

# WDM-Conscious Synaptic Receptor Assisted by SOA+EAM

Margareta V. Stephanie<sup>(1)</sup>, Michael Waltl<sup>(2)</sup>, Tibor Grasser<sup>(2)</sup>, and Bernhard Schrenk<sup>(1)</sup>

<sup>(1)</sup>AIT Austrian Institute of Technology, Center for Digital Safety&Security / Security & Communication Technologies, 1210 Vienna, Austria.

<sup>(2)</sup>Institute for Microelectronics, TU Wien, Gusshausstrasse 27-29, 1040 Vienna, Austria.

Author e-mail address: margareta.stephanie@ait.ac.at

**Abstract:** We experimentally demonstrate the simultaneous weighing and summation of two 23-nm spaced, frequency-coded spike trains with 100-ps spike width. Operation of the synaptic receptor at low BER is confirmed at 10 Gb/s information rate.

## 1. Introduction

Neuromorphic opto-electronic circuits have attracted interest as they promise a paradigm shift in the field of HPC [1] and a new generation of artificial intelligence handling GHz information rates at ultra-low latency [2, 3]. To harness the advantages of bio-inspired artificial neural networks through efficient photonic implementations, key building blocks such as excitable neurons with non-linear activation function or analog multiply-accumulate (MAC) operations need to be realized and scaled up in networked configurations [4]. Earlier works on synaptic receptors have demonstrated the required methods for signal processing, involving the weighing and summation of its input signals. Programmable circuits based on single-wavelength Mach-Zehnder interferometer (MZI) meshes [5] have demonstrated the possibility to scale up optical signal processing. However, the control of the phase is limited to the MHz range. Concerning spiking neural networks, WDM-enabled MAC operations have been demonstrated in both, non-coherent and coherent schemes, leveraging balanced detection in combination with reconfigurable, multi-wavelength add/drop operation [6], or self-homodyne detection employing phase-tuning for the local oscillator [7].

In this work, we propose and experimentally demonstrate a synaptic receptor that aims at simultaneous weighing and summation of frequency-coded synapses. A semiconductor optical amplifier (SOA) with co-integrated electro-absorption modulator (EAM) is modified to serve as wideband frequency demodulator before the photodetection of multiple WDM channels. We experimentally demonstrate simultaneous MAC operation at two wavelengths carrying spike trains with 100-ps spike widths and further evaluate the reception sensitivity of the proposed synaptic receptor.

## 2. Synaptic Receptor for WDM-Conscious MAC Based on SOA+EAM

The process of weighing requires an optical transfer function that allows determining the magnitude and sign of the detected signal. Such a weight function can involve a symmetric MZI structure, as found in electro-optic modulators [8]. In this case, the transmission is a sinusoidal function of the bias voltage, allowing to adjust the polarity and the magnitude of the transmitted optical signal.

However, the symmetric MZI is wavelength-agnostic and cannot weigh more than one wavelength simultaneously, which does not bode well with the principal strength of optical neural networks: to incorporate the WDM dimension to relax the interconnect issue in scalable neural networks significantly. The compatibility with WDM necessitates a spectral periodicity in the nm-range. In the present work we build on an earlier demonstration [9] for wavelength re-use in optical access. In detail, a monolithic integrated SOA+EAM with partially reflective front-facet and highly reflective back-facet is operated as a frequency-selective detector (Fig. 1a). The SOA is employed as a pre-amplifier for the EAM photodiode. Due to a weak reflection at the front-facet, the SOA gain spectrum is not flat but intentionally shows a gain ripple (Fig. 1b). This gain ripple will be used for frequency demodulation combined with frequency-coded synapses, whose information would not be visible to the photodetector without preceding frequency-to-intensity conversion. The gain ripple shows a comb-like transfer function  $T$  having a free spectral range (FSR) that is determined by the optical length of the SOA+EAM device. Moreover, the FSR is in the range of the ITU-T DWDM grid spacing. This allows simultaneous WDM operation and summation over multiple input signals.

In order to weigh incoming synapses to yield excitatory and inhibitory stimuli, the frequency-coded signals are spectrally tuned to a transmission peak of the comb, or vice versa. By suppressing either the mark ( $v_1$ ) or the space component ( $v_0$ ) of the frequency-coded spike train, a negative or positive response is accomplished for the

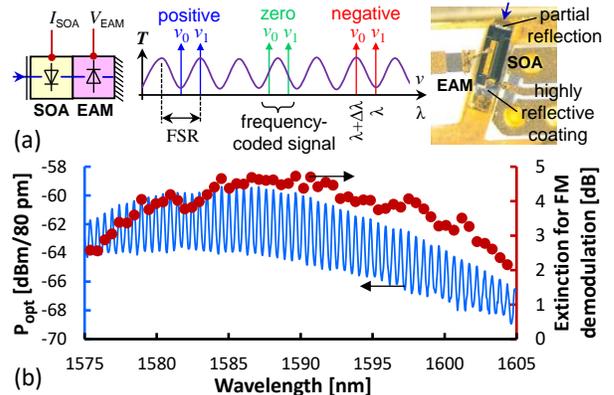


Fig. 1. (a) Synaptic receptor principle. (b) Optical comb function.

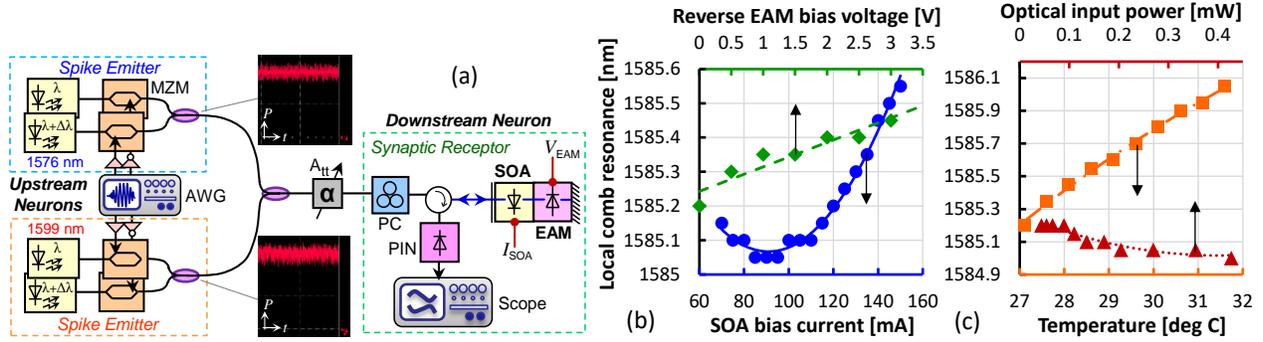


Fig. 2. (a) Experimental setup. (b) SOA+EAM transfer function shift with SOA and EAM bias, and (c) temperature and optical input power.

detected signal (Fig. 1a). Flipping the sign of the received signal at its full magnitude would then translate to shifting the comb by FSR/2. Weighing in terms of magnitude can be achieved by partially detuning the comb function so that the mark and space components do not fall onto the comb function's spectral peaks and notches. In the extreme case, both,  $v_0$  and  $v_1$ , experience the same transmission when passing through the comb, leading to a suppressed spike train after photodetection. This is equivalent to a weight with zero magnitude ('zero' in Fig. 1a).

### 3. Experimental Setup and Characterization of the SOA+EAM Receptor

The experimental setup is presented in Fig. 2a. Two spike emitters of upstream neurons are connected to the synaptic receptor of a downstream neurons. Each emitter employs a pair of differentially-driven Mach-Zehnder modulators (MZM) to conduct wavelength-switched optical frequency modulation. The constant-power output of the frequency-coded signals was -1 dBm and showed an intensity extinction ratio of 0.72 dB (Fig. 2a). Two wavelength pairs at 1576 and 1599 nm have been used. The deviation  $|v_1 - v_0|$  for optical frequency modulation, which is given by the spacing  $\Delta\lambda$  between the two optical sources of the same wavelength channel, has been adjusted to the contrast in the comb function  $T$ , so that  $\Delta\lambda = \text{FSR}/2$ . The frequency modulators are driven by an arbitrary waveform generator (AWG) with two waveforms: The first is a spike train with 100-ps spike width and a duty cycle of 1/16, which leaves enough space in the temporal dimension to time-multiplex other downstream synapses, as demonstrated shortly. The second waveform is a pseudo-random bit sequence assisting bit error ratio (BER) measurements. For the latter, a variable optical attenuator ( $A_{\text{att}}$ ) has been placed before the synaptic receptor.

The synaptic receptor builds on the SOA+EAM (Fig. 1a). Its bias points  $I_{\text{SOA}}$  and  $V_{\text{EAM}}$  are chosen according to the desired weight setting. Polarisation drift along optical fiber patchcords used in the experiment necessitates a manual polarisation controller (PC) to compensate for the polarisation-dependent characteristics of the SOA+EAM device. However, chip-scale implementations of neuromorphic circuits would eliminate the need for polarization control. Due to the unfortunate loss of RF response for the EAM, a PIN-based out-of-cavity photodetector had to substitute the EAM as a detector. Nevertheless, the efficiency of the in-cavity detector scheme is underpinned by [9]. The demodulated frequency-coded signals are digitized through a real-time oscilloscope for further analysis.

The transfer function of the L-band SOA+EAM, which serves as a demodulator for the frequency-coded synapses, is reported in Fig. 1b in terms of optical emission spectrum. The comb-like transfer function, which has a FSR of 0.55 nm, features a peak extinction of 4.73 dB ( $\bullet$ ). An extinction of more than 3 dB is found over an optical bandwidth of 23.75 nm. As we will prove, a low BER can be obtained despite this moderate extinction.

Tunability of the comb function is accomplished through adjustment of the SOA+EAM biases. Figures 2b and 2c present the tuning efficiency due to SOA bias current and EAM bias voltage, together with the influence of changes in temperature and optical input power. The corresponding spectral shifts are 1.34 GHz/mA for the SOA ( $\bullet$ ), 9.94 GHz/V for the EAM ( $\blacklozenge$ ), 22.5 GHz/ $^{\circ}\text{C}$  for temperature fluctuations ( $\blacksquare$ ), and -155.6 GHz/mW of optical input power ( $\blacktriangle$ ). For example, flipping the sign of the received signal at its full magnitude, which translates to shifting the comb by

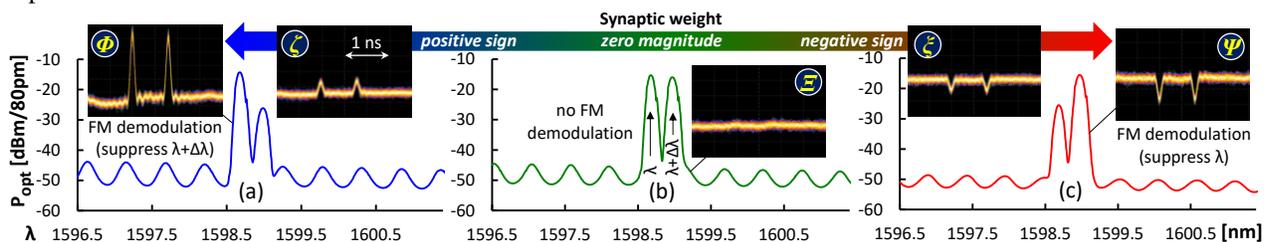


Fig. 3. Signal spectra and received spike train for the weighing process with SOA+EAM: (a) positive sign, (b) zero magnitude, (c) negative sign.

FSR/2, can be therefore facilitated through switching the SOA bias by 49 mA<sub>pp</sub> at a level of 120 mA.

#### 4. Reception Performance and Simultaneous Two-Channel WDM Operation

The impact of the detuned comb on the frequency demodulation is presented in Fig. 3, which shows the respective optical signal spectra at the output of SOA+EAM and the received spike trains. We report the results for the 1599-nm channel when suppressing the optical carrier at  $\lambda+\Delta\lambda$  (Fig. 3a), at  $\lambda$  (Fig. 3c), and for equal suppression of both carriers (Fig. 3b). In the last case, there is no frequency demodulation, leading to a received signal with constant amplitude ( $\Xi$ ). This corresponds to a synaptic weight with zero magnitude. Optical frequency demodulation applies for either of the two other cases. It leads to a positive ( $\Phi$ ) or negative ( $\Psi$ ) sign for the detected spike train for suppressing  $\lambda+\Delta\lambda$  or  $\lambda$ , respectively. Moreover, the extinction in frequency demodulation, which can be tuned through the relative position to the local comb maximum, determines the magnitude of the weight ( $\zeta$ ,  $\xi$ ).

Finally, the performance of the synaptic receptor has been evaluated in terms of BER measurements using a 10 Gb/s pseudo-random bit sequence (Fig. 4a). As a reference, we draw a comparison to the case where only the optical carrier  $\lambda$  is present, meaning to transmit an intensity-modulated signal from the upstream spike emitter. This would correspond to ideal frequency demodulation with infinite extinction of  $\lambda+\Delta\lambda$ . At 1599 nm, we obtain a reception sensitivity of -17.2 dBm to the SOA+EAM at a BER of  $10^{-4}$  (○). This would allow an optical budget of more than 16 dB at the dendritic tree between synaptic emitters and receptors. When demodulating the frequency-coded signal launched by the spike emitter with the SOA+EAM, we experience a reception penalty of 1.1 and 5.5 dB for suppressing  $\lambda+\Delta\lambda$  (□) and  $\lambda$  (△), respectively. This penalty is attributed to the finite extinction of the optical frequency demodulation and could be reduced through a refinement of the SOA+EAM cavity parameters. Nonetheless, there is no BER floor and the eye diagram is clearly open (Fig. 4a). For the second synaptic channel at 1576 nm, we see a sensitivity degraded by 1.6 dB for an intensity-modulated signal (●). Penalties of 3.5 and 3.9 dB apply for the reception of frequency-coded signals when suppressing  $\lambda$  (▲) and  $\lambda+\Delta\lambda$  (■), respectively.

Finally, we jointly delivered both wavelength channels at 1599 and 1576 nm to the SOA+EAM. We chose an emitter-side spectral alignment that results in the 1599-nm channel yielding positive spikes, while the 1576-nm channel being weighed negatively. Figure 4b shows the detected

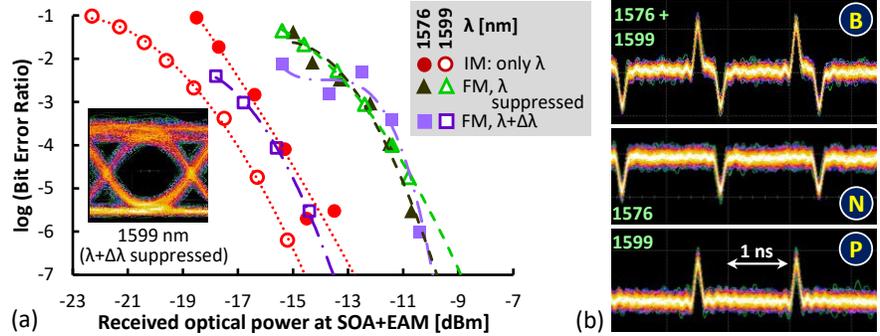


Fig. 4. (a) BER performance. (b) Simultaneous MAC for spike trains at 1576 and 1599 nm.

spike train (B), which proves the correct reception of signals from two spike emitters with alternating sign. We also compare to only one channel being present (P, N).

#### 5. Conclusion

We have demonstrated a synaptic receptor that exploits a DWDM-centric and spectrally periodic transfer function for simultaneously weighing spike trains with 100-ps spike width. Two spike trains with a spectral spacing of 23 nm have been jointly frequency demodulated by a SOA+EAM configuration and summed upon detection. Reception at low BER has been experimentally confirmed. Operation with a functional in-cavity detector is left for future work.

Acknowledgment: This work was supported by the ERC under the EU Horizon-2020 program (grant agreement No 804769) and by the Austrian FFG agency through the JOLLYBEE project (grant n° FO999887467).

#### 6. References

- [1] J. D. Kendall and S. Kumar, "The building blocks of a brain-inspired computer," *Appl. Phys. Rev.* **7**, 011305 (2020).
- [2] T. Ferreira de Lima et al., "Machine learning with neuromorphic photonics," *JLT* **37**, 1515-1534 (2019).
- [3] J. Robertson et al. "Ultrafast optical integration and pattern classification for neuromorphic photonics based on spiking VCSEL neurons," *Sci. Rep.* **10**, 6098 (2020).
- [4] H.-T. Peng et al., "Neuromorphic Photonic Integrated Circuits," *JSTQE* **24**, 6101715 (2018).
- [5] F. Shokranch et al., "A single layer neural network implemented by a  $4 \times 4$  MZI-based optical processor," *Phot. J.* **11**, 4501612 (2019).
- [6] A. Tait et al. "Broadcast and weight: An integrated network for scalable photonic spike processing," *JLT* **32**, 4029-4041 (2014).
- [7] R. Hamerly et al., "Large-Scale Optical Neural Networks Based on Photoelectric Multiplication," *Phys. Rev. X* **9**, 021032 (2019).
- [8] G. Mourgias-Alexandris et al, "Neuromorphic Photonics With Coherent Linear Neurons Using Dual-IQ Modulation Cells," *JLT* **38**, 811 (2020)
- [9] B. Schrenk et al., "Colorless FSK Demodulation and Detection With Integrated Fabry-Pérot Type SOA/REAM," *PTL* **22**, 1002-1004 (2010).