Coherent Homodyne Synaptic Interconnect with Sign- and Weight-Tunable Detection

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Abstract

We experimentally investigate a synaptic interconnect with low-complexity emitter and coherent receiver. Phase tuning of the LO enables the signed multiplication of the detected signal, which is demonstrated for 130-ps spikes at 1-GHz repetition rate.

I) Introduction

Artificial neural networks are being recognized as an attractive alternative to traditional computing [1]. For this reason, the porting of constituent neuro-inspired functions to the optical domain, such as array multiplication and summation or the non-linear activation function, is now being intensively researched. The field of neuromorphic photonics provides an optically driven acceleration in terms of ultra-low latency, good interconnect scalability and high energy efficiency. In such optical neural networks, a large number of interconnects and a high fan-in per neuron can be supported through the WDM and TDM dimensions. With respect to the multiply-accumulate function, several proposals have been made [2-5], including arrayed multiplication through serial TDM operation of a tunable weighting element. This time-sharing of optical receivers at the dendritic tree further contributing to a reduction in the overall system complexity. Signed weighting has been demonstrated through exploiting the complementary outputs of a micro-ring filter [2] or a balanced receiver [3]. However, in these differential implementations, the signed result is strictly mapped to a physical port and cannot be configured on demand.

In this work, we experimentally demonstrate a single-ended coherent homodyne receiver that is reconfigurable in the sense that the sign and magnitude of the weight for the detected spike train can be flexibly chosen. We exploit an electro-absorption modulated laser (EML) as a simplified and multi-functional opto-electronic element [6] for both, spike generation in the optical phase domain and “signed” coherent homodyne detection at a single synaptic interconnect. Moreover, we experimentally demonstrate burst-wise sign switching for the weighted reception.

II) Coherent Optical Synaptic Interconnect

The proposed neuromorphic network architecture is presented in Fig. 1 and builds on a passive split for filterless signal distribution. It accomplishes a configurable synaptic interconnect and a high fan-out/in by means of ultra-dense WDM in combination with coherent reception. Multiply-accumulate functionality is integrated with the coherent detection process. This paper aims to demonstrate low-
complexity coherent reception and the feasibility to integrate positive and negative weighting, while the non-linear activation function of a neuron is considered to be facilitated through opto-electronic means and left for future work.

Coherent homodyne reception yields a frequency- and phase-stable translation of the optical signal to the electrical domain, without the need for additional digital compensation. However, homodyne detection requires a precise matching between input signal and local oscillator (LO), which can significantly increase the complexity of the detection process. Different methods have been proposed towards this direction, including optical phase-locked loops or injection locking [7,8]. In this work, we build on a greatly simplified homodyne detector: the EML. Its EAM section serves as fast photodetector, at which the optical input signal and the emission of the DFB section are beating. The DFB is injection-locked by the input signal to yield DSP-free homodyne operation, which has been earlier validated for digital data and analogue radio signals [9].

While the frequency offset between the input signal and the LO is suppressed by virtue of injection locking, the optical phase of the locked slave laser, which represents the LO, depends on the frequency offset $\Delta \nu = \nu(k) - \nu_{LO}$ between optical input signal and the LO at its native (corresponding to the free-running) emission frequency. It is given by

$$\varphi_{LO} = -\arcsin\left(\frac{\Delta \nu}{LR}\right) - \arctan \alpha$$

where LR is the locking range and $\alpha$ is the linewidth enhancement factor [10]. A detuning of the LO between the locking boundaries ($\Lambda$) leads to a LO phase ($\Phi$) that covers a 180° range (Fig. 1). This phase shift will be exploited to implement single-ended signed coherent reception, for which the sign of the received electrical signal can be chosen by means of LO tuning (Fig. 1). This simplifies the multiply function, while at the same time supporting a high fan-in through the ultra-dense WDM scheme at the synaptic interconnect.

![Fig. 1. Coherent synaptic interconnect with phase-tunable local oscillators.](image)

### III) Experimental Setup

The proposed concept has been evaluated in the experimental arrangement shown in Fig. 2a, which resembles an interconnect branch of an optical neural network, including an optical spike generator at the transmitter side, and an optical weighing/multiplication function at the receiver side. The signal representation in the current work is chosen in a way that electrical spikes are converted to optically phase-modulated signals, and vice versa.
Transistor-outline (TO) EMLs are employed for the purpose of optical signal emission and reception. The EMLs operate at 1577 nm and feature a micro-cooler, which is employed for coarse alignment, while bias current and EAM bias tuning can be used for fine alignment and locking. The optical emitter EML is fed by electrical spikes and serves as optical phase modulator by means of chirp modulation with pulse reformatted driving signal [11]. For this purpose, its DFB section is directly modulated and accomplishes a π-phase swing for a drive of 12 mA

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The optical emitter is connected to the optical receiver through a variable optical attenuator (A

Polarization alignment of the incident signal at the receiver is conducted due to the fiber-based interconnect, however, would not be required in case of a chip-scale artificial neural network. The optical receiver EML is biased at -0.75V at its EAM section. The detected signal is post-amplified by a 50Ω low-noise amplifiers (LNA).

IV) Reception Performance and Detector Tuning

The coherent homodyne detection methodology ensures a greatly simplified receiver, but also necessitates a precise wavelength matching. This is facilitated by control of the temperature and DFB bias current in the experiment. In a practical implementation of a chip-scale neural network, small temperature differences can be compensated by bias adjustment, which is evidenced by the present work: When operating the two discrete TO-can EMLs used at the optical emitter and the coherent receiver at the same temperature, the same DFB and EAM biases, the resulting beat frequency at the output of the coherent receiver was only 1.7 GHz. Together with the DFB current tuning efficiency of 0.54 GHz/mA, this small spectral deviation can be easily compensated through bias adjustment to eventually enable homodyne detection.

Figure 3(a) presents the output spike train of the analogue EML receiver when being detected at the upper and the lower boundary of the locking range. The spike width was 130 ps and the repetition rate, meaning the bit rate of the pseudo-random spike sequence, was 1 GHz. The sign of the detected spikes alters between positive (P) and negative (N) at the two locking boundaries, which results from the optical phase change of the LO. This property allows to choose the sign of the weight during coherent reception of an input synapse. Moreover, the spike train is received without further digital post-processing by virtue of the coherent homodyne detection process, which guarantees the simplicity sought for the detector when scaling up neural networks.

The magnitude of the weight can be adjusted by tuning the EAM bias and thus the absorption property of the detector. Figure 3(b) shows the relative magnitude of the received electrical signal as
function of the detector bias. A difference of 5.3 dB in terms of spike magnitude is obtained when the EAM bias is swept from 0 to -0.88V.

Fig. 3. Selection of (a) weight sign through LO tuning and (b) weight magnitude through detector bias. (c) BER performance. (d) Sign switching. (c).

Finally, we have measured the bit error ratio (BER) performance for the detection of a spike train that is driven by a pseudo-random bit sequence, as function of the received optical power. For this purpose, the received spike stream has been digitized with a real-time scope for the purpose of error counting. Figure 3(c) reports the BER performance. A sensitivity of -20.7 dBm is obtained at a BER of $2.10^{-4}$. Given the optical launch of 4 dBm for the optical emitter, an optical budget of more than 24 dB (equivalent to a filterless 128:1 fan-in) is compatible at this BER level, while filterless synaptic interconnects can be potentially supported. Further improvement of the optical budget is expected for coherent EML detectors that are co-integrated with a transimpedance amplifier.

V) Time-Switched Signed Coherent Reception

In order to demonstrate the fast sign alteration for the coherent detection process at the synaptic interconnect, the optical LO phase has been switched by a pulse generator (PG) that drives the bias of the DFB-based LO ($\sigma$ in Fig. 2a). A frequency of 40 MHz has been chosen for this LO phase control frequency, which causes the sign of the detected pulses to flip periodically. This is demonstrated through the received spike trace in Fig. 3d at the output of the coherent receiver. Depending on the phase polarity of the LO, spikes are signed either positively or negatively. This allows to switch the sign of the weights for TDM-centric synaptic interconnects, for which the parallelism of synapses in space is substituted by a serial framing in time [3]. It shall be stressed that an electrical feed-forward compensation for the DFB modulation is locally required at the coherent receiver in order to cancel
its intensity modulation, similarly as it is known from downstream cancellation techniques in optical access networks [12].

VI) Conclusions

We have experimentally investigated a synaptic interconnect concept that exploits the phase and responsivity tunability of a low-complexity coherent homodyne receiver for the purpose of signed multiplication and weighing. We demonstrated that EML-driven emitter and receiver architectures enable a wavelength-selective detection of spike trains with spike widths of 130 ps and a repetition rate of 1 GHz. The sensitivity obtained enables a filterless fan-in of 128:1 to the neuron receiver. Dynamic operation was confirmed through burst-wise sign switching. The exploration of WDM and TDM domains to enable scalable multiply-accumulate operation is left for further study.

VII) References

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