Exploring the bandwidth-limited readout in coherent photonic reservoir computing

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Summary. In this work, we shed light on an essential component in photonic reservoir computing: the photodetector. Through numerical investigations, we showcase the effects of its bandwidth-limited response on the performance of a coherent time-multiplexed system on two different benchmark tasks: the bitwise XOR and the Santa Fe time-series. Our results suggest that fast sampling of lower bandwidth (i.e. slower) photodetectors might improve overall prediction accuracy.

Historically, reservoir computing (RC) emerged in the early 2000s to circumvent the limitations of training deep neural networks. With the progress in deep learning during the 2010s, the bulk of interest in RC has been redirected towards physical implementations. Many photonic implementations have been explored in the literature, driven in large part by the promise of high speeds and low energy consumption. In the first on-chip silicon photonics demonstration of RC [1], it was shown that a largely passive, linear photonic system can be used for RC as the readout is performed anyway with a photodetector, which provides a sufficient nonlinearity by producing an output that is proportional to the square of the electric field. Indeed, this is mainly the case for interference-based coherent systems (i.e. operating on a single wavelength), as the complex-valued electric fields do add up linearly, but their corresponding intensities do not. For the simple case of interference between two beams of identical wavelengths and with optical intensities I_1 and I_2 and phase difference of $\Delta\phi$, the resultant intensity I_{res} is:

$$I_{res} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\phi) \tag{1}$$

Considering two independent, non-interfering beams, the last term is dropped and the intensity of the sum of the two beams becomes equivalent to the sum of their individual intensities. What this entails is that, as long as there are paths for optical interference, one can indeed imply that the nonlinearity is being done at the readout stage, due to the nonlinear dependence of the total intensity on the phase shift between the different participating beams. This is particularly the case for all-optical coherent RC implementations [1, 2, 3], and also in the optical perceptron [4]. On the other hand, in the case of the optoelectronic approach [5], the photodetector participates purely as a readout mechanism, as there are no paths in the optical part of the system which lead to interference. Thus, the standard photodetector itself does not 'perform' any nonlinearity (a slight semantic inaccuracy sometimes in the literature), it simply emerges from the act of probing the corresponding intensity of multiple interfering fields. Complex temporal dynamics can be achieved by using simple passive elements and providing optical feedback, which can be done using a variant of our recently proposed architecture in [3], as shown in Fig.1. Varying the phase shift on one of the waveguides allows the reconfiguration of the rich temporal dynamics of the system.

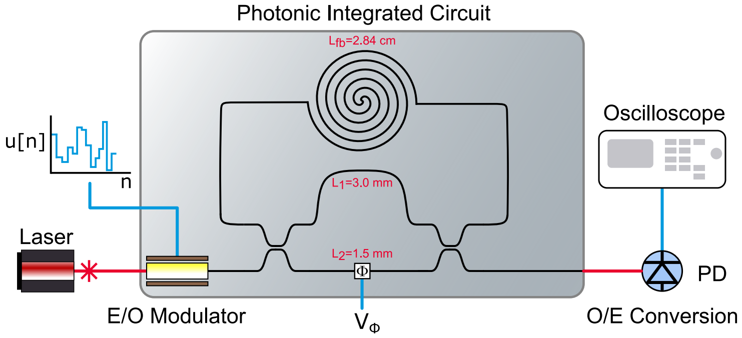

Figure 1: Conceptual diagram of the system. A modulator and a photodetector (both can be either integrated or off-chip) perform the electro-optic and optoelectronic conversions, respectively. Passive waveguides in feedback yield rich interference patterns. The delay line can also be integrated by leveraging (for example) the low-loss lithium niobate on insulator platform.

One could thus utilize this 'free' nonlinearity as long as:

1. The system is perturbed periodically within the timescale of its own dynamics, governed by the optical path lengths experienced by the signal before it gets to the readout;
2. There is no requirement for many physical nodes/layers.

In the act of probing the time-averaged optical intensity, the photodetector 'imprints' associated noise on the signal as well as a filter-like response due to the imposed RF-bandwidth limitations from the detector electronics. In most implementations so far, a high-speed detector is assumed beneficial as it would capture more of the optical dynamics. In this investigation, the output is passed through different p-i-n photodetectors (modeled with associated noise and a subsequent 4th order butterworth filter), and a fixed sampling rate of 40GSa/s so as to realize 20 time-multiplexed nodes obtained by a high-speed oscilloscope. Furthermore, the input mask - normally used in time-delay RC - is no longer considered so as to simplify the study. The output is used to train (using 1000 examples) a least-squares regression model, which is then applied on a test set of another 1000 samples. The prediction accuracy is then assessed using the bit error rate (BER) and normalized mean square error (NMSE) metrics.

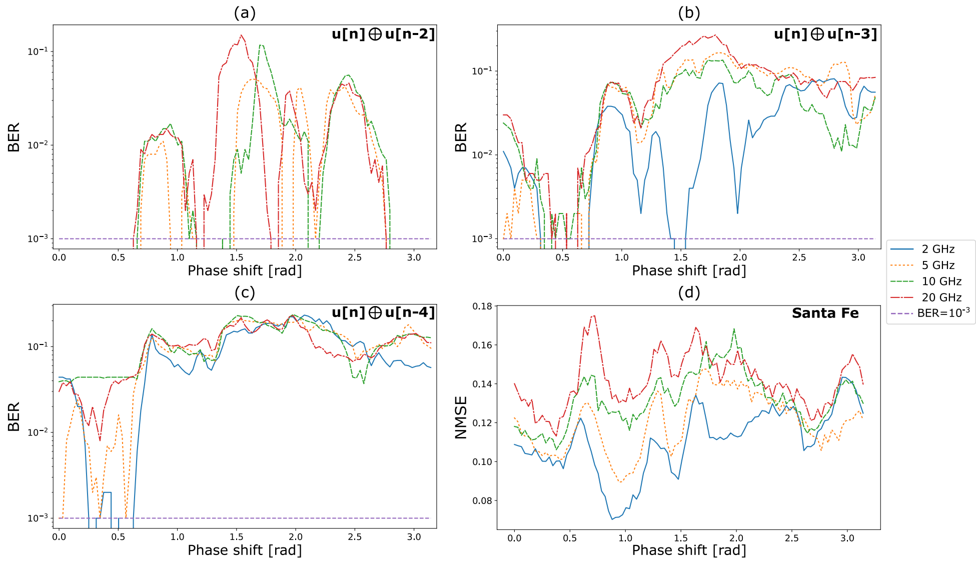

Figure 2: Results for XOR with (a) two, (b) three, and (c) four bits into the past, and (d) Santa Fe time-series prediction.

The results shown in Fig 2 consistently show better performance for slower photodetectors. For the temporal bitwise XOR task, the results for $u[n] \oplus u[n-1]$ are not shown as BER=0 everywhere. In Fig. 2(a) the BER remains below the accepted value using a 2 GHz photodetector. Furthermore, the BER is consistently lower for the slower detectors, as shown in (b),(c). The results for the one-step ahead Santa Fe prediction follow a similar trend. These preliminary findings suggest that engineering the readout mechanism, which is often neglected, can provide nontrivial gains which can be as important as engineering the complex system (reservoir) itself. In this case, it is due to the fact that we take into account the additional timescales introduced by the photodetector's bandwidth. Moreover, having slower detectors allows to relax some constraints in terms of responsivity, noise, and overall design.

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