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Reception of Frequency-Coded Synapses through Fabry-Perot SOA-REAM Integrating Weighting and Detection Functions

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Abstract *We experimentally demonstrate a synaptic receptor for 2.5 Gb/s frequency-coded signals, functionally integrating weighting and single-ended photodetection based on a Fabry-Perot (FP) type semiconductor optical amplifier (SOA) monolithically integrated with a reflective electro-absorption modulator (REAM). Comparison is made with a micro-ring assisted receptor.* *©2022 The Author(s)*

Introduction

As data generation is escalating exponentially, the current von-Neumann oriented compute architecture reaches a bottleneck for moving large amount of data between processing unit and storage [1]. Neuromorphic photonics emerges with the promise to mitigate the bandwidth limitations of microelectronics. By employing photonics devices, a brain-inspired neural network can be established to perform analog multiply-accumulate operations, by virtue of the massive parallelism, the low propagation loss and the large bandwidth of photonic implementations. Optical neural networks are therefore touted to support high-speed data processing with GHz information rates at ultra-low latency [2]. Several architectures have been proposed to realize photonic-based neural networks. Optical reservoir computing has a collection of connected neurons with pre-defined weights, which only requires the output to be trained [3]. Programmable integrated circuits such as Mach-Zehnder interferometers (MZI) exploit the coherent nature of light to scale up the computational density [4]. However, both approaches are focused on the processing of a single wavelength. Multi-wavelength operation has been introduced by using an integrated array of micro-ring resonators (MRR) to weigh a multiplexed set of synapses [5], yet at the expense of a balanced detector configuration required to perform analogue summation. Similarly, symmetric MZI structures have been used as a weight matrix in a photonics neural network [6], however, again under the restriction of being limited to single-wavelength operation.

In this work we build on the colorless operation of SOA-REAM technology, which is adopted as integrated demodulator and detector for weighting frequency-modulated (FM) signals. We prove correct operation at 2.5 Gb/s through a low BER of 10^{-10} and compare its function as synaptic receptor with implementations assisted by a silicon MRR and a tunable optical filter.

Synaptic Weight with Integrated Detector

The proposed synaptic receptor resorts to the fact that the polarity and magnitude for frequency-to-intensity conversion can be chosen by tuning the suppression of the respective sideband (ν_1, ν_2) of a frequency modulated (FM) signal, hence providing weighting functionality as sketched for a positive polarity in Fig. 1a. The detection weight is set by the relative alignment of comb and FM input, through tuning either the comb or the wavelength of the input. The ability to choose the sign of the weight during FM demodulation simplifies the photodetection towards a single-ended configuration. The periodic response of a comb-like FM discrimination function allows for a simultaneous weighting of WDM-aggregated inputs. Practically, the FM demodulation can be accomplished through a MRR or a monolithic integrated FP-SOA-REAM device, as proposed by us recently [7]. Here, we extend our previous work by integrating detection with the weight element (Fig. 1b): The front facet of a SOA-REAM device is partially reflective, yielding an active cavity with a gain ripple whose free spectral range (FSR) is in the range of the

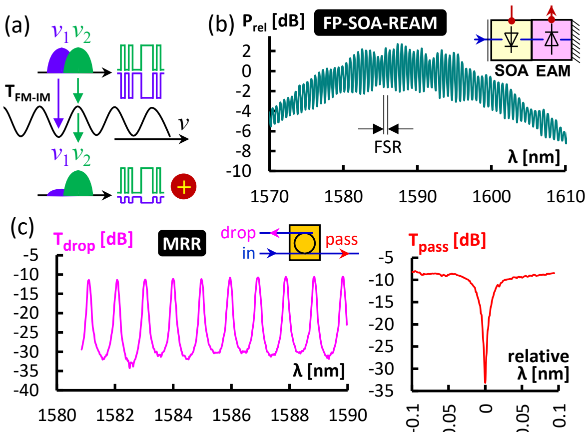

Fig. 1: (a) Weighted reception and comb-like transmission accomplished through (b) FP-SOA-REAM and (c) MRR.

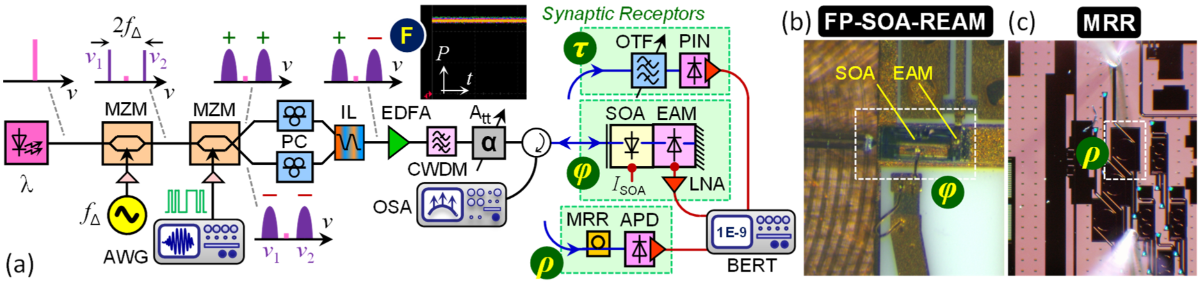

Fig. 2: (a) Experimental setup. (b) FP-SOA-REAM and (c) MRR devices employed at the synaptic receptors.

DWDM spacing. Frequency-coded synapses are demodulated to an intensity-modulated (IM) signal and detected through the frequency-agnostic EAM photodiode integrated in the active cavity. As such, the integrated FP-SOA-REAM serves as colorless demodulator and detector.

Experimental Setup

The FM signal is generated by firstly modulating a CW signal at λ = 1585.57 nm with a tone at f_Δ = 15 GHz using a Mach-Zehnder modulator (MZM) (Fig. 2a). This frequency is adjusted to (i) FSR/2 of the demodulating comb function, and (ii) the even/odd transmission windows of an optical 25/50 GHz interleaver (IL). The bias of this first MZM is set to obtain carrier-suppressed double-sideband modulation (CS-DSB), leading to two spectral lines at ν_1 and ν_2 spaced by $2f_\Delta$. A second, dual-output MZM modulates both lines with the same 2.5 Gb/s signal. Its two complementary outputs are then interleaved so that a constant-power signal modulated in frequency (ν_1,ν_2) is obtained. The residual IM patterning on this FM signal had an extinction ratio of 0.26 dB (F in Fig. 2a). The signal was boosted and the ASE peak of the EDFA was filtered with a 1591-nm CWDM filter. The input power to the synaptic receptor is controlled through a variable attenuator. The receptor based on the FP-SOA-REAM (φ and Fig. 2b) had SOA and EAM sections with lengths of 400 and 70 µm, respectively, leading to a FSR of 0.54 nm (Fig. 1b). The optical gain spectrum of the SOA had a 3-dB bandwidth of 23.2 nm and was centered at 1587.5 nm. Since the EAM section is polarization-sensitive, we employed a manual polarization controller (PC) in each of the interleaver branches. In an integrated neural network, this would not be necessary. The photocurrent of the EAM photodiode is post-amplified with a low-noise amplifier (LNA) and evaluated in terms of BER performance.

For comparison, we employed two more frequency-demodulating receivers. The first was a single-polarization silicon MRR followed by an APD/TIA receiver that accounts for the fiber-to-fiber coupling loss of 8.4 dB when passing through the MRR (ρ). The MRR, shown in Fig. 2c, had been fabricated on a silicon-on-insulator platform with a 220×500 nm^2 waveguide cross-section, had a FWHM bandwidth of 14.6 GHz and a FSR of 0.95 nm for its drop response (Fig. 1c). The second was a tunable optical filter (Santec OTF-350) with a steep filter edge of 23.8 dB/0.1nm and an insertion loss of 2.8 dB, combined with a PIN/TIA receiver (τ in Fig. 2).

Results and Discussion

Figure 3 reports the optical signal spectra for (a) the FM transmitter and the synaptic receptors based on (b) the FP-SOA-REAM, (c) the MRR and (d) the OTF, together with the transfer functions of the respective optical elements. The optical carrier suppression after CS-DSB modulation is 16.8 dB, with the two modulated lines clearly being separated in the FM signal (Φ). The suppression in the adjacent waveband of the interleaver (ι) is 20.4 and 19.6 dB for the odd (o) and even (ε) signal, respectively. This

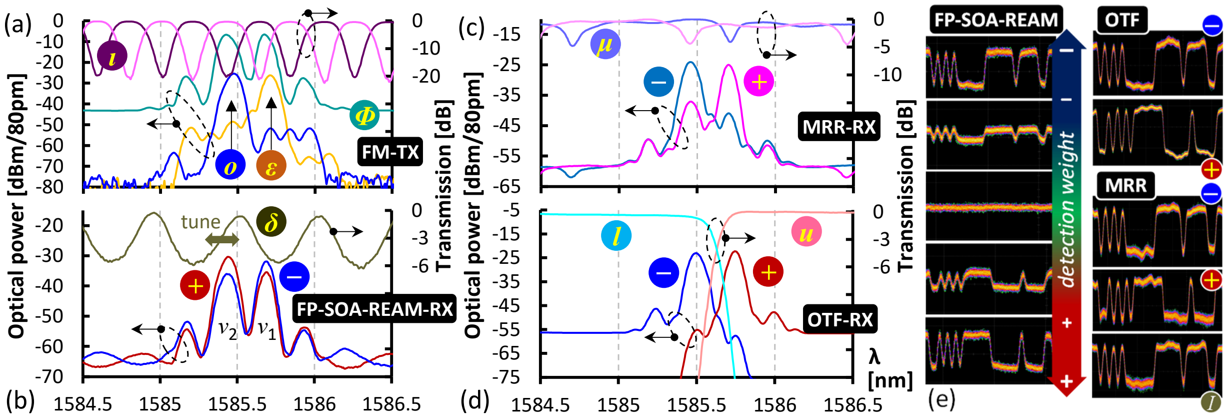

Fig. 3: Signal spectra for (a) FM transmitter, (b) FP-SOA-REAM, (c) MRR and (d) OTF receptors. (e) Received patterns.

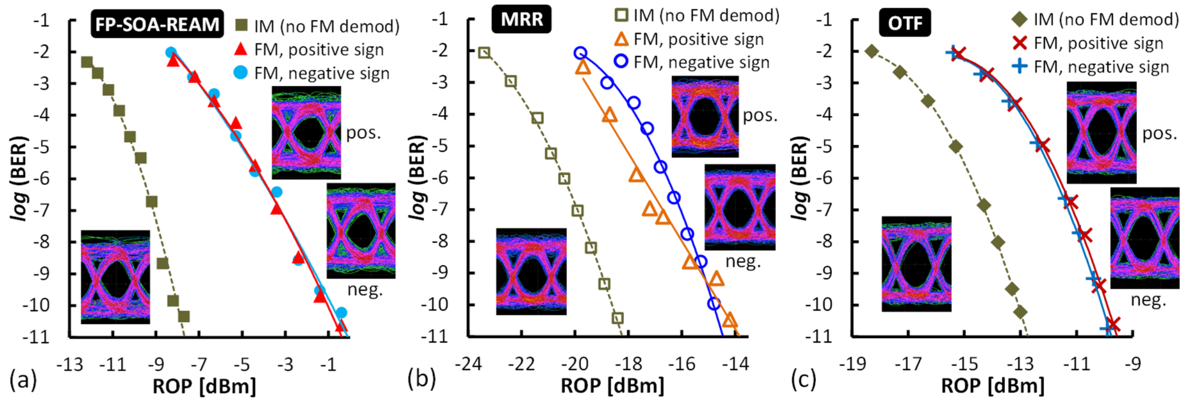

Fig. 4: BER performance for (a) FP-SOA-REAM and (b) MRR- and (c) OTF-assisted synaptic receptors.

ensures a sufficiently low crosstalk for the complementary tributaries of the FM signal.

The demodulation function of the FP-SOA-REAM (δ), observed from its reflected (i.e. power-complementary) signal (Fig. 3b), features an extinction of 4.9 dB and can be tuned through SOA current, EAM bias or temperature [8] to suppress either tributary at ν_1 or ν_2. This leads to a positive or negative polarity for the received signal, for which the upper (+) or lower (–) sideband is emphasized, respectively. An extinction of 5.4 dB can be achieved for FM-to-IM demodulation, as visible from the difference in peak powers in the upper and lower sidebands of the suppressed optical carrier λ. This extinction has been found to be dependent on the FP-SOA-REAM cavity loss and thus on the EAM bias. A similar weight selection can be made for the MRR (Fig. 3c). The spectral notch of its pass-through port (μ) is spectrally tuned to reject the corresponding FM tributary (ν_1,ν_2), leading to an extinction of 15.9 dB for FM demodulation. In case of the OTF the bandpass is tuned to pass either the lower (l) or upper (u) sideband (Fig. 3d). The FM demodulation features a high extinction of >32 dB by virtue of the sharp filter roll-off within $2f_\Delta$.

Figure 3(e) reports the detected signals. A continuous weighting in sign and magnitude is accomplished through shifting the comb-like FP-SOA-REAM transmission. The weight can be similarly set for the OTF and the temperature-tuned MRR. For the latter, Fig. 3(e) compares the received signal after FM demodulation (–) with the case of having an IM input signal (I), meaning that just one FM tributary (ν_2) is present at the input of the FM demodulator.

The reception performance of all three synaptic receptors has been evaluated in terms of BER for a pseudo-random data input as function of the received optical power (ROP). Figure 4 shows the BER performance for (a) the FP-SOA-REAM receptor and (b,c) the MRR- and OTF-assisted receptors. For the FP-SOA-REAM, the reception sensitivity for the FM demodulated signals at a BER of 10^{-10} is -0.9 dBm and shows a small difference of 0.2 dB between positive (▲) and negative (●) weights. The penalty with respect to an IM input signal (■) is 7.1 dB, of which 3 dB account for the paired FM spectrum consisting of ν_1 and ν_2 rather than of a single line (ν_2). Another 2.9 dB are attributed to the sensitivity penalty due to a finite demodulation extinction ratio (δ in Fig. 3b) [9]. The rather high ROPs required for the FP-SOA-REAM receptor are attributed to (i) the mode-field mismatch between the asymmetric InP waveguide and the tapered single-mode fiber, and (ii) the EAM-LNA detector, which performs worse than an EAM-TIA receiver [10].

For the MRR-assisted receptor with APD/TIA detector (Fig. 4b), the reception sensitivity is -14.7 dBm (△,○) and the penalty to an IM input (□) is 3.9 dB. The <1-dB penalty is attributed to the high extinction of the MRR notch used for FM-to-IM demodulation. The high ROP levels in combination with the APD receiver are explained by the high fiber-to-fiber coupling loss (Fig. 1c). In case of the OTF-based demodulator (Fig. 4c) with PIN/TIA receiver, we obtained a sensitivity of -10.1 dBm (+,×), whereas the penalty with respect to an IM input (◆) is 3.1 dB. This agrees well with the expected 3-dB offset for an excellent suppression of an FM tributary.

Conclusions

We have experimentally demonstrated a synaptic receptor that integrates weighting and photodetection functions as offered by a FP-SOA-REAM configuration and confirmed its correct operation at 2.5 Gb/s through a low BER. Comparison made with an MRR-assisted FM discriminator offering a high contrast in its transfer function indicates improvement potential for the demodulation efficiency of the FP-SOA-REAM receptor, whose intensity extinction ratio after FM-to-IM conversion was 5.4 dB. Further gain in sensitivity is expected through co-integration of the EAM photodiode with a noise-optimized TIA.

Acknowledgements

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