Interconnected VCSEL-based Photonic Synapses for Neuromorphic Processsing Architectures

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***Abstract*— Pairs of interconnected brain-inspired photonic synapses (connected in-parallel and in-series) are developed using Vertical Cavity Surface Emitting Lasers (VCSELs). We discuss the operation of each configuration and demonstrate their capability to perform different spike-based processing tasks including information encoding, temporal filtering, and Multiply-and-Accumulate (MAC) operations.**

Keywords— VCSELs, Neuromorphic Photonics, Artificial Neural Networks

I. Introduction

Artificial synapses capable of weighting optical signals are key to the success of the promising new neuromorphic photonic computing platform. Therefore, with a rising interest in artificial neural networks (ANNs) for machine learning applications such as image processing and computer vision [1], a number of weighting technologies have emerged. In photonics, synaptic weighting demonstrations have used memristive devices [2], microrings [3] and phase change materials (PCMs) [4]. However, one alternative method uses commercially-available, telecom VCSELs as optical weighting elements, yielding high-speed, low-energy, fully adjustable (11.6-bit precision) input weight tuning [5]. These systems have demonstrated that under the optical injection of short (150 ps-long) optical pulses, it is possible to controllably weight (and amplify) the peak output power by manipulating the bias current of the VCSELs (below their lasing threshold). Here, we demonstrate that these VCSEL-based photonic synapses enable interconnectivity in both in-parallel and in-series configurations; hence permitting multiple optical spike-based processing tasks at high speed rates, including the encoding of information, the temporal filtering of input pulses and even Multiply-and-Accumulate (MAC) operations (widely used in convolution and image processing tasks).

II. Method

The developed VCSEL-based photonic synapse systems operate with short (150 ps-long) optical pulses arriving at the VCSEL from an external modulated laser source (for full details on the experimental setup used see [5]). When driven below threshold (<95%) the VCSELs act as VCSOAs, where their bias current can be used to alter the resonant frequency of their gain peak. We exploit the on-off resonance of the VCSOA gain peak with the frequency of optical injection to control the weighting of input pulses, as shown in the weight tuning curve of Fig. 1. In this work we demonstrate interconnected photonic synapses both in-parallel and in-series configurations. The in-series configuration is created by connecting two 1300 nm VCSOAs, where the output of VCSOA-1 is connected as the input of VCSOA-2; hence subjecting the input (150ps-long optical pulses) to sequential weighting layers before analysis. The in-parallel configuration was built using a 1300 nm and a 1550 nm VCSOAs (see [5]) with a photodetector combining the optical outputs of the two devices before analysis. In both cases the weights of each synapse were set independently and had the capability to be programmed dynamically at high speeds (up to GHz rates) through fast modulation of the VCSOA's bias currents.

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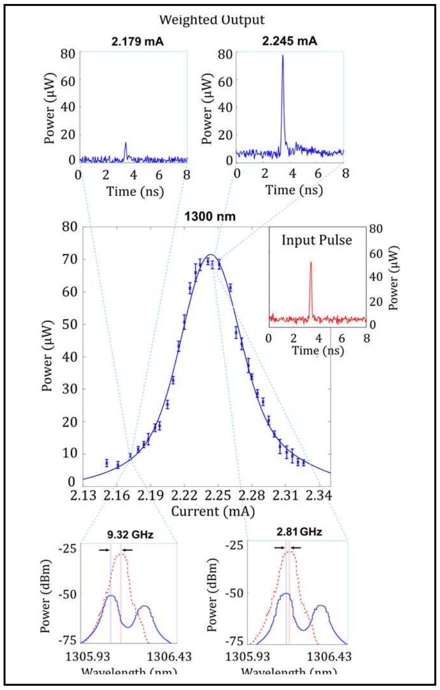

Fig. 1. Weighting curve of a 1300 nm VCSOA synapse. Optical input pulses (middle-inset), weighting curve (middle), output pulses (top) and resonant frequency offset between input and VCSOA (bottom). Control of the VCSOA's bias current demonstrates amplification (dampening) of 44.5 µW peak power pulses.

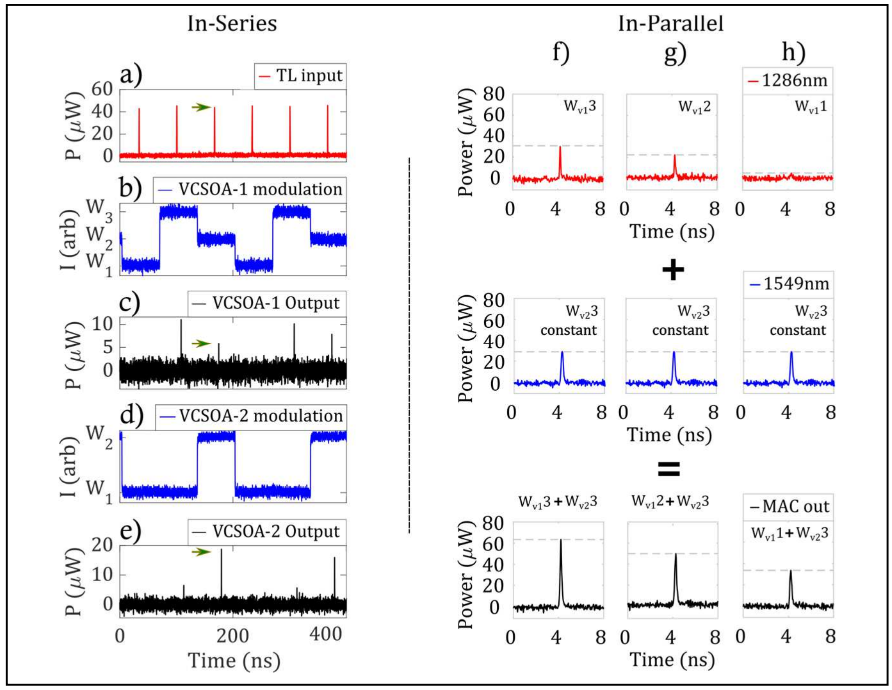

Fig. 2. Two VCSOA synapses connected in series (a-e) showing the ability to apply accumulative weights for temporal filtering. 150 ps input pulses (a) are injected into VCSOA-1 that is modulated with a 3-level signal (b), producing 3 weighted output pulses (c). These enter VCSOA-2, which is modulated with a 2-level signal (d), temporally filering and amplifying the (green) highlighted pulse (e). Two VCSOA synapse operated in parallel (f-h). Weighted pulses from VCSOA-1 (operating at 1286 nm) (f-h, red), are combined with a weighted pulse from VCSOA-2 (operating at 1549nm) (f-h, blue), yielding a summation of the weighted output (f-h, black), thus realising a MAC operation.

III. Results

Fig. 1 shows the weighting mechanism of a 1300 nm VCSOA synapse as the bias current is swept 0.22 mA. Fig. 1 reveals that as the current is swept, the frequency detuning between the VCSOA and the external input is varied controllably. As a result of this process, the VCSOA realizes full-range optical weighting of fast (150ps-long) and low input power (10s of µW) pulses with an amplification factor of up 1.79 and a calculated 11.6 bit-precision. Importantly, this technique permits high-speed dynamical weight tuning (up to GHz rates) via the simple control of the bias current applied to the VCSEL. Additionally, interconnected (in-series and in-parallel) VCSEL-based photonic synapses are possible. In Fig. 2 we reveal input (150 ps) optical pulses entering a sequential (in-series) two-VCSEL photonic synapse. Here the first VCSOA encoded information in the amplitude of the output pulses before a second VCSOA temporally filters the selected (green arrow) pulse. Finally, in Fig. 3, a two in-parallel VCSOA synaptic system is demonstrated (built with VCSELs operating at 1286 and 1549 nm) in which their respective weighted optical outputs are combined in a photodetector. VCSOA-1 generates 3 different weighted pulses, which subsequently combine with VCSOA-2's weighted pulses, to successfully realize a wavelength-independent pulse summation (multiple-and-accumulate function).

IV. Conclusion

We reveal that VCSEL photonic synapses can weight short (150 ps), low input power (10s of µWs) optical pulses with high-speed dynamical weight tuning (up to GHz). We also report that VCSEL synapses can be interconnected in-series, to realize accumulative weighting for information encoding and temporal filtering of pulses, and in-parallel to perform optically MAC operations.

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References

[1] E Callaway. "'It will change everything': DeepMind's AI makes gigantic leap in solving protein structures." Nature, vol. 588(7837), pp. 203-204, Dec 2020
[2] A. Emboras, et al, "Opto-electronic memristors: Prospects and challenges in neuromorphic computing," Appl. Phys. Lett., vol. 117, 230502, 2020.
[3] A. N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal, "Continuous Calibration of Microring Weights for Analog Optical Networks," IEEE Photon. Technol. Lett., vol. 28, pp. 887–890, 2016.
[4] J.Wang, L.Wang, and J. Liu, "Overview of Phase-Change Materials Based Photonic Devices," IEEE Access, vol. 8, pp. 121211–121245 (2020).
[5] J. A. Alanis, J. Robertson, M. Hejda, and A. Hurtado, "Weight adjustable photonic synapse by nonlinear gain in a vertical cavity semiconductor optical amplifier," Appl. Phys. Lett., vol. 119(20), 201104, 2021.