Simplified Synaptic Receptor for Coherent Optical Neural Networks

Bernhard Schrenk, AIT Austrian Institute of Technology

***Abstract*—Advancing artificial neural networks to the coherent optical domain offers several advantages, such as a filterless synaptic interconnect with increased routing flexibility. Towards this direction, a coherent synaptic receptor with integrated multiplication function will be experimentally evaluated for a 1-GHz train of 130-ps spikes.**

I. Introduction

The unquenchable explosion of information and the need for data processing are unquestioned. Being inspired by the human brain, neuromorphic computing promises a paradigm change in the realm of information processing, both in terms of computing and energy efficiency. Although all-optical realizations of neurons have been proven feasible [1], their scaling to a network level is highly challenging. For this reason, hybrid opto-electronic neural network implementations operating at GHz rates are currently being intensively investigated, together with their enabling functions such as multiply-accumulate operations [2-5].

This work proposes a coherent optical neural network architecture and experimentally investigates one of its key enablers: a simplified coherent synaptic receptor. I will demonstrate the operation of such a receptor for a 1-GHz train of 130-ps wide spikes using no more than an electroabsorption modulated laser (EML). Signed weighing will be accomplished without further optical elements.

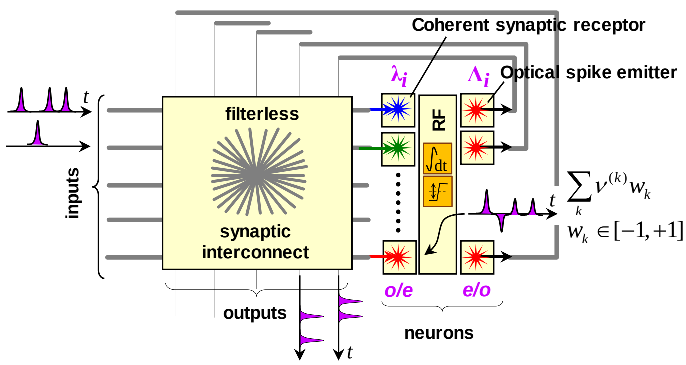

Fig. 1. Optical neural network with coherent synaptic receptors and filterless synaptic interconnect.

II. Filter- and Directionless Synaptic Interconnect

The optical neural network architecture presented in Fig. 1 builds on a passive split between down- and upstream neurons. The latter are implemented as opto-electronic nodes, with the neural integration and activation functions being accomplished in the RF domain. Synaptic receptor and spike emitter will in general operate at two different wavelengths λ_i and Λ_i, respectively, whereas the mapping between any pair of optical frequencies shapes the synaptic connection as a coherent pipe.

The spectral decoupling of receptors and emitters through a hybrid photonic/RF implementation for the neurons also permits the realization of feed-forward and recurrent neural networks. Towards this direction, the synaptic interconnect of the optical neural network greatly benefits from the adoption of coherent optics. It permits an any-to-any architecture that builds on a passive fabric for filterless signal distribution. Coherent pipes can be established between any neurons in the context of ultra-dense WDM signal distribution, making the network flexible in terms of fan-in and fan-out at both, dendritic and axonal arbors. At the same time, the loss inherent to a star split can be overcome through the sensitivity gain offered by coherent reception.

III. Coherent Synaptic Receptor

A prerequisite for the adoption of coherent neural networks is a high degree of simplicity for its sub-systems: the spike emitter and, more importantly, the coherent receptor. Due to the nature of analogue signal transmission, the use of DSP is strictly prohibited, raising the question for analogue homodyne receivers. Figure 2a presents the EML-inspired synaptic receptor that is considered in this work. Owing to the requirement of multiply-accumulate functionality at the dendritic tree, the receiver

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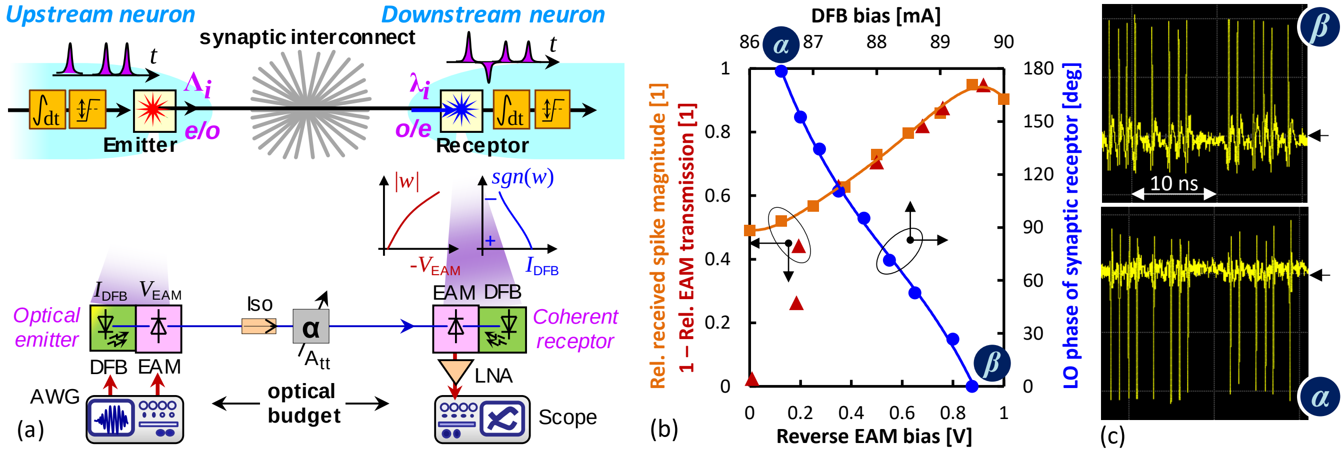

Fig. 2. (a) Concept and experimental setup for the coherent synaptic receptor. (b) Characterization of its integrated multiplication. (c) Received spike trains.

builds on three key notions. First, it accomplishes homodyne detection by means of optical injection locking [6]. For this reason, the locked distributed feedback (DFB) laser emission, representing the local oscillator (LO), down-converts the downstream synapse at the electro-absorption modulator (EAM) based photodiode. Second, the LO phase can be tuned through the DFB bias current within a π-phase range [7], in order to alter the sign of the photocurrent that is generated at the EAM photodiode. Third, responsivity tuning through the EAM bias permits to define the detection weight and both, excitatory and inhibitory downstream synapses can be facilitated.

IV. Experimental Proof and Discussion

The proposed coherent synaptic receptor has been experimentally evaluated in the setup shown in Fig. 2a. It resembles a coherent pipe between an EML-inspired optically phased spike emitter and an EML-inspired homodyne receptor with integrated weighing. At the emitting EML, spikes are optically phase encoded in a (0,π) alphabet through 1-GHz chirp modulation of the DFB using a pulse-reformatted drive having a 130-ps spike width. Suppression of residual intensity modulation through the EAM yields a constant envelope for the optical synapse, which is launched at 4 dBm. The optical budget for the synaptic interconnect has been set to 22 dB.

The EAM at the synaptic receptor is biased according to the weight setting, for which the detected spike magnitude (■) is shown in Fig. 2b, together with the response $\rho = 1 - T_{eam}$ of the EAM (▲), with T_{eam} being the measured transmission function of the EAM. The detected photocurrent was post-amplified through a 50Ω low-noise amplifier. This is due to the use of transistor-outline EMLs for the experiment, which prevents the use of transimpedance amplifiers as no close co-integration with low bond capacitance is possible. Optical locking of optical spike emitter and synaptic receptor at a wavelength of 1577 nm and subsequent sign alteration for the detection weight is accomplished through fine-tuning of the DFB current at either of the two identical EMLs. The locking range corresponded to a range of 3 mA in terms of DFB current. The LO phase has been characterized by means of pilot tones and shows a detuning by a phase of π within this range (Fig. 2b, ●).

The impact of the LO phase tuning on the sign is presented in Fig. 2c, showing the detected spike train at the output of the synaptic receptor. There is no intermediate frequency noticeable since coherent homodyne detection through the EML leads to a down-converted electrical signal at the baseband. A bit error ratio of $<10^{-6}$ has been validated for a PRBS-sourced spike train through error counting after real-time acquisition. This confirms the high signal integrity. When changing between points *α* and *β* in the LO phase setting (Fig. 2b), the sign of the detected signal flips (Fig. 2c). These results confirm that multiplication can be functionally integrated with the low-complexity, EML-inspired synaptic receptor.

Polarization management has been applied in the current experiment but can be omitted in a fully integrated optical neural network. Moreover, the formation of bidirectionally stable coherent pipes in face-to-face emitter-receptor configurations without optical isolation in the lightpath has been experimentally confirmed earlier [8]. Further architectural extension of the proposed concept towards a tempo-spectral allocation of synapses is feasible and underpinned by virtue of the fast locking time of homodyne receiver under a wide spectral locking range [9]. Another interesting aspect is the use of a transmitter-centric device as coherent receiver. Such a dual-function feature of synaptic transceivers opens the door for versatile on-demand building blocks, where coherent receptors and spike emitters can be interchangeably used in the context of a configurable neural fabric, similar as in optical communication nodes [10].

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