# Photonic processing for a 56 GBaud PAM-4 100 km Transmission System

arXiv:2105.07990 [eess.SP]

Irene Estébanez[1)], Shi Li[2)], Janek Schwind[1),3)], Ingo Fischer[1)], Stephan Pachnicke[2)], and Apostolos Argyris[1)].

1) Instituto de Física Interdisciplinar y SistemasComplejos IFISC (CSIC-UIB), Campus UIB, Palma de Mallorca, 07122, Spain.
2) Chair of Communications, Kiel University, Kiel, 24143, Germany 3) Institute of Applied Physics, University of Münster, Münster, 48149, Germany

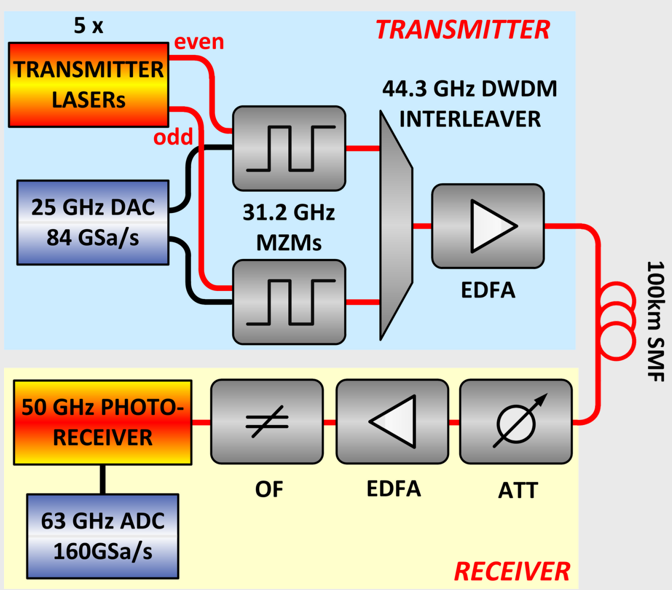
## Analog Photonic Computing Approach to Optical Transmission Systems

**Analog photonic computing** has been proposed and tested in recent years as an **alternative approach for data recovery in fiber transmission systems.** Here **we propose** to use the **two** most-approved random-projection techniques in feed-forward and recurrent neural network **approaches: extreme learning machines (ELMs)** [1] **and reservoir computing (RC)** [2]. Although in fiber transmission systems and tasks related to data recovery **the reservoir recurrency** offers an internal memory that **may prove beneficial for the computation performance** [3], we show that this is **not always** the case. We demonstrate that the effectiveness of the internal fading memory **depends** significantly **on the properties of the signal to be processed.**

## Methodology

We can distinguish 3 different stages: transmission, masking, and processing.

### 1. Transmission



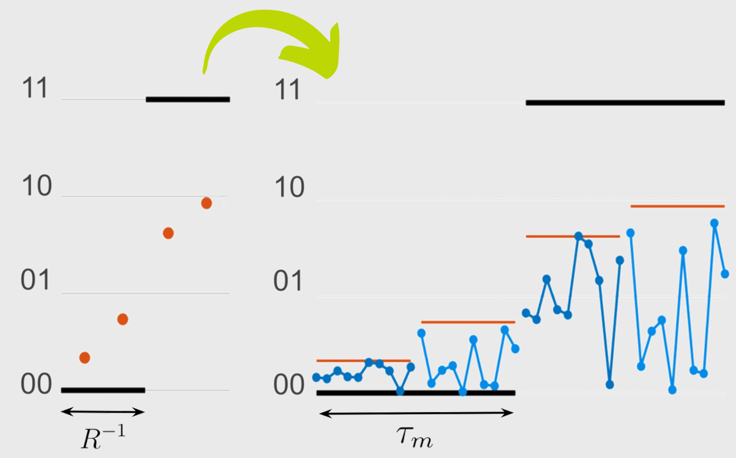

We built a **fiber transmission system** [5] with 5-channel, **56 GBaud**, dense wavelength multiplexing (**DWDM**), **100 km transmission** with **direct detection**, and 4-level pulse amplitude (**PAM-4**) with sideband (**SSB**) **enconding.**

- OSNR varied by noise loading from the second amplification unit.
- Photodetected signal acquired with 2 samples per symbol (SpS).
- Extended chromatic dispersion.

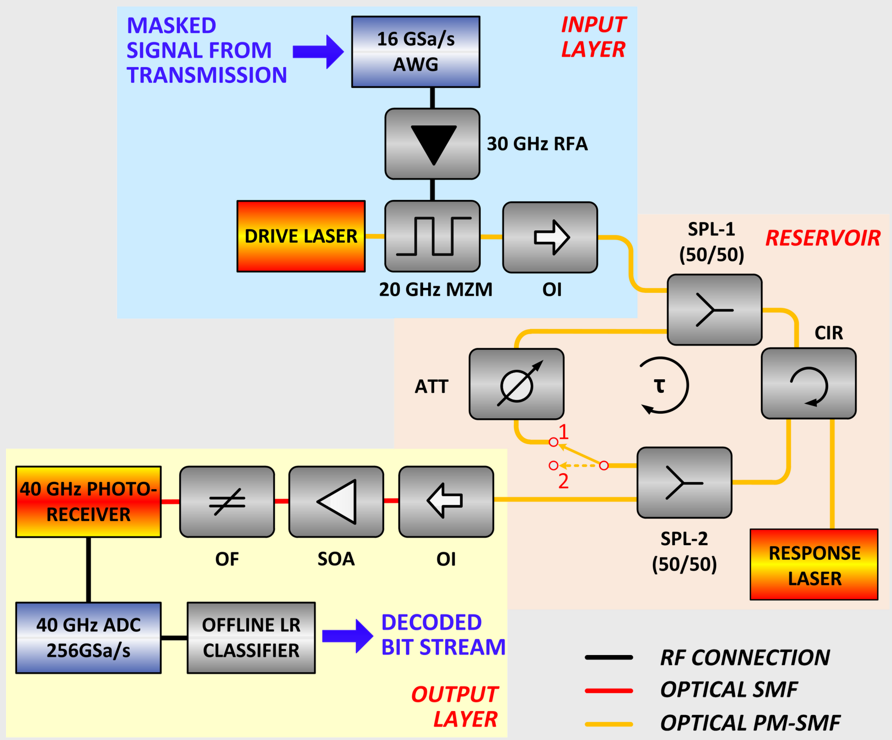
### 2. Masking

After transmission, the signal is multiplied offline with a random sequence (mask) to **expand the dimensionality** of its state-space representation.

- The **2 SpS** (red dots) are expanded to **N samples** after masking (blue dots).
- Masking introduces a **speed penalty** of $\tau_m/R$, where $\tau$ is the mask duration and R the encoding rate.
- $\tau_m = N{\cdot}\theta$, where N is the dimensionality and θ is the sampling rate.




### 3. Processing



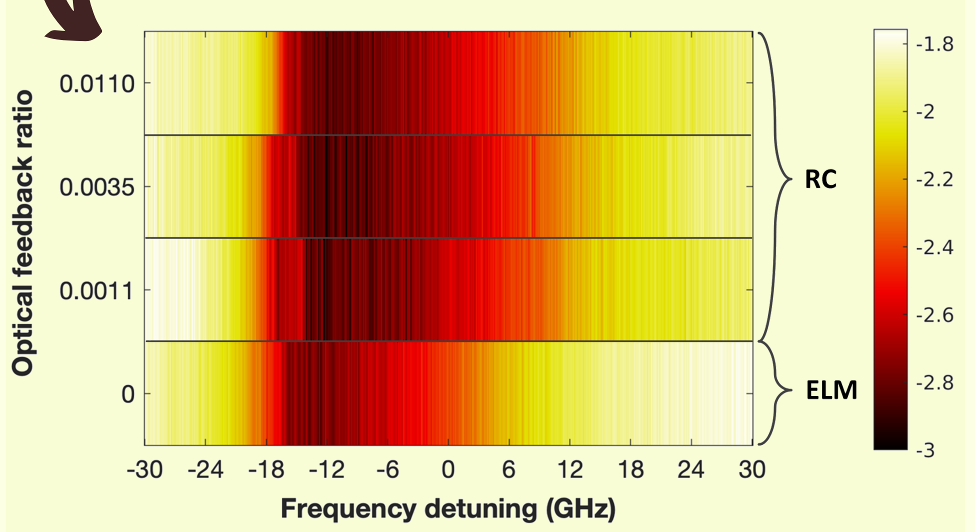

- The **masked signal** is **injected** using an arbitrary wave generator (**AWG**) plus a Mach-Zehnder modulator (**MZM**).
- Then, the information enters into the reservoir layer. This layer can behave as [4]:
  - **RC.** Switch in position 1, defining a photonic reservoir with a delay loop $\tau$ = 24.5 ns. Feedback strength varied with an attenuator.
  - **ELM.** When the switch is in position 2 the feedback is eliminated.
- The **output** stream is photodetected **to train a linear classifier** and to **evaluate** the classification **performance.**

## Comparing Different Analog Photonic Computing Methods to Kramers Kronig (KK) receiver

First, we processed **one symbol per reservoir time delay (τ)** for different optical ratios of the photonic reservoir.

- Mask dimensionality fixed to N = 20.

Below, data recovery performance ($\log_{10}$(BER)):

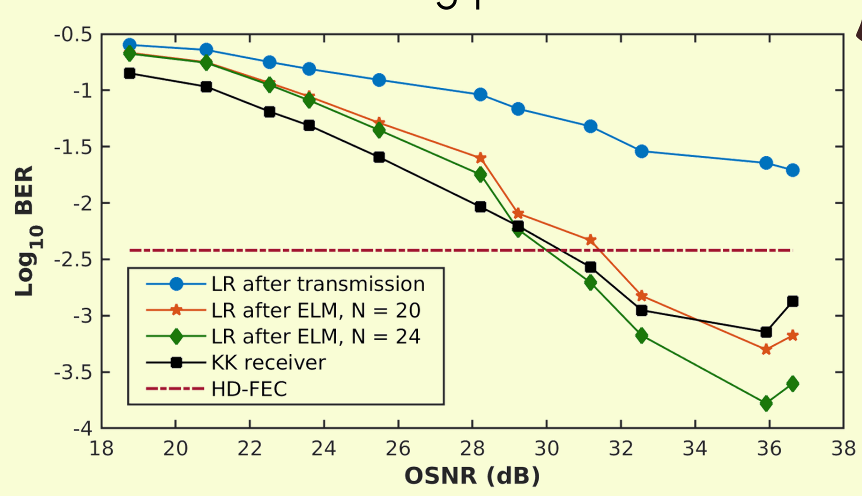



- **Lowest error rates** within the **same region** of frequency detuning: Δf ~ -16 to -8 GHz → **Partial injection locking** region.
- **Lowest BER** obtained for **moderate optical feedback** ratios ($\log_{10}$BER = -3).
- Open-loop configuration **(ELM)** yields **similar results** ($\log_{10}$BER = -2.87).

We investigate the performance for **different OSNR with the ELM** scheme:

- Simplifies the scheme
- Increases computational speed
- Connects symbols through inertia

Considering the optimal value of Δf, we obtained the following performances.




- When N = 24, the lowest $\log_{10}$BER = -3.8 for OSNR = 35.9 dB. **Improving more than 2 orders compared to KK** receiver [5,6].
- The HD-FEC BER limit is achieved for values above 30 dB for N = 24.
- This limit is increased to 31.5 dB when N = 20, but also the computational speed increases by 20%.

## Conclusions

✓ ELM system providing efficient data recovery for 56 GBaud PAM-4 DWDM 100 km.

✓ ELM~TDRC in performance, while ELM avoids disadvantages imposed by the time delay.

✓ BER performances leading error-free decoding for signal OSNRs above 30 dB.

✓ Above 30 dB, our hardware processing implementation performs even better than a DSP-implemented KK receiver.

## References

[1] G.-B. Huang, Q.-Y. Zhu, and C.-K.- Siew. Neurocomputing 70 (1-3), 2006.
[2] H. Jaeger and H. Haas. Science 304 (5667), 2004.
[3] A. Argyris, J. Bueno, and I. Fischer. Scientific Reports 8 (1), 2018.
[4] S. Ortín et al. Scientifc Reports 5 (1), 2005.
[5] S. Li, S. Ohlendorf, S. Pachnicke. ECOC 2019.
[6] S. Ohlendorf, S. Pachnicke and W. Rosenkranz. ACP 2018.

This work received funding from MINECO (Spain), through project TEC2016-80063-C3 (AEI/FEDER, UE), from the Spanish State Research Agency, through the Severo Ochoa and María de Maeztu Program for Centers and Units of Excellence in R&D (MDM-2017-0711) and from the European Union's Horizon 2020 Research and Innovation Programme under the Marie-Skłodowska Curie grant agreement No 860360.