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# A novel experimental approach for information processing in photonics

M. C. Soriano[1], D. Brunner[1], L. Appeltant[2], C. R. Mirasso[1], I. Fischer[1] and L. Larger[3]

[1] Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC) CSIC-UIB,
Campus Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
[2] Applied Physics Research Group (APHY), Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Bruxelles, Belgium
[3]Institut FEMTO-ST, CNRS UMR 6174, Université de Franche-Comté, Besançon 25030 Cedex, France
Email: miguel@ifisc.uib-csic.es

**Abstract**—In recent years, the dynamical properties of nonlinear optical systems with delay have inspired various new applications. Chaos-based optical communications and encryption, generation of random numbers, microwave generation and chaotic lidars benefit from the peculiar properties of these dynamical systems. In this work, we propose a novel scheme in which photonic information processing can be performed using an optical system with delayed feedback. Unlike traditional computers, where the processing of information is typically handled in a sequential manner, a novel computational paradigm known as reservoir computing has recently emerged. It shows that complex networks of nonlinear dynamical elements can perform efficient information processing by emulating the way our brain process information. We show that the complex network can be replaced by a single optoelectronic oscillator with delay without loosing performance.

## 1. Dynamical systems with delay

Delayed feedback can have a significant impact on the dynamical behavior of a wide variety of phenomena in life sciences, physics and technology, chemistry and economics [1]. It can e.g. lead to characteristic instabilities, induce synchronization between subsystems, or also lead to stabilization. The presence of a delayed feedback implies that the phase space of the system becomes mathematically infinite dimensional, as the current state of the system is defined by a continuous function in the interval $[t-\tau, t[$, with $\tau$ being the delay time.

Delayed feedback systems have been extensively studied in the literature. The typical evolution equation for a delayed feedback system is

$$\frac{dx(t)}{dt} = F(x(t), x(t-\tau)), \qquad (1)$$

where $F$ describes a dynamical system with an intrinsic time scale $T$. If the delay time is comparable or larger than the intrinsic time scale of the system, new dynamical states can arise in the system.

In practice, optical systems with delayed feedback have turned out to be versatile systems for novel applications such as chaos communications [2], random number generation [3], and generation of ultra-high spectral purity microwaves [4]. Furthermore, a single nonlinear electronic oscillator with delayed feedback, the simplest form of a delayed system, can perform information processing with very good results in speech recognition and time series prediction tasks [5].

## 2. New approaches for information processing

Reservoir computing [6, 7, 8] is a recently introduced computing paradigm inspired in the way our brain appears to process information. In conventional reservoir computing, a recurrent neural network (RNN) is used as a reservoir that is not trained but instead read out by a simple external classification layer. This recurrent network can perform information processing by using the transient response occurring in a complex system due to an input signal. It has been shown that reservoir computing serves universal computational properties; any potential operation could be realized, outperforming other approaches for certain tasks [7, 9]. While numerical implementations of this concept exist, optical hardware implementations are still lacking.

In this context, we propose to employ simple delay systems instead of complex networks without losing functionality. Such architectures reduce the usually required large number of nodes to only few, or even one nonlinear element with delayed coupling. Delay systems indeed fulfill the required demands of high-dimensionality and fading memory, essentials for reservoir computing [5]. The suggested approach simplifies the reservoir computing concept, opening new perspectives for high-speed photonics implementations. Using delay systems, similar or even better performances than conventional reservoir computing approaches are likely to be expected in certain tasks, as recently proposed in the European Project PHOCUS (www.ifisc.uib-csic.es/phocus).

## 3. Experimental implementation

Our hardware implementation of the reservoir computing concept is based on an optoelectronic oscillator with delay, which is depicted in Figure 1. This optoelectronic oscillator is capable of allowing the dynamical regimes typically observed for the Ikeda low pass dynamics, including a period doubling route to chaos [10, 11]. Figure 2 shows the power spectrum of the oscillator response once the system is driven into the chaotic regime [12]. As it can be seen in Fig. 2, relevant spectral contributions can be estimated up to ~ 6 MHz.

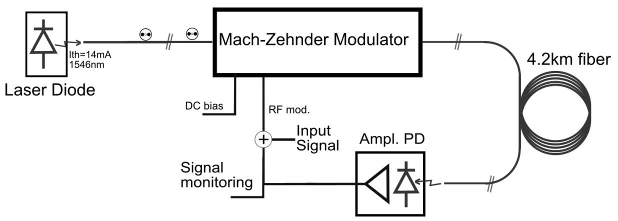


Figure 1: The experimental implementation is composed by a semiconductor laser diode, an integrated optics Mach-Zehnder modulator performing a sine squared non-linear transformation, a fiber delay line, and an optoelectronic feedback for intensity detection, linear filtering, and amplification. This feedback serves as the drive of the MZ modulator, closing the delayed oscillation loop (delay time 21$\mu$s).

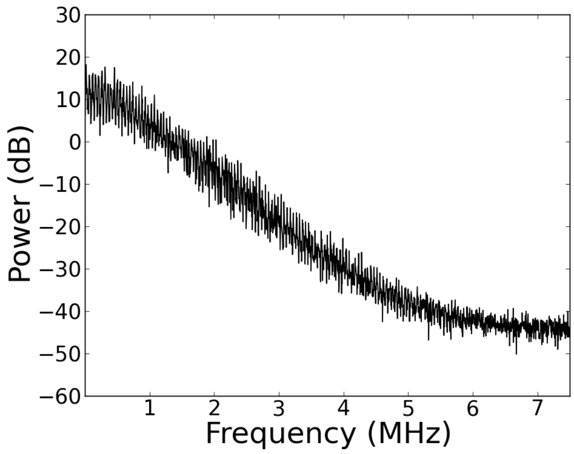


Figure 2: Experimentally recorded power spectrum of the delayed optoelectronic oscillator operating in the chaotic regime.

The implementation of a photonic realization of reservoir computing with an optoelectronic oscillator allows for information processing at MHz speeds. However, all-optical photonic implementations can eventually push the information processing speed towards the GHz range.

In order to evaluate the capability of the nonlinear optoelectronic oscillator to process information, we test the performance of the system to solve several given benchmark tasks. As an example, we show in Fig. 3, the response of the optoelectronic oscillator for a sample digit in a spoken digit recognition task [13, 14]. The black curve in Fig. 3 is the input signal (pre-processed audio waveform) and the gray curve is the nonlinear response. The nonlinear transformation performed by the optolectronic oscillator allows a better classification of the spoken digits. For the information processing, each sample of the input signal is expanded over a time interval of length 21$\mu$s (delay time) and multiplied by a processing mask before is injected into the nonlinear oscillator [5].

For reservoir computing purposes, the optoelectronic oscillator is biased in a stable regime (fixed point of the dynamics) without external input. However, the addition of an external input induces a complex transient response in the dynamical system. The classification task is improved by exploiting the transient response of the system to each sample digit.

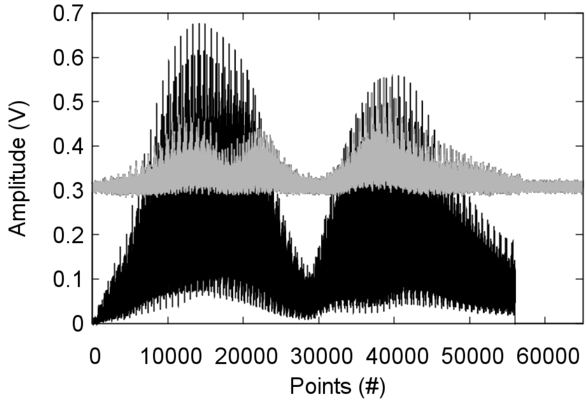


Figure 3: Nonlinear response of the optoelectronic oscillator (gray) for a sample digit (black) in a spoken digit recognition task.

The experimental hardware realization of the optoelectronic oscillator with delay feedback can be described by the following dynamical equation[15]:

$$\frac{dx(t')}{dt'} = -x(t') + \beta \sin^2[x(t' - \tau) + \varphi + u_I(t' - \tau)], \quad (2)$$

where $t'$ is the time in normalized units ($t' = t/(240 \text{ ns})$, $\beta$ is the feedback strength, $\tau$ is the delay time, $\varphi$ is the Mach-Zehnder phase and $u_I(t')$ is the external input signal. The parameters have been rescaled to match the experimental conditions and the external input signal is added as a modulation of the Mach-Zehnder.

A detailed numerical study allows for the search of the parameters leading to an optimum performance of this optical system with delay for reservoir computing purposes.

## 4. Results and discussion

Our preliminary results show that an optoelectronic oscillator with delayed feedback can indeed replace a complex network and perform information processing. For instance, we have found that this dynamical system is capable of identifying isolated spoken digits with a good performace. We report a single misclassification in 500 independent digits after the system has been trained (0.2% word error rate). In Figure 4, we show the word error rate as a function of the Mach-Zehnder phase for $\beta = 0.4$. The best performance (lowest error) is obtained for $\varphi \sim 0,\ \pi/2,$ and $\pi$.

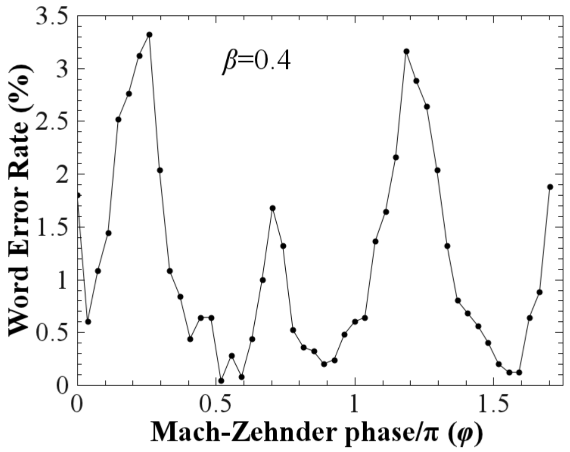


Figure 4: Word error rate (%) in a spoken digit recognition task as a function of the Mach-Zehnder phase.

Besides the spoken digit recognition task, reservoir computing has been successfully applied to pattern classification, time series prediction, noise modelling and robotics [8]. Delay systems as a new method to achieve reservoir computing inherits its basic properties. Therefore, we expect this research to have an impact not only in information science, but also in dynamical systems, neuroscience, photonics and electronics.

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