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Experimental Demonstration of Nonlinear fibre Distortion Compensation with Integrated Photonic Reservoir Computing

Stijn Sackesyn [(1,2)], Chonghuai Ma[(1,2)], Joni Dambre [(3)], Peter Bienstman[(1,2)]

[(1)] Photonics Research Group, Department of Information Technology, Ghent University - imec, Belgium. stijn.sackesyn@ugent.be
[(2)] Center for Nano- and Biophotonics (NB-Photonics), Ghent University, Belgium.
[(3)] IDLab, Department of Information Technology, Ghent University - imec, Belgium.

Abstract *Optical reservoir computing is a machine learning technique in which a photonic chip can be trained on classification tasks of time signals. This paper presents experimental results where linear and nonlinear fibre distortions are mitigated to below the* 0.2×10^{-3} *FEC limit using a photonic reservoir.*

Introduction

The ever-increasing drive for faster and denser communication in all aspects of the current digital society (video streaming, cloud services) keeps pushing the underlying optical technology forward at a high pace. One of the fundamental problems when data rates increase to even higher values in bandwidth-limited media is the Kerr effect in optical fibres which can be responsible for multiple nonlinear optical effects[1]. In this paper, we will only handle single wavelength signals, therefore only Self-Phase Modulation SPM will be of influence.

Several methods exist to correct for linear as well as nonlinear effects. The linear effects have been studied extensively in the past, and good-working solutions are established. Optical examples are dispersion compensating fibres and dispersion shifted fibres. In the electrical domain, Tapped Delay Line filters (TDL) and Decision Feedback filters (DFE) are widely used. In terms of nonlinear impairment compensation, Digital Back Propagation (DBP) and nonlinear Volterra series are the most important electronic solutions, but both are power-hungry[2]. Important optical methods are optical phase conjugation (OPC) and Phase-conjugated twin wave (PC-TW). However, OPC will limit the system flexibility drastically as the link-length needs to be known beforehand. PC-TW limits the spectral efficiency (SE) due to an additional twin wave that needs to be transmitted[3].

Numerous optical implementations of reservoir computing for optical signal processing applications are being investigated now for over a decade and can be divided into delay line based reservoirs and spatially distributed reservoirs[4]. In reservoir computing[5], a recurrent neural network (RNN) is used as a means to enrich the feature space of a given time signal. This RNN is called the reservoir and will not be changed throughout the procedure. It is only the readout stage that will be trained, where the states of a subset of the nodes will be linearly combined to match the desired output as closely as possible. Recently, different flavours of it have been investigated for applications in telecommunications specifically[6]–[9].

In this work, we will experimentally show a photonic reservoir chip to compensate for linear as well as nonlinear impairments for the first time. Our approach processes the data in parallel by design and consequently has a very low latency cost. Furthermore, the equalization part of signal processing can be tackled in real time in the optical domain which keeps conversion to power-hungry electronics to a bare minimum. We present first experimental results on fibre distortion mitigation using a waveguide-based photonic reservoir implementation. First, the design of the reservoir is discussed. Subsequently, we discuss the experimental setup that was used to perform the experimental measurements. Lastly, the results are presented in which our photonic reservoir is able to compensate below the Forward Error Correction (FEC) limit for the distortion induced by the combination of a nonlinearity-inducing amplifier and 25km of optical fibre.

Photonic reservoir design

The design of this photonic reservoir is based on the four-port architecture which is a power efficient evolution of the swirl architecture[10]. The reservoir studied in this paper has 32 nodes in a 4 by 8 configuration as is shown in Figure 1. All sig-

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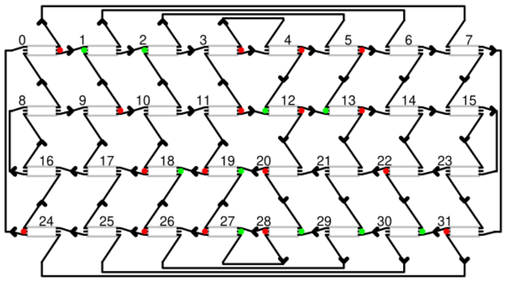

Fig. 1: Schematic drawing of the 32-node four-port reservoir, with in green the input nodes (1,2,12,13,18,19,27,28,29,30) and in red the output nodes (0,3,4,5,9,11,12,13,18,19,20,22,24,26,27,28,31).

nals are coupled to and from the chip by means of grating couplers. The chip can only be optically probed from 17 ports out of 32 nodes, which are distributed throughout the structure. The optical input signal is coupled to the chip at a single grating coupler and thereafter distributed on-chip through a tree of multimode interferometer (MMI) splitters to 10 nodes, enhancing the uniformity of the power distribution in the reservoir structure. The signal is routed between nodes by photonic waveguides, for which the propagation delay of the signal travelling through one such connection corresponds to one bit period for all the inner waveguides. The outer waveguides have varying lengths, but are always chosen to be a multiple of one bit period. This delay strategy is based on simulations and is intuitive to do, as it will synchronize bits that are coming from different nodes and then being combined again at a given node. The longer delay lines at the outer side of the reservoir increase the intrinsic memory and also break the symmetry within the reservoir which prevents it from having too similar outputs. The chip was fabricated in the SG25H4 SiGe BiCMOS technology platform from IHP technology, to operate at 1550nm.

Experimental setup

The experiments presented in this paper are all done using an electrical readout strategy. This means that the nodes are optically probed and detected by a photodiode one at a time. These electrical time traces are saved on a computer and the linear combination of these traces is done in post-processing on a computer. This is in contrary to the optical readout strategy, where the optical signals are weighted and combined on-chip. The latter method has a higher degree of integration, which naturally brings more challenges. The optical readout case is subject to ongoing experiments and out of the scope of this paper.

The experimental setup is shown in Figure 2. Light at 1550mm, generated by a commercial CW laser (Santec TSL-510) is modulated (Photline MX-LN-40) in a random stream of On-Off keyed bits at a rate of 32 Gigabit per second (GBPS). The random stream was generated by the Mersenne twister algorithm. This signal is amplified (all amplifiers are Keopsys CEFA-C-HG-SM-50-B201-FA-FA) and sent through a single mode fibre of 25km. The amplifier in front of the fibre is an artificial means of increasing nonlinear distortion effects in the fibre and thus specifying the difficulty of the task to be solved by our reservoir computer. An amplifier after the fibre increases the optical power again to a set value which is the same for all experiments, irrespective of the power sent through the fibre. This ensures that the optical power that is sent through the reservoir is constant for all experiments, resulting in a fair way of comparing these tasks. Without this, the higher the power sent trough the fibre, the higher the power sent through the reservoir and the better the signal quality will be after detection after the reservoir. Due to suboptimal design and fabrication, a third amplifier is needed to amplify the signal to within the detection range of the photodetector. Finally, the signal is saved electronically and post-processed on a computer.

The photonic reservoir will be compared to a tapped delay line filter (simulation model). For a fair comparison, the tapped filter should have the same number of degrees of freedom as the reservoir. Therefore, it is constructed by taking N copies - N is the number of probed reservoir nodes (17) - of the distorted signal, each with a delay equal to a multiple of the bit period and within a range of 30 bits. To compensate for timing uncertainties coming from the independent measurements of the different channels, the 17 time offsets are optimised using a Gaussian optimisation algorithm[11] which minimizes the BER. The N copies are then linearly combined. Care was taken to ensure that this procedure for the tapped filter is exactly equal to the algorithm used for the reservoir nodes, so as to have a fair comparison.

Experimental results on the fibre distortion task

The experiment was executed for three different levels of fibre distortion, provoked by driving the first amplifier to 10dBm, 14dBm and 18dBm respectively. In Figure 3, eye diagrams are shown for the case where the random stream is ampli-

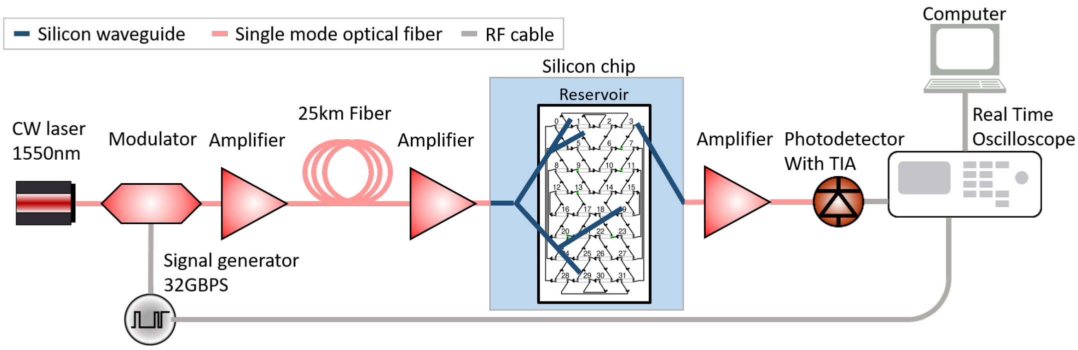

Fig. 2: Schematic illustration of the setup used in the experiment.

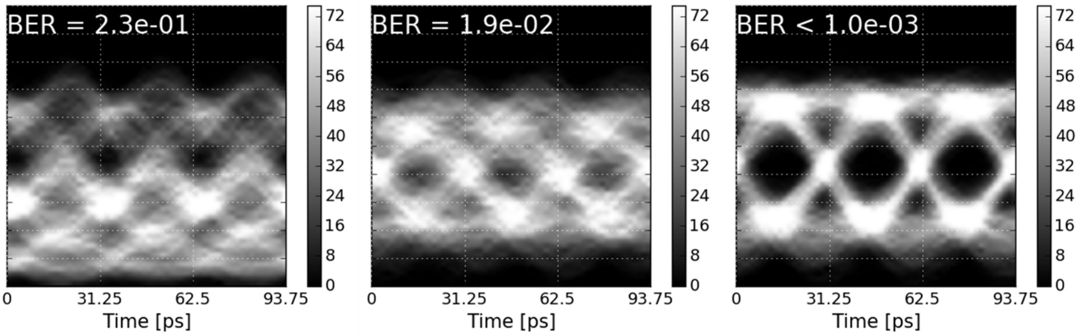

Fig. 3: Eye diagrams for respectively the distorted signal (left), the signal after a tapped delay line filter equalizer (center) and the signal after the photonic reservoir equalizer (right).

fied to 14dBm of optical power and sent through the optical fibre. The Bit Error Rate (BER) of the original signal is 2.3×10^{-1} and the signal is visibly distorted in a nonlinear way. After linear filtering by the tapped delay line filter, the BER remains as high as 1.9×10^{-2}, indicating that for this power level, a considerable amount of nonlinear distortion is present. The BER retrieved after the reservoir chip is below the FEC limit, as zero errors are measured from the stream of 10^5 test bits. This limits the BER resolution to roughly 10^{-3}. A more precise number can not be reliably given with this test size[12], and scaling up the number of bits would mean a nontrivial change to the setup due to memory limitations of the signal generator, or switching to PRBS signals. An overview of the performance of the reservoir compared to that of the tapped delay line filter is given in Figure 4 for the three different amplifications of the signal. The BER of the tapped filter increases with increasing nonlinear distortion, which is to be expected. On the other hand, the reservoir can solve the task errorless within the measurement resolution for 10dBm as well as 14dBm, while for 18dBm, a BER of 5×10^{-4} is obtained, still below the 0.2×10^{-3} FEC limit. The reservoir is thus capable to correct for linear as well as for nonlinear fibre distortion effects.

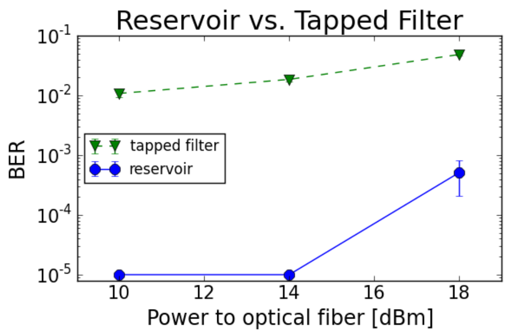

Fig. 4: The photonic reservoir equalizer in comparison to the tapped delay line filter.

Conclusion

This paper demonstrated the first experimental results for nonlinear fibre distortion mitigation of a waveguide based photonic reservoir, being a real-time, integrated optics approach. We compared the reservoir to a tapped delay line filter for three types of distortion. The reservoir outperforms this linear baseline and stays overall below the 0.2×10^{-3} FEC limit for all cases. Further work will include implementing the linear combination on-chip in the optical domain.

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