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# Photonic Reservoir Computing based on Optical Filters in a Loop as a High Performance and Low-Power Consumption Equalizer for 100 Gbaud Direct Detection Systems

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**Abstract** *We propose and numerically simulate a passive neuromorphic processor performing equalization in C-band IM-DD links, that employs a spatial reservoir computing scheme based on recurrent optical filters. Followed by a feed forward equalizer, the system achieves sub HD-FEC performance up to 60km in 224 Gbps/λ.*

## Introduction

The transition from 4G to 5G is accompanied by a sharp increase in data traffic. The 100G transceivers, which had conquered the market after 2015, are being replaced by 400G ones, with 800G emerging as the next big thing [1]. Although coherent technology is a very attractive candidate for next generation 800G links, it hardly fits in the tight power requirements of quad- or octa-small form-factor pluggables (15 W), while Intensity Modulation-Direct Detection (IM/DD) systems consume even below 8 W for 400G transmission [2]. On the other hand, IM/DD solutions face the problem of scalability, as 4x100Gbd PAM-4 are needed for 800G. Even if Mach-Zehnder Modulators (MZM) are employed, in such high symbol rates the Inter Symbol Interference (ISI) caused by chromatic dispersion and low component bandwidth will result in severe degradation even for transmission distances below 5 km. To combat these impairments, powerful but power hungry DSP methods must be employed both in the transmitter and the receiver side [3].

In this work we propose and numerically study a neuromorphic scheme for the mitigation of the dispersion induced ISI based on reservoir computing (RC) with the use of spatial recurrent nodes that for the first time target different spectral areas of the input signal. Previous works that address transmission impairment compensation through RC, rely mostly on time-multiplexed schemes [4] which do not offer coherent processing, impose extra complexity due to mask application and their performance is a trade-off between node number and processing time. Spatial RCs for telecom applications have been proposed in [5], where a 16-node swirl topology was used to achieve coherent processing, however requiring 16 photodetectors at the readout level. In this work, we also achieve coherent processing implemented by only two optical filters with feedback that act as RC nodes. The two optical filter nodes slice the optical spectrum in different parts as in [6], thus treating separately lower and higher optical frequencies. In contrast to [6], here the RC processing takes place directly in the optical domain through the optical feedback in the filtering process, thus minimizing required DSP to a simple feed forward equalizer that acts as a linear regression stage for the RC system. The proposed spectral slicing method from a filter-in-a-loop allows sub-HD FEC performance for up to 60Km optical links in the C-band and for a rate exceeding 224Gbaud/λ. The minimum hardware complexity and cost of the scheme renders it suitable for a vast range of edge-cloud application scenarios.

## System Description

The basic unit of our system is the recurrent node consisting of a first order optical filter, a coupler and a feedback loop of delay $T_d$ *equipped* with a variable optical attenuator (VOA) and a phase shifter (φ in fig. 1) so as to adjust the feedback strengh and phase respectively. The other branch of the coupler is followed by a PD and an Analog to Digital Converter (ADC). The whole architecture can be monolithic integrated on silicon photonics and optical filters such as Mach-Zehnder Delay Interferometers (MZDI) or Micro-Ring Resonators (MRR) can be used (Fig.1). The transfer function of such a filter in a loop is easy to analytically obtain. In (1) we consider the transfer function of a typical first order filter where $f_0$ is the central frequency of the filter and *BW* is the 3-dB single sideband bandwidth. In (2), we



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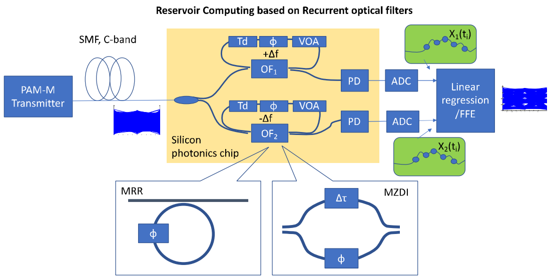


**Fig. 1:** The recurrent node, implemented by optical filters in a loop of delay $T_d$. The receiver employs two filters with frequency detuning Δf with respect to central signal frequency. Its node is followed by a PD and an ADC. The two outputs are jointly processed by an FFE/linear regression unit.

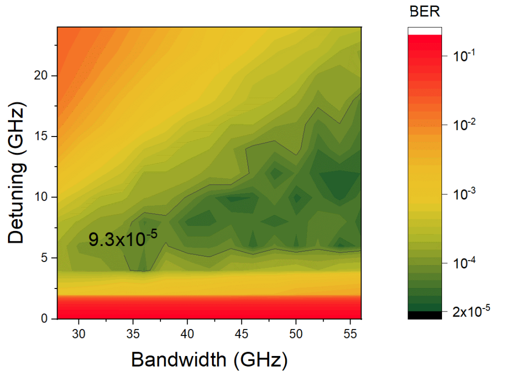


**Fig. 2:** The role of detuning and filter's bandwidth mitigation performance. The two filters partially overlap. For a filter with 56 GHz bandwidth, a detuning of 10 GHz (+/-5GHz difference from signal carrier) achieves the best results.

express the transfer function of each filter node in a loop where $L_{in}$ are the input losses, $L_{loop}$ are the losses in the feedback loop including output coupler losses and VOA induced losses, $T_d$ is the total delay of the loop and $\varphi$ the phase shift that can be tuned with the use of a phase shifter.

A set of such spatial reservoir nodes slicing recurrently a signal in different spectral areas constitutes a photonic recurrent neural network able to selectively amplify or attenuate frequency components at high resolution and thus target time and frequency dependent problems like time series prediction, voice recognition and most importantly ISI due to dispersion. In order to minimize the number of required electronic components (PDs, ADCs) that increase the cost of the receiver, we limit our RC system to only two recurrent nodes, each targeting at a slightly different part of the input signal dictated by $f_0$ and $BW$ in (1). It is important to stress out that a higher number of nodes assure better performance, but in the environment of Data Center Interconnects (DCI) the hardware limitations are strict, thus we keep RC requirements to the bare minimum. For our benchmark, we numerically simulate an externally modulated distributed feedback (DFB) laser source whereas with the integration of nonlinear Schrödinger equation using the split-step Fourier method, the transmission of PAM-4 and PAM-8 pulses along a typical single mode fiber are modelled. Baud rates of 56-112 Gbd for PAM-4 and 37-74 Gbd for PAM-8 are assumed, aiming to investigate performance for the established 100 Gb/s/λ but also next generation 200 Gb/s/λ optical links and explore how the transmission reach can be extended using the proposed scheme compared to the state of the art. In addition, we consider an optical pre-amplifier at the receiver side, which is modelled as a gain element with noise figure equal to 5 dB. After photonic processing, we sample the output of each PD with an ADC of 8 bits resolution, with one sample per symbol and we carry out linear regression at the output by combining 51 symbols, half of them being the succeeding and half of them the preceding of the symbol for which BER is estimated. This linear regression processing is equivalent to an FFE block. The PDs have a responsivity R=1.0 A/W, whereas typical noise (shot noise, thermal noise) is taken into account.

$$H(f) = \left[1 + i\left(\frac{f - f_0}{BW}\right)\right]^{-1} \quad (1)$$

$$H_{FIL}(f) = \frac{H(f) * L_{in}}{1 - H(f)\, L_{loop}\, e^{-i(2\pi f T_d + \varphi)}} \quad (2)$$

We evaluate the efficiency of the system through direct counting of the Bit Error Rate (BER) in a testing set of $10^7$ bits in order to achieve a resolution of $10^{-5}$. The training set consists of 20000 symbols.

## Results

The processing power of the scheme originates from the selective amplification and processing of different frequency components per spatial node. From this point of view, we investigate the role of the two filters' bandwidth and detuning with respect to the signal's central frequency. The contour plot of Fig. 2 shows how the BER of a 56 Gbaud PAM-4 signal is affected by the interplay of these two factors. It is evident that the two filters must accommodate at least 60% of the initial bandwidth. Lower bandwidth filters translate to lower bandwidth photodiodes, which is beneficial from the hardware point of view. 30 GHz photodiodes can easily detect the two sliced spectra of the 56 GHz optical signal without loss of information. On the other hand, the broader the bandwidth of each filter is, the higher the flexibility with respect to the optimal detuning of the two filters that can be selected from BER perspective. The detuning of the two filters that offers ultra high equalization performance is within 5GHz to 15 GHz for the studied baud rate. Always the two

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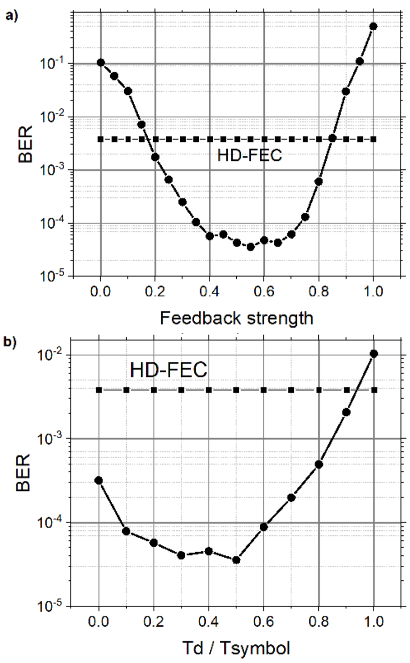


**Figure 3:** BER as a function of a) feedback strength and b) feedback delay time for 56 Gbd and 60 km of transmission.

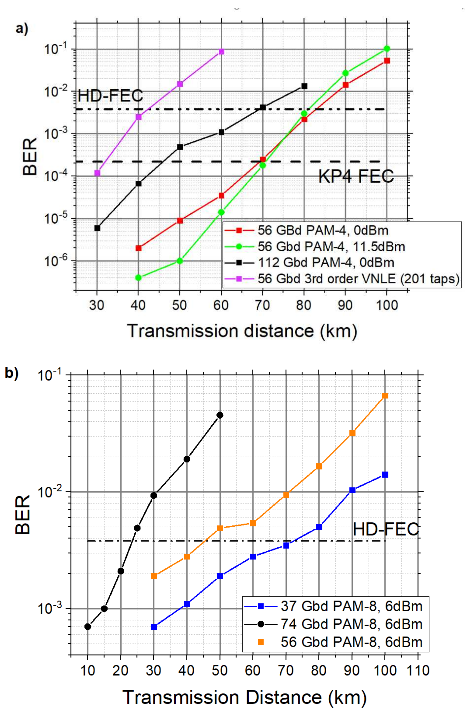


**Figure 4:** BER results for a) PAM-4 and b) PAM-8 in various baud rates.

filters are placed symmetrically with respect to signal carrier frequency (+/- detuning/2).

The second important feature of the scheme is the feedback loop whose main functionality is to act as a memory element that enables the interaction of past and current symbols. In this context, If the loop delay is chosen smaller than the symbol period, the feedback loop correlates components of the optical field within the same symbol acting as an ultrafast oversampling mechanism in the optical domain. In Fig.3 the effect of feedback strength and feedback delay ($T_d$) are examined. As feedback strength we define the portion of the signal's intensity at the output that is re-inserted back to the input of the recurrent node. The amount of feedback also affects the Received Optical Power (ROP). It seems reasonable that the best results are achieved for a balanced value close to 50% that assures enough power for the receiver but also adequate feedback that enhances RC memory and processing power. With respect to $T_d$, delays approaching $T_{symbol}/2$ lead to a record low BER below $10^{-4}$. Fig. 4 presents BER performance vs. transmission distance for PAM-4 and PAM-8 in various baud rates. In the case of 56 GBd PAM-4, 80 km transmission under HD-FEC limit is achieved, revealing that the system is mostly noise limited. The red line corresponds to transmission with optical pre-amplifier and 0 dBm transmitted power while the green is for unamplified signal with 11.5 dBm transmitted power. For comparison, a 3rd order VNLE with 201/51/15 taps and one sample per symbol is used in the same datasets. The improvement offered by our hardware accelerator of almost zero consumption is unprecedented. 60 km transmission under HD-FEC is accomplished for 112 Gbd PAM-4. In PAM-8 case, 70 km transmission is achieved for 37 Gbd or 112 Gb/s/λ.The aforementioned results are very promising as exceptional performance here coincides with small power consumption. Similar results were obtained by considering in (1) the transfer function of a MRR or a MZDI, proving the versatility of the architecture. Taking into account that state of art solutions for ultra-high baud rates in next generation DCI rely on sophisticated DSP [7], our neuromorphic photonic accelerator emerges as a promising alternative.

## Conclusions

The paper proposes a photonic neuromorphic system based on optical filters with optical feedback that perform optical slicing and recurrent processing in the spectral domain. The scheme, when operated with two filters as a dispersion equalizer, shows remarkable BER performance below HD-FEC limit up to 60 km in 224 Gb/s C-band transmission with the aid of a low complexity FFE at the reception.

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