Continuous Weight Tuning for WDM-based neuron addition in an SOA-Based InP Cross-Connect

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In this work, we realize the weighted addition of neuron on a monolithically integrated 8×8 cross-connect chip, based on semiconductor optical amplifier (SOA) and arrayed waveguide grating (AWG) technology, with four10Gb/s on-off key WDM input channels. We analyze the weight tuning range of each channel. The results show that a weight reading error below 0.08 can be achieved with a maximum weight tuning range of 20dB. It opens the way towards a high fidelity cross-connectivity of up to 8 neurons for input layer to next hidden-layer with a data precision of at least 3bits for photonic integrated deep neural networks.

Introduction

Artificial neural network (ANN) architectures are increasingly attracting attention since the large volume of data nowadays demand faster processing speed and the ability of meaningful feature extraction. ANNs can allow to compute a variety of tasks such as speech and image recognition with higher computing speed and power efficiency with parallel computing. Researchers have already developed advanced electronics that implement ANNs [1-4]. However, the bottleneck between memory and processor limits the operation computing speed, which is at the few GHz regime.

Modern integrated photonics technology is matured to provide high performance sophisticated integrated circuitry to process information with a higher speed and at a lower energy consumption [5]. It also enables the highly complexity of monolithic integration with many components such as laser, modulator, photo-detector, etc.

Photonics approaches to realize neuromorphic computing are already under investigation. The coherent approach with stages of interferometers [6], the WDM approaches with micro-ring resonators [7], reservoir computing [8] are well known examples. Phase noise sensitive and multi-stage operation in photonic deep neural networks [6] result in cross-talk accumulation and synchronization problems, while the low dynamic range based neurons [7] require complicate calibration of thermal cross-talk.

In this letter, we employ an InP cross-connect, which co-integrated the Semiconductor Optical Amplifier (SOA) and Array Waveguide Grating (AWG). The SOAs increase the dynamic range of the weight and the on-chip filters eliminate the noise. This chip performs one stage operation for one neuron layer, which is not phase noise sensitive and has negligible thermal cross-talks. We use a part of the cross-connect to demonstrate weight addition and continuous weight tuning through controlling the gains of SOAs for four different input data. Then we analyze the reading error from the output of the neuron on-chip.

Methods

The Deep Neural Networks (DNN) contains many layers of neurons. Fig. 1a depicts a 4 layer structure of DNN [9], with one input layer, two hidden layers and one output layer. The artificial neuron basic model includes the weighted addiction and activation function. In Fig. 1b, this is shown for 4 inputs. Fig. 1c depicts the schematic of four neurons in a column, which used SOAs to tune the weight and AWG to remove the SOA noise, with WDM signal for the at-neuron calculation. In particular in this paper we focus on one neuron only (shown in Fig. 1c, red rectangle). By fine tuning the gain of weight control SOA, the weight factor is applied to the input data and their optical power amplitude results modulated.

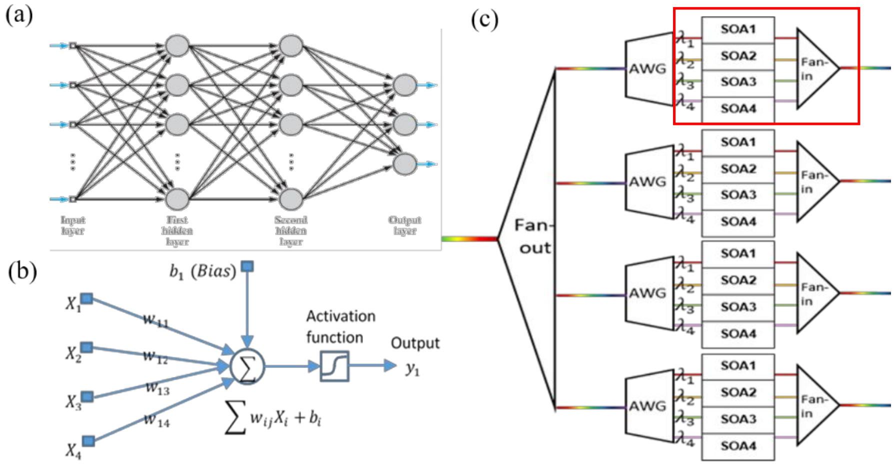

Fig. 1 (a) A 4-layer DNN structure, (b)the model of one Artificial neuron (c)schema of four neurons in one layer with SOAs and AWGs. Red rectangle: One neuron is studied in this work, with SOA 1 to 4 tuning the weight of channel 1 to 4, respectively.

The InP cross-connect is already fabricated that contains the co-integrated AWGs and SOAs to allow for space and wavelength selection of WDM signals of eight channels from up to eight input ports. Fig. 2a shows a micrograph of the fabricated neuron with 4:1 connectivity from 4 different input channels into one output.

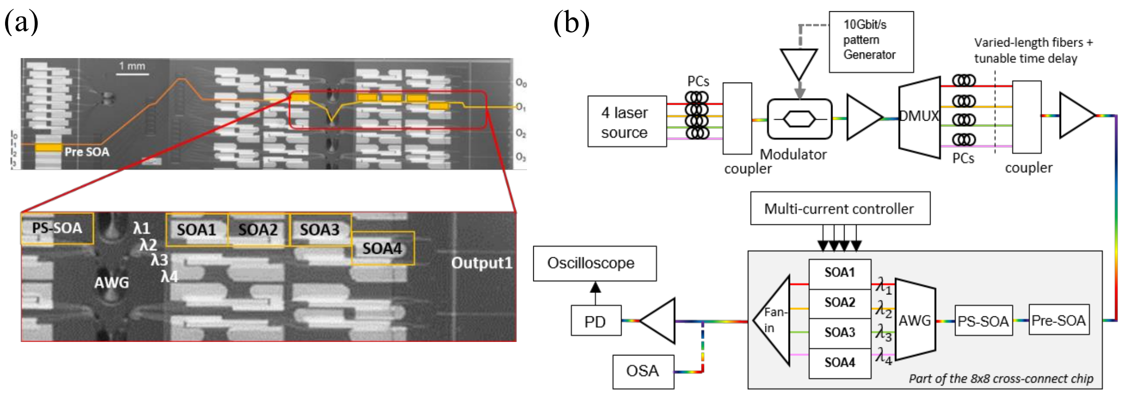

Fig. 2 (a) A micrograph of the fabricated 4:1 neuron is displayed. (b) Experimental set up to analyze the weight tuning at the neuron.

Experimental results

Fig. 2b illustrates the experimental setup for demonstrating the weighted addition and weight control at the 4:1 neuron. There are four channels in the inputs. The operation wavelengths of these four laser sources are: 1539.71 nm, 1543.21 nm, 1546.38 nm and 1549.32 nm. After being combined with broadband couplers, the optical beam is modulated with 10 Gb/s pseudo random bit sequence (PRBS) of $2^{23}-1$ bits length, amplified using an erbium doped fiber amplifier (EDFA, PriTel) and de-multiplexed to four channels. The data are time de-correlated using varied length fibers and tunable time delays before being combined again at the input port 1.The input peak power for each of the channels is set to -0.5 dBm. Polarizations of the inputs are optimized to maximize the on chip SOA gains. The weights of each channel data are controlled by the weight control SOAs, which are labeled as SOA1 to SOA4 for λ_1 to λ_4, respectively, in Fig. 2b. A multi-current controller supplies and controls the injection currents. The weighted signals, thereafter combined at the output port, are then detected through a pre-amplified avalanche photodiode receiver (DSC-R402APD) and an optical spectrum analyzer.

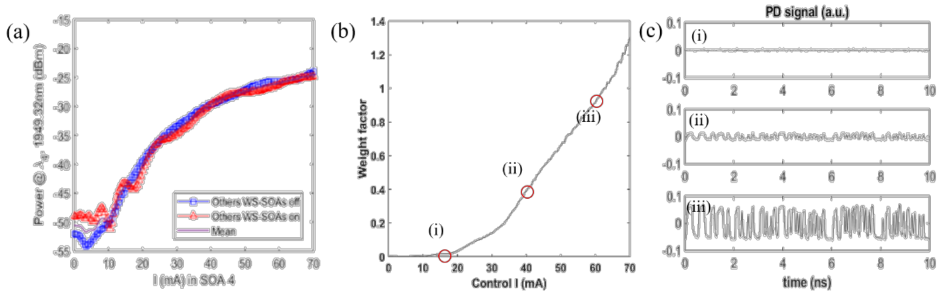

Fig. 3 (a) the power variations respect to the control currents of the SOA4. The peak power of λ_4 is recorded by tuning the injection currents of SOA4 when the other weight control SOAs are off (blue rectangle) and when the other weight control SOAs are set at 70mA (red triangle). The mean curve from these two situations are plot with solid line. (b)Weight vs. tuning current of channel 4. The red circles indicate control current at (i) 15mA, (ii) 40 mA and (iii) 60mA. (c)The corresponding time traces of the detected signal are shown.

We record the power curves with respect to injection current, from the optical spectrum analyzer. For this first prototype, the fabricated AWG brings in optical cross-talk, meaning that each optical path will influence the gain control of the other channel paths. A calibrated tuning scheme is generated by considering an average operation condition for the power control with maximum cross-talk and minimum cross-talk. Fig 3a presents the power control curves obtained from the OSA when increasing the injection current of the controlled weight SOA4 from 0 to 70 mA. The blue curve (empty rectangles) is recorded when all the other weight SOAs are off. The red curves (empty triangles) are recorded when all the other SOAs are set to 70mA. These curves indicate a tunable range from -45.5dBm to -25dBm, which means a dynamic range above 20 dB. One can see from the zero point that there is an offset between blue and red curves, which is attributing to the cross-talk from other paths (when SOAs in these paths are on). The curve oscillations (heavier when the cross-talk induced by other paths is increased) might be due to interference between the cross-talk signal and the signal in the desired path. We use the mean curve from these two extremes to generate the control curve for the weight factor. Fig. 3b plots the weight versus current line obtained from the mean control curve in Fig. 3a and the corresponding time traces at (i) 15 mA, (ii) 40 mA and (iii) 60 mA are shown in Fig. 3c.

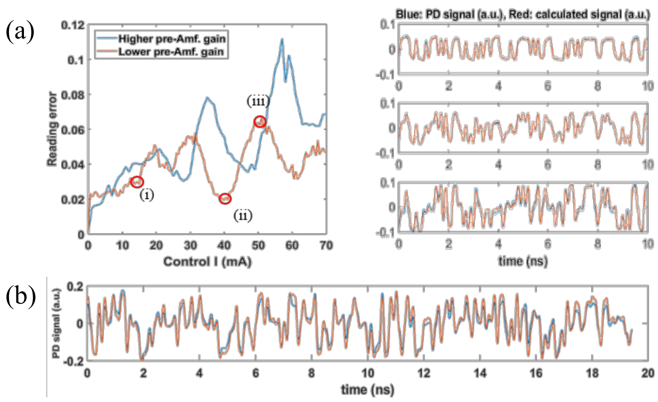

Fig. 4 (a) Weight addition reading error from the measured two-channel added signal (one with a fixed weight, the other with a tuning weight) to the calculated signal, when on-chip pre-amplification gain is higher (blue curve) and 4 dB lower (red curve). The corresponding comparisons between measured and calculated addition signals from (i) to (iii) are shown at the right side. (b) The recorded 4 channel weight sum signal (blue) and the calculated signal (red) when randomly setting current of four weight control SOAs, resulting in reading error of 0.06.

To estimate the reading error, the time trace signals are measured when tuning the injection current in weight SOA4 for two-channel (λ_3, λ_4) addition, with channel λ_3 set to a fixed weight factor. The normalized deviation error between measured and calculated signals is calculated. Fig. 4a plots the weight addition reading error with respect to the tuning current in SOA4. The pre-amplification provided by on-chip pre-SOA and PS-SOA of blue line is 4 dB higher than the red line. A reading error below 0.08 is obtained when a lower pre-amplification is applied. The example time traces (i) (ii) (iii) are plotted at the right side. At the end, a 4-channel weight sum is demonstrated with randomly setting current of all the weight control SOAs. The resulting time trace (blue) comparing the calculated time trace (red) is shown in Fig. 4b, with a reading error of 0.06.

Conclusion

The continuous weight tuning of four WDM channels has been realized on the 8x8 InP cross-connect by tuning gains of the SOAs for different input signals. For weighted addition operation, this chip shows a reading error that is less than 0.08, which is comparable to the work in [7], with a higher dynamic range of 20dB.

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