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EXECUTIVE SUMMARY

This document reports on the experimental and simulation progress of integrated reservoir computing systems. Experimental results of the neuromorphic photonic structures that will be used for signal processing in the work of ESR 9 Sarah Masaad are presented. The results include high-speed measurements that bypassed the integrated optical readout. This approach was needed due to the higher than expected losses of the spirals. Moreover, simulations on this reservoir architecture were performed to optimize a processing pipeline for the nonlinear compensation of a fiber link. Details of the telecommunication system and the simulation results are also presented in this document. Finally, an overview of the photonic integration of time-multiplexed and frequency-multiplexed reservoir computing schemes is presented. A collaboration between ESR 11 Tigers Jonuzi and 12 Alessandro Lupo for the integration of frequency multiplexed reservoir computing schemes is also discussed.

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LIST OF ACRONYMS

DAC	Digital-to-Analog Converter
KK	Kramers Kronig
MMI	Multimode Interferometer
PCB	Printed Circuit Board
PDK	Photonic Design Kit
QAM	Quadrature Amplitude Modulation
RC	Reservoir Computing

1 INTRODUCTION

This document reports on the experimental and simulation progress of integrated reservoir computing systems. In Chapter 2, experimental results of the neuromorphic photonic structures that will be used as signal processors in the work of ESR 9 Sarah Masaad are presented. The results include high-speed measurements that bypassed the integrated optical readout. This approach was needed due to the higher than expected losses of the spirals. The reservoir used here is a spatially multiplexed implementation and this architecture is termed the four-port architecture. Simulations on this reservoir architecture were performed to optimize a processing pipeline for the nonlinear compensation of a fiber link. Details of the telecommunication system and the simulation results are presented in Chapter 3. In Chapter 4, an overview of the photonic integration of time-multiplexed and frequency-multiplexed RC schemes is presented. A collaboration between ESR 11 Tigers Jonuzi and 12 Alessandro Lupo for the integration of frequency multiplexed reservoir computing schemes is also discussed.

2 MEASUREMENTS ON 4 PORT ARCHITECTURE

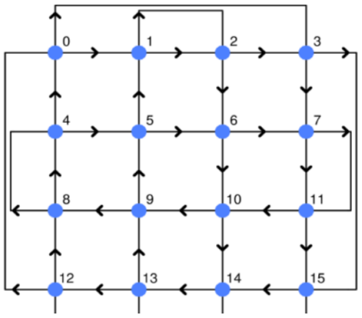


Figure 1 Four-port architecture with 16 nodes

This photonic reservoir is a large photonic interferometer built of nodes separated by waveguide spirals. An abstract view of this architecture, with 16 nodes, is shown in Figure 1.

The physical structure is mainly composed of the following passive components: waveguide spirals, waveguide crossings, and 3 x 3 multimode interferometers (MMI's) which form the nodes. For the testing of this reservoir, a mask containing the reservoir's structural building blocks was printed to perform passive optical transmission measurements. These measurements help in characterizing the building blocks to ensure that the overall structure performs as expected. From characterizing the waveguides on 2 different chips, the propagation loss was estimated as 2 dB/cm which is 10 times higher than predicted by the PDK. This made for lossier spirals than was accounted for, which is likely attributed to the bending radius. A follow-up run to investigate the effect of different bending radii is underway. Besides the building blocks, the mask also contained a passive test structure for the complete reservoir architecture consisting of 32 nodes, as shown in Figure 2.

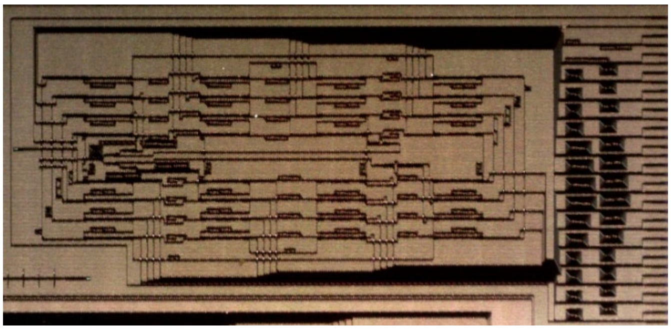


Figure 2 passive reservoir for electrical readout

Figure 3 shows the spectra from all nodes, cut off at a transmission of -60 dB. The green line shows the sum of the optical powers (after detection).

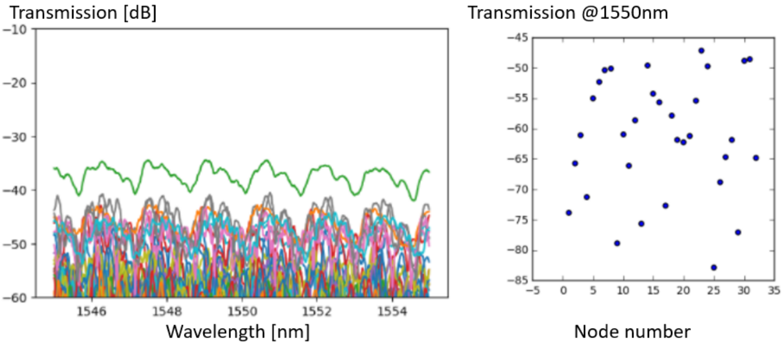


Figure 3 Left: Transmission spectra and their sum (green) of the reservoir nodes. Right: The transmission at 1550nm, for all the nodes. Below -55dB becomes challenging to measure with our high-speed equipment

From this, the total insertion loss of the reservoir was calculated to be around 24dB at 1550nm. This is more than expected and originates mainly from the larger than expected loss in the spirals. Once transmission gets below -55dBm (for individual nodes), it becomes hard to measure the signals with the high-speed equipment to perform actual machine learning tasks.

For a fully integrated reservoir computing system, the readout weights should allow control over the individual node outputs. Heater-based weighting structures were included on the mask for testing. These 700 nm heaters were included in the combiner tree, where node outputs are weighted and combined. These elements required a driving current between 30 mA to 65 mA to cover their dynamic range. However, this was not supported by the DAC used, whose current range maxes out at 30 mA.

Measurements that bypassed the optical weighting stage were possible by implementing an electrical readout. This was done by measuring the node outputs one at a time, therefore bypassing the weighting and combining stage which was beneficial for the power budget. Nonetheless, only 14 nodes could be measured while the remaining nodes had transmission levels too low to be picked up by the photodiode. The electric readouts needed to be aligned in time in a way that conserved their realistic relative timings. Measurements were conducted at 28 Gbps to realise the schematic shown on the bottom left of Figure 4. The figure also shows the measurement setup.

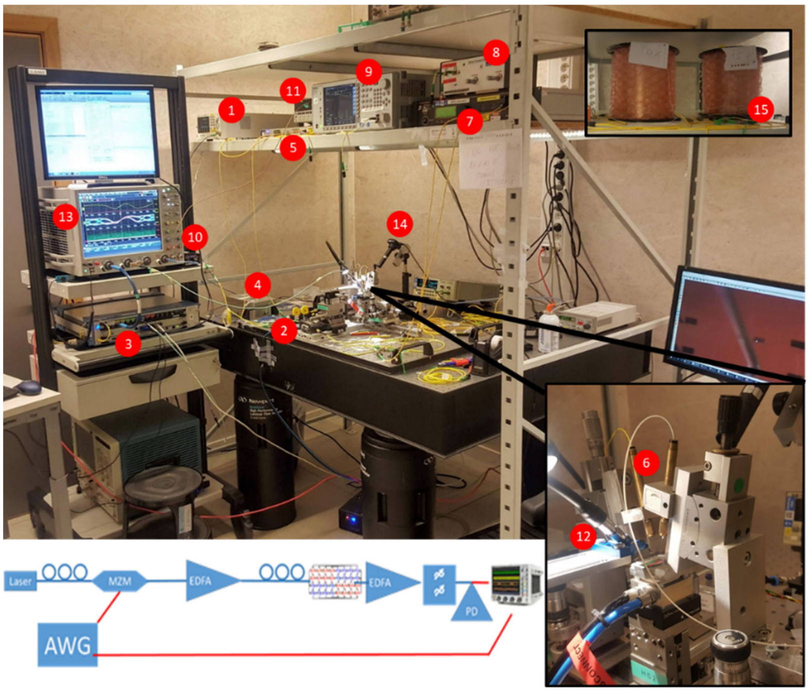


Figure 4 Measurement Setup
1: Santec TSL-510 tunable laser. 2: 3-paddle manual polarization controller.
3: arbitrary waveform generator, Keysight M8195A. 4: optical modulator (no brand, 40GBPS)
5: erbium-doped fiber amplifier (EDFA, Keopsys CEFA-C-HG) 6: Zoom-in on vertical coupling stage for optical coupling to the grating couplers on the reservoir chip. The stage is temperature controlled by a Peltier element and a water cooler as heat sink.
7: erbium doped fiber amplifier (EDFA, Keopsys CEFA-C-HG) 8: tunable filter (Santec OTF-350)
9: Optical spectrum analyzer (Anritsu) 10: Photoreceiver (Lab-buddy)
11: Keithley 2400 IV source to bias on-chip detectors. 12: Zoom in on RF (GS) probe
13: RTO (Keysight DSA-Z 634A Oscilloscope). 14: camera on the stage for fiber handling.
15: optical fiber spools (SSMF) of 10km and 15km (these fibers are not used in these first characterization measurements).

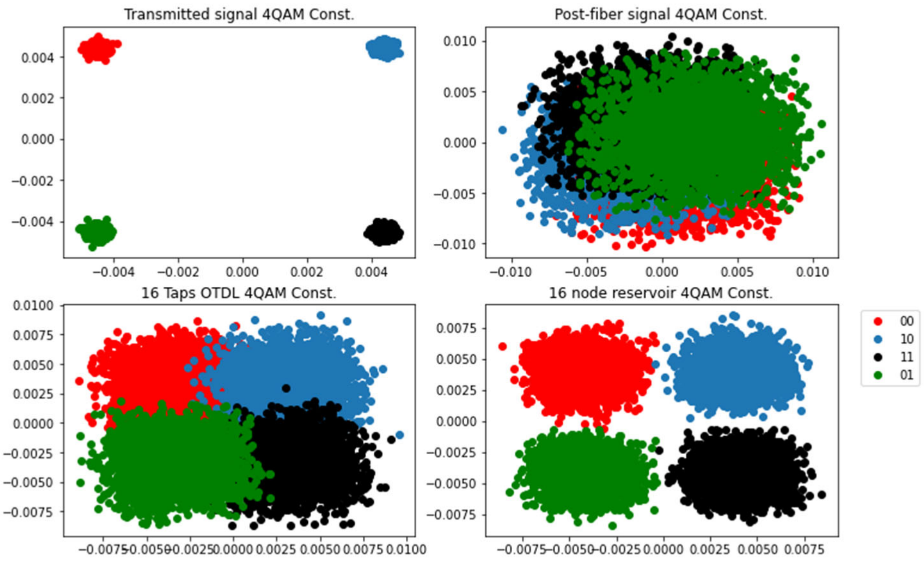
3 SIMULATIONS FOR A TELECOM APPLICATION – 4 PORT ARCH.

A Kramers Kronig receiver is a scheme for the direct detection of coherently modulated signals. While information is carried in both the phase and amplitude of the signal, the amplitude alone will suffice in extracting the phase encoded information. To make this possible, a few conditions need to be met, but primarily the presence of a large power subcarrier. The carrier to signal power ratio (CSPR) is an important attribute of the signal which will facilitate its accurate reconstruction. Thus, this high-power signal is transmitted through the fiber for direct detection at the receiver. Unfortunately, the high-power densities contained within the fiber lead to larger nonlinear effects which are challenging to compensate for.

In the receiver’s algorithm, signal processing after the detection is required to retrieve the phase information. This includes several nonlinear steps, for example exponentiating the signal. To minimize the cost associated with additional stages in the pipeline, the receiver’s nonlinear transformations are leveraged and used as the required nonlinear stage after the reservoir.

The reservoir itself is passive and performs linear mixing of the signal with past copies of itself. The weighting elements are placed at every node of the 16-node reservoir and used to weight the signals. After the weighting, the signals are summed and detected by a single photodetector. The KK algorithm then reconstructs the signal, and the signal can be compared to the target. The weight updates happen by backpropagating through the KK algorithm.

Simulations on a 4 QAM signal propagating through a 40 km fiber show very promising results. Due to the high-power carrier in the signal, nonlinear effects were present at this length. The reservoir performance was compared to that of a 16 tapped delay line (performing linear compensation) for benchmarking. In this transmission scenario, the BER was reduced to 2.9e-4 using the reservoir and limited backpropagation training (< 5 minutes). In comparison, the optical tapped delay line with 16 taps had a 3.8e-2 BER.



Transmitted signal 4QAM Const.

Post-fiber signal 4QAM Const.

16 Taps OTDL 4QAM Const.

16 node reservoir 4QAM Const.

Figure 5 Constellation diagrams for the transmitted signal (top left), unprocessed signal after the fiber (top right), processed signal using tapped delay line with 16 taps (bottom left), and processed signal using a 16-node reservoir (bottom right).

Further trials on higher modulation schemes and longer lengths are underway which include more realistic models of the transmitter and detector.

4 TIME AND FREQUENCY MULTIPLEXED RC SCHEMES

ESR 11 Tigers Jonuzi is working on the integration of Reservoir Computing (RC) scheme in a single monolithic chip. Both the photonic integration of time-multiplexed and frequency-multiplexed RC schemes have been studied, with the aim to increase the processing speeds of current optical RC approaches as well as reducing overall power consumption. The potential to fabricate a final device that co-integrates both systems for an improved parallelization will also be explored.

A first prototype for the time-multiplexed RC scheme has been already designed and currently is in fabrication phase. The aim of the device is to perform an analog readout of a delay-based optical RC, where weights are applied optically by thermal phase shifters or by amplitude modulators, and the sum of the different contributions is retrieved by coherent summation of the time-delayed neurons. The circuit consists of a network of 16 delay lines (multiple of 30 ps, which define the time distance of the neurons generated by an AWG operating at 33.33 GHz), phase shifters, and MMIs for the coherent summation of the time delayed neurons. The designed device also integrates a coherent detector to retrieve information on both amplitude and phase of the output response. The device is expected to operate at data rate of ~2 GHz.

Concerning frequency-multiplexed RC, a design concept for an integrated readout has been studied. It is based on the scheme on which ESR 12 Alessandro Lupo is working and consists of a circuit capable of filtering and attenuating, individually, the contributions of each neuron to the spectrum (wavelength) of the light propagating in the setup. Next step will be the study of the integration of the fiber loop, which would improve stability and maximum data rate.

In conclusion, we remark that all the studied integrated schemes are compatible with current optical RC implementations with the possibility to exploit either time- or frequency-multiplexing, and even a combination of both.

ESR 12 Alessandro Lupo is working on frequency-multiplexed schemes for RC. The current experimental setup is built in fiber optics (Fig. 1) and has been already demonstrated to work (arXiv:2008.11247). Recent improvements in the setup stabilization allow the experiment to run stably also in an “optical weighting” mode, in which output weights are applied optically, while the subtraction between positive weighted neurons and negative weighted neurons is still executed electronically (results to be published). The information processing speed is limited by the length of the fiber loop constituting the reservoir, which currently has a roundtrip time of 50 ns, equivalent to a data input rate of 20 MHz. The presence of the long fiber loop also sensibly contributes to the instability of the system, which requires sophisticated compensation mechanisms against drifts in operating condition and noises. Integration of this system would increase both maximum speed and stability.

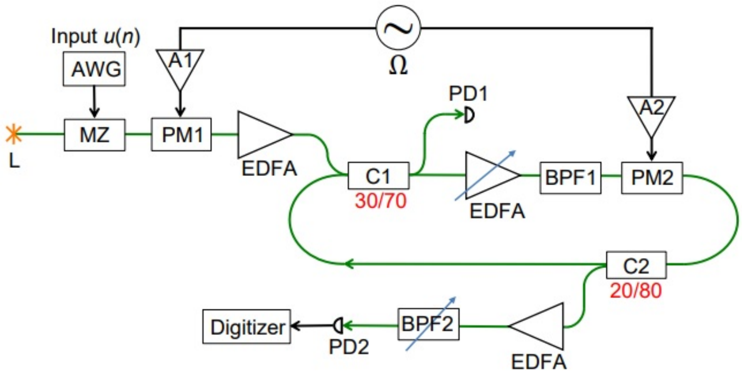


Figure 6 Frequency-Multiplexed Reservoir Computer setup. L: Laser source. AWG: Arbitrary Waveform Generator. MZ: Mach Zehnder modulator. PM: Phase Modulator. A: RF Amplifier. ~: RF source. EDFA: Erbium Doped Fiber Amplifier. BPF: BandPass Filter. C: Coupler. PD: PhotoDiode

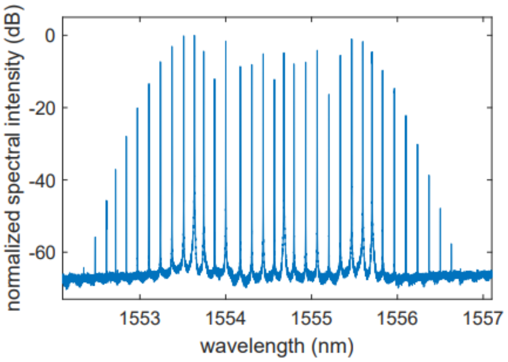


Figure 7 Spectrum of the light propagating in the setup. Each line of the frequency comb encodes the state of one neuron

In summer 2021, a collaboration between ESR 11 Tigers Jonuzi and ESR 12 Alessandro Lupo started with the intent of identifying the best solutions for the integration of the frequency-multiplexed scheme. The main integrated photonic solution, which is currently being analyzed (also experimentally, by ESR 11), is a fully optical output layer circuit that addresses the problem of summing (with signs) the weighted output variables of the reservoir. The output variables of the experimental reservoir are encoded in the intensity of different lines of a frequency comb, each line representing a neuron of the network (Fig. 2). Weights can be applied through optical attenuation, but the main problem is to execute subtractions without the aid of electronics. The scheme under study addresses this problem by exploiting cross gain modulation in SOAs to encode the two signals to subtract in two coherent light beams, so that the subtraction can be executed interferometrically.