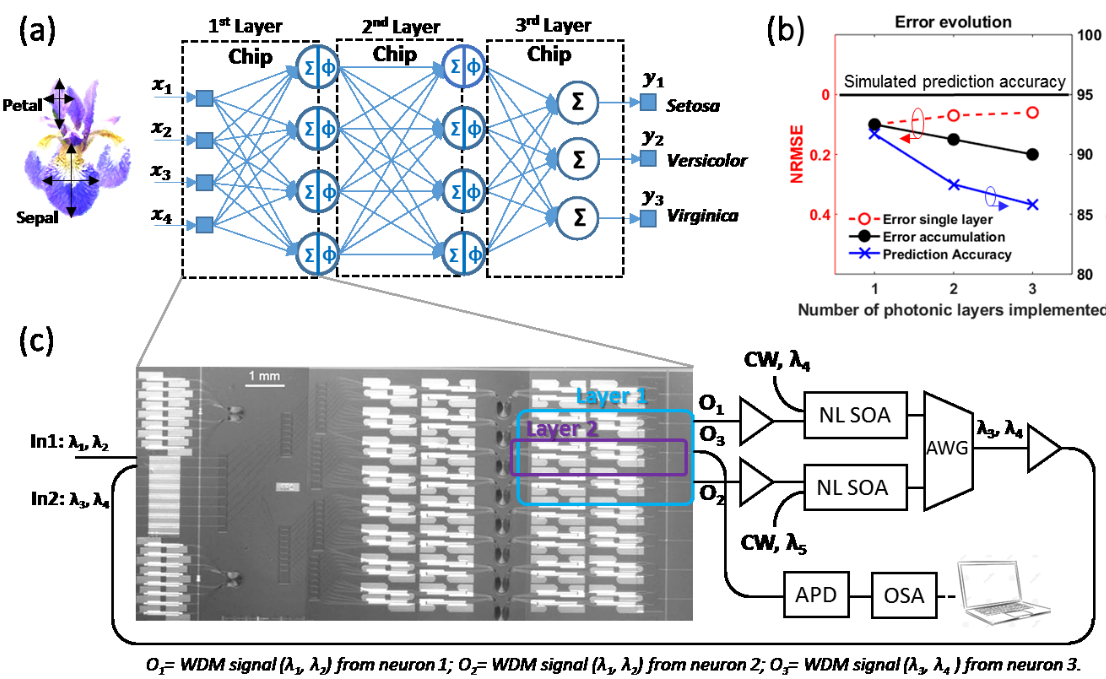


Fig. 1 (a) Three layer deep neural network for image classification. (b) Error evolution and contribution analysis. (c) All-optical 2 layer neural network.

By applying different currents to the SOAs, we perform multiple multiplications between the input channels and the trained weight-SOA matrix. The output signals are then summed up via an optical combiner, followed by a photodetector, to finalize the weighted addition operation. The thresholding function is not co-integrated in this first demonstration (see Fig. 1a). In this paper, we perform weighted addition of 4 input channels per neuron for a total number of four (best performing) neurons per layer  We perform the weight calibration per neuron, resulting in a normalized root mean square error smaller than 0.08 and a best case dynamic range of 27 dB. The 4 input to 1 output  weighted addition operation is executed on-chip and is part of a neuron, whose non-linear function is implemented via software instead. A three feedback loop optimization procedure is demonstrated to enable an output neuron accuracy improvement of up to 55%. The exploitation of this technology as neural network is evaluated by implementing a trained 3-layer photonic deep neural network to solve the Iris flower classification problem (Fig. 1a). Prediction accuracy of 85.8% is achieved, with respect to the 95% accuracy obtained via a computer. A comprehensive analysis of the error evolution in our system (see Fig. 1b) reveals that the electrical/optical conversions dominate the error contribution, which suggests that an all optical approach is preferable for future neuromorphic computing hardware design [4].

Until now, no demonstration of a full all-optical integrated neuron with continue input data sequences has been reported. As a consequence, we investigated the use of an InP weighted addition layers with an optical and discrete non-linear function to demonstrate for the first time that all-optical two-layer feed-forward neural networks are possible. The operation of the NL-SOA based wavelength converter is investigated. We employ the on-chip photonic cross-connect and the off-chip optical nonlinear function to process binary sequences through our two-layer all-optical deep neural network (see Fig. 1c) [5]. The first layer is made of two neurons, each of them getting in 2 inputs and providing 1 output. The two outputs from the 1st layer, are then combined and fed into the second layer which is now made of one single neuron which provides a final output. The all-optical neuron interconnectivity is realized with the NL-SOA (Kamelian, NL-SOA) based wavelength converter, who converts the power summation of the weighted multi-wavelength signal into the power at one single wavelength as an optical output and feed to the next layer. These wavelength converters could be integrated on the InP platform in the future. And in fact, this is also validated via the investigation of a complete photonic neuron which is monolithically integrated on an InP SOA (semiconductor optical amplifier)-based single chip, where both the weighted addition and a non-linear function are co-integrated. The obtained lossless and high accuracy data processing open the way to a scalable all-optical photonic neural network architecture.

## 4. Conclusions

Integrated optoelectronic circuit technology offers a radical reduction in physical size and assembly complexity. When adopting semiconductor optical amplifier (SOA)-based technology, it becomes possible to include optoelectronic devices which are fast enough to accommodate for future fast training in a multi-layer optical processor. The investigation of an all-optical photonic neuron and of a 2 layer photonic deep neural network results in a lossless neuronal operation, suggesting that a scalable all-optical neural network is possible via InP large-scale circuitry.

## 5. Acknowledgements

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