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56 Gbaud PAM-4 Transmission Equalization using Implicitly Masked Parallel Micro-Ring Resonator Reservoir Computing

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Abstract *We show that variation of the coupling ratios of parallel micro-ring resonators can replace masking in time-delay reservoir computing while being line-speed capable. Superior BER performance is demonstrated compared to previous photonic reservoirs and Kramers-Kronig DSP for a 100 km 56 Gbaud PAM-4 transmission. ©2022 The Author(s)*

Introduction

As the symbol rates in optical communication systems continue to increase, so do the demands on digital signal processing. For future scaling of the data rate, Optical Signal Processing (OSP) will become increasingly important. OSP will make it possible to scale the speed of signal processing even beyond the physical limits of electronic components. A popular approach for OSP is Neuromorphic Signal Processing (NSP), where machine learning methods such as Artifical Neural Networks (ANNs), are implemented with photonic components [1-2], allowing channel equalization and mitigation of non-linear transmission effects without electrical bandwidth limitations.

As an alternative to direct implementations of ANNs, which often require a large number of optical components, Reservoir Computing (RC) exploits the inherent non-linear properties of a reservoir. Silicon-on-Insulator Micro-Ring Resonators (MRRs) are particularly well suited for integration in existing foundries and have been investigated as reservoirs with different topologies, such as the 4×4 swirl topology [3].

Alternatively, by introducing a masking sequence and applying it to the input signal, a reservoir with a single non-linear element can be realized, e.g. with a semiconductor laser in combination with an optical feedback fiber, effectively introducing virtual reservoir nodes [4]. Applying this Time-Delay (TD) scheme to a single MRRs is sufficient to form a reservoir by exploiting its distributed 3rd-order, free-carrier, and thermal non-linear properties [5]. Recently, the parallelization of TDRC is being investigated, enhancing the nonlinear channel equalization capabilities compared to single element reservoirs [6-7].

However, while reducing the number of elements in TDRC is desirable in contrast to other, more complex topologies, masking of the input signal often requires Optical-Electrical-Optical (OEO) conversion. Furthermore, the detection of the virtual nodes requires high oversampling rates, rendering its application to the equalization of high baudrate transmission difficult.

In this paper, we present a parallel photonic reservoir topology that exploits the non-linear behavior of MRRs, realizing implicit masking by using differently coupled parallel, but independent MRRs. To our knowledge, this is the first demonstration of TDRC without explicit masking. Furthermore, we study the signal recovery performance numerically with data from a 56 Gbaud PAM-4 100 km transmission experiment with 5 Dense Wavelength Division Multiplexing (DWDM) channels. We show, that the equalization performance of this topology exceeds the one of offline Kramers-Kronig (KK) processing and other MRR based TD photonic reservoirs.

System Setup

The experimental transmission has been described in [8] and is schematically shown in Fig. 1 a. Here, 107,520 randomly generated symbols have been gray-coded and converted into a Pulse Amplitude Modulated (PAM)-4 sequence before being pulse-shaped into root-raised cosines with a roll-off factor $\beta = 0.1$. By pre-emphasizing the signal, bandwidth limitations of different components were compensated before the signal is modulated by Mach-Zehnder Modulators (MZMs) and converted into a Single Side Band (SSB) signal with five External Cavity Lasers (ECLs), each detuned by 24.5 GHz from the center of its channel and filtered by an interleaver filter with a bandwidth of 44.3 GHz. In this experiment, the Carrier-to-Signal Power Ratio (CSPR) was optimized to ensure low signal-signal beating interference and fulfillment of the minimum phase condition. After the transmission over 100 km uncompensated Standard Single-Mode Fiber (SSMF),

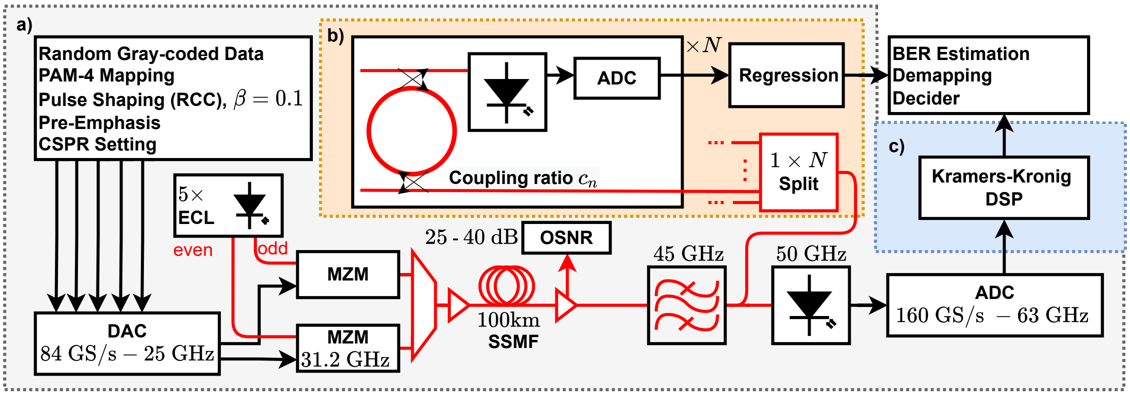

Fig. 1: a) Experimental 56 Gbaud PAM-4 IM/DD SSB 100 km transmission system with 5 DWDM channels [8]. b) Numerically simulated photonic reservoir computer with *N* parallel silicon micro-ring resonators. c) Offline Kramers-Kronig DSP.

Tab. 1: Parameters of the PIN junction-based MRRs.

Parameter		Value	Unit
Detuning	Φ	0	1
FDC /FCA	μ	30	1
Eff. group index	n	4	1
Linear Loss	α	92.2	m^{-1}
Eff. ring area	A	$2 \cdot 10^{-13}$	m^2
FCA	σ	$1.45 \cdot 10^{-21}$	m^2
Kerr	γ	$3.1 \cdot 10^{-11}$	m/W
Thermo-optic	δ_T	10^{-7}	K^{-1}
Heat capacity	C	$1.65 \cdot 10^{6}$	$J/m^3 K$
Carrier lifetime	τ_c	10^{-10}	s
Photon lifetime	τ_{ph}	$1.16 \cdot 10^{-8}$	s
Thermal relaxation time	τ_{th}	10^{-7}	s

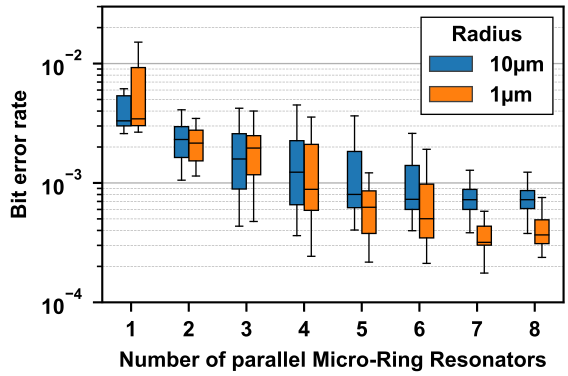

Fig. 2: Influence of the radius on the BER for different numbers of parallel micro-ring resonators for a transmission with an OSNR of 36.6 dB.

different Optical Signal-To-Noise Ratios (OSNRs) sets were obtained by noise loading. At the receiver, the signal is equalized either digitally (Fig. 1 c) or optically by a parallel MRR reservoir computer (Fig. 1 b). The digital equalization in [8] is done using KK processing, matched filtering and Feed-Forward Equalization (FFE) with up to 96 taps.

Numerical Simulation

To model the propagation of the field E through the silicon waveguide of a PIN junction-based MRR with reverse bias numerically, as shown in Fig. 1 b, with a temperature t and carrier concentration n_c, the modified Lugiato-Lefever Equations (7) - (9) from [9] are used. This system of differential equations is solved using the odeint function from [10] for the initial state ($E = 0$, $t = 0$, $n_c = 10^8$) and with the parameters shown in Tab. 1. Each MRR is characterized by its radius and a coupling ratio c_r, a factor of its critical coupling, resulting in over-coupling for $c_r > 1$ and under-coupling for $c_r < 1$. In contrast to other reservoir topologies with multiple elements, there is no influence between each MRR, enabling independent numerical simulation. Splitting of the optical signal for each element, detection and ADC conversion are assumed to be ideal and therefore without bandwidth limitations, power loss and additional influence of noise.

To investigate the difference between explicit masking of the input signal and implicit masking by variation of coupling into each of the parallel MRRs, 16 different coupling ratios in the range $[10^{-4}, 4^2]$ for radii between 1 µm and 10 µm were simulated for different OSNRs. The Bit Error Rate (BER) is approximated with Monte-Carlo Cross Validation with 10 repetitions and random 90 % test / 10 % training splits. When predicting of a symbol with ridge regression, its 20 neighboring symbols on each side are considered, analogous to [5], enabling the compensation of effects like inter-symbol interference. For parallel reservoirs, the features of each MRR are used for the regression.

Results and Discussion

As shown in Fig. 3, the equalization performance of the TDRCs from [5] sampled with 16 Samples per Symbol (SPS) and OEO conversion of the input signal for digital masking outperformed the

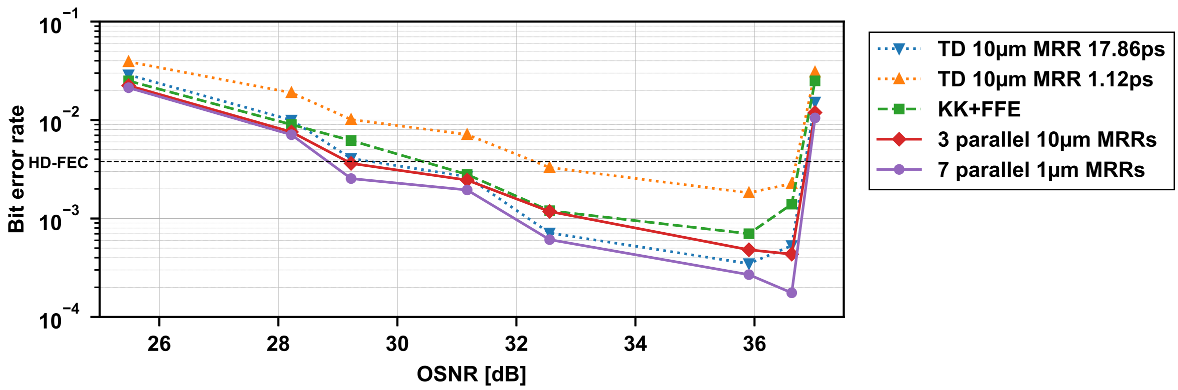

Fig. 3: Comparison of the bit error rate after equalization with time-delay reservoir computing with a single micro-ring resonator, 16 virtual nodes with node separations of 17.86 ps (3.5 Gbaud) and 1.12 ps (line-speed, 56 Gbaud) [5], Kramers-Kronig with Feed-Forward Equalization (KK+FFE) [8] and the best configuration of coupling ratios for parallel micro-ring resonators with 3 and 7 elements.

KK Digital Signal Processing (DSP) from [8] with a virtual node separation of 17.86 ps. However, this system was not working at line-speed, which would require a virtual node separation of only 1.12 ps (for 16 virtual nodes the TDRC must operate at 16 $\times$ the speed of the incoming 56 Gbaud signal). In contrast, the proposed parallel reservoir with only 3 MRRs, a radius of 10µm and coupling ratios of $\{5^{-4}, 10, 200\}$ is able to match or exceed the equalization performance of the KK DSP at line-speed with 2 SPS without the need for explicit masking. If instead 7 parallel MRRs are utilized working at 56 Gbaud, a radius of 1 µm and coupling ratios of $\{10^{-3}, 10^{-1}, 5^{-1}, 5, 50, 100, 200\}$, the performance in terms of BER is even superior to the above mentioned TDRC working with 16 virtual nodes.

In general, a higher number N of parallel MRRs reduces the BER until a lower limit dependent on the radius is reached, as shown in Fig. 2. Here, the BER for a transmission with an OSNR of 36.6 dB is compared for parallel reservoirs with different combinations of coupling ratios, drawn from a discrete uniform distribution of the aforementioned selection of 16 coupling ratios for each MRR, while all other parameters, including the radius, are kept identical. The equalization performance of the parallel MRRs with a radius of 1 µm matches the one of the KK DSP from [8] using only 2 parallel rings at this OSNR. If more parallel rings are utilized, the BER can further be reduced.

Conclusion

We have presented a parallel topology for photonic reservoirs with micro-ring resonators as non-linear elements that is able to exploit the benefits of micro-ring resonators operated in their non-linear regime without the need of explicit masking and high oversampling. Unlike swirl or similar topologies, where the non-linear behavior of the reservoir is also a result of interaction between multiple elements, each micro-ring resonator acts independently. We have shown, that three non-linear elements in this configuration match the performance of conventional DSP with FFE and up to 96 taps for signal recovery in a PAM-4 56 Gbaud 100 km transmission system over the entire investigated OSNR range. By increasing the number of parallel elements, the BER can be reduced further, exceeding the performance of more complex time-delay reservoirs.

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