High-Speed Neuro-Inspired Information Processing Using Semiconductor Lasers

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Abstract– Photonic information processing has regained considerable interest due to the possibility to implement neuro-inspired concept in photonics hardware using delayed feedback systems. Employing induced transient dynamics of a semiconductor laser with delayed feedback, we can perform optical information processing at high data rates. Via time-multiplexing, we emulate a complex nonlinear photonic network using only a single or few lasers. Based on the induced dynamics of the network, classification tasks, time series prediction tasks, as well as vector and matrix operations can be implemented. Excellent performance can be achieved injecting the information all-optically at rates up to several GSamples/s.

1. Introduction

To learn from the brain how to process information has been a fascinating perspective for several decades. Many advances have been made, and powerful computational schemes have been introduced. Reservoir computing (RC) is a particularly promising approach, allowing the processing of sequential information using very simple training techniques. Nevertheless, even basic mechanisms and requirements of neural information processing remain unclear.

In order to gain more insights, we choose a minimal design approach [1], allowing for the implementation of neuro-inspired computational concepts and in particular RC in photonics hardware. In the original RC concept, nonlinear transients were induced in a reservoir of multiple, randomly interconnected nonlinear elements [2], [3]. By using time-multiplexing and data pre-processing, such a nonlinear network can be realized with a single nonlinear element [1]. By reducing reservoir computing and related concepts to their bare essentials, we find that nonlinear transient responses of a simple nonlinear photonic system enable the processing of information with unprecedented performance and speed [4,5,6]. A single dynamical element with a delayed feedback loop suffices and moreover, allows us to investigate the underlying mechanisms and properties.

Besides the relevance for the understanding of basic mechanisms, this approach opens direct technological opportunities.

2. Experimental Implementation

Our experimental implementation of reservoir computing is based on a semiconductor laser with delayed optical feedback, into which information can be injected for processing purposes. Injection of information can be obtained either electrically by direct current modulation or all-optically. The experimental scheme is depicted in Fig. 1. The semiconductor laser used in the experiments is a standard edge emitting laser with an emission wavelength of λ=1542nm and a solitary threshold current of $I_{th,bias}$=7.7 mA. The emission of the laser, is collected using free-space optics, and injected into a fiber-optical delay line. Changing the distance of collimating and focusing optics using the translation of the manual positioner, allows for accurate control of the delay time of the optical feedback. Alternatively, we have employed a packaged fiber-coupled laser. Polarization controllers and variable attenuators set the feedback conditions. A tunable laser serves as injection source, with information being encoded in the amplitude modulation using a Mach-Zehnder (MZ) modulator. The arbitrary waveform generator (AWG) provides the information to be injected. For the case of electronic signal injection, the AWG directly modulates the laser pump current via a Bias-Tee. The response of the laser to the injected signal is recorded using a fast photo-diode.

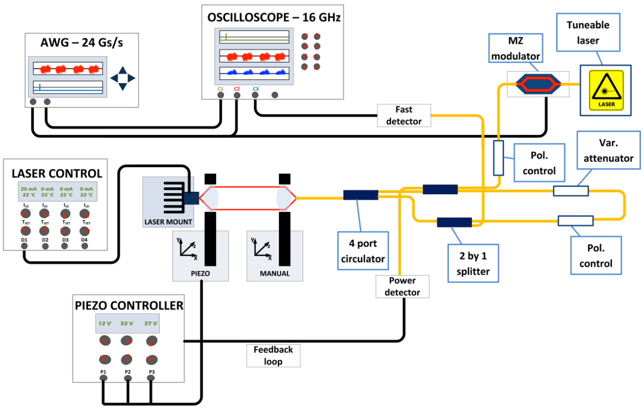


Figure 1: Schematic illustration of the reservoir computing setup using a semiconductor laser with delayed optical feedback.

3. Performance

Employing this setup for information processing, we find that the performance is optimized when the timing of the input injection and the delayed feedback are properly matched. Therefore, the delay of the optical feedback is adjusted to the clock signal of the injected information, chosen both as 77.6 ns. With this roundtrip delay we obtain a reservoir with N=388 virtual nodes.

Our scheme allows for optical and electronic information injection methods. Since the two methods perturb the laser differently, also the transient responses of the laser are significantly different. While the electrical modulation acts on the population inversion of the laser, the optical injection might even be utilized to injection lock the delayed-feedback laser to the injected information.

We illustrate the performance of this system with results implementing the spoken digit recognition task, which is a standard benchmark test for machine learning techniques. The spoken digit database comprises 500 isolated digits, spoken by five females speakers repeating the digits from 0 to 9 ten times each. In Fig. 2 we depict the obtained word error rates (WER) for the two types of information injection. In both experiments, the optical feedback was set to polarization-rotated optical feedback (PROF) and attenuated by 20 dB. The electrical signal had a modulation amplitude of ~8 mA. The optical signal was embedded in the intensity modulation of an external injection laser, which was aligned in wavelength to the delay-feedback lasers' emission to an accuracy of $\lambda_{inj}=\lambda \pm$ 0.4 GHz. The injection data rate in both cases was 5 Giga samples per second. For optical injection and a bias current close to threshold, we achieve a practically zero word error rate (0.014+0.051/-0.014)%. Using electrical injection, we achieve a still very competitive error rate of (0.64±0.17)% [5].

To demonstrate the parallel information processing capabilities of RC, we used the same reservoir responses to train 5 additional classifiers for speaker recognition using optical information injection. The results are depicted in Fig. 2 b). Speaker recognition errors of below 1% have been achieved, illustrating that different tasks can be performed simultaneously with good performance at the same operating point of the reservoir.

A second class of problems that we tested is the prediction of a nonlinear dynamical system. In this test, we use the Santa Fe Time Series Competition data, which originates from experimental data of a chaotic laser in a dynamical regime well described by the Lorenz attractor. We particularly studied the prediction error and its dependence on the laser bias current and the attenuation of the parallel optical feedback. Results are shown in Fig. 3, comprising the bias current and feedback dependence.

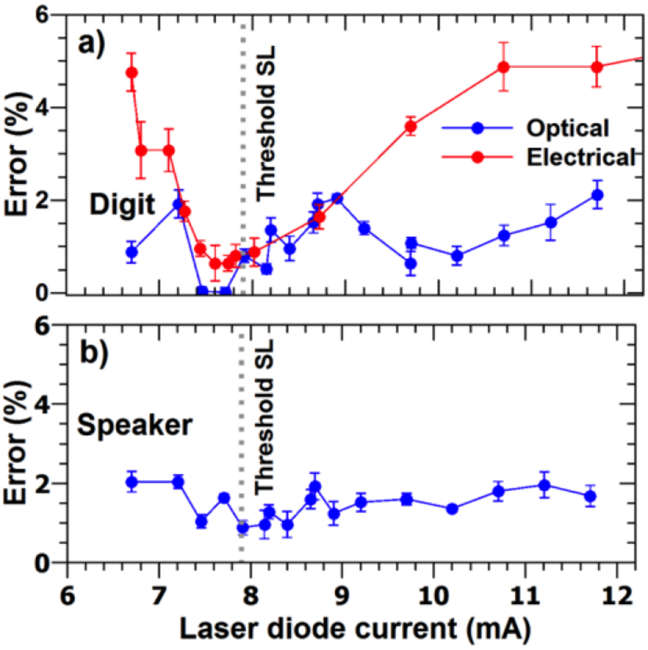
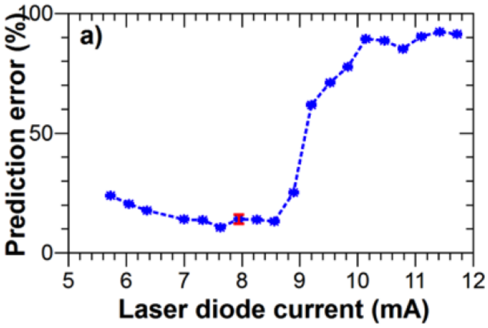


Figure 2: a) Spoken digit recognition using optical and electrical signal injection. Optical feedback was polarization-rotated and attenuated by 20 dB. For optical injection, a word error rate of 0.014 % is achieved. b) Parallel speaker identification, utilizing the identical reservoir response as in a).

Using I_{bias}=7.6 mA, optical feedback aligned parallel to the laser emission and attenuated by 10 dB, we achieve high-quality chaotic time-series prediction, resulting in a prediction error of 9.9%. By averaging 5 transients this can be further lowered to 5.5%. The importance of consistency can be recognized from both dependencies depicted in panel a) and b). Already a minor increase of feedback attenuation or pump current results in a significant performance reduction. This is due to a loss in consistent responses originating from delayed feedback instabilities. Moreover, for low current values, the delayed-feedback laser remains locked to the injection laser. At higher current values, the injection-locking is lost and characteristic features of the injected information are no longer reflected in the reservoir's transient responses.



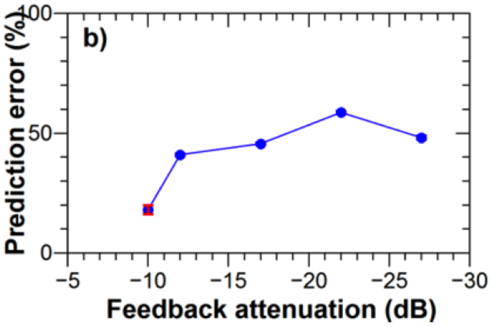


Figure 3. a) Time-series prediction performance in dependence on the bias current and b) on the feedback attenuation.

Besides the aforementioned tasks, we have performed optical computation at high data rates, comprising multiplication of a scalar with a vector, vector dot and cross products, and the multiplication of a matrix and a vector, using the same system [6]. In contrast to the experiments before, we just opened the feedback loop, since in this task no memory is required. Information was injected all-optically at a rate of 5 Giga Samples per second, corresponding up to $5 \cdot 10^8$ operations per second . Each of the individual tasks posed a different computational challenge to the system. Multiplying a vector by a scalar could be achieved with as little as 10 transient states, with an error corresponding to about 4% for ≥15 transients. More demanding calculations like vector dot and cross product resulted in approximately twice the error as compared to the scalar multiplication for a network size of >30 (virtual) nodes. The most computationally demanding task was the multiplication of a vector by a matrix. For a size of the network of ≥50 the lowest error achieved was similar to the one for vector dot and cross product. For all reported tasks, the error between computed values and their targets was significantly below 10% for computations based on more than 25 transients. Given the data input sampling rate, this corresponds nominally to a range of $5 \cdot 10^7$ to $5 \cdot 10^8$ operations per seconds for computations using between 10 and 100 transients, respectively. For each operation, the computation accuracy approached or exceeded 4 Bit resolution, which was mostly limited by about 5% detection noise in our experiments.

4. Towards multiple lasers

The question arises, in how far one can extend the system towards multiple lasers, thereby improving performance or speed. In order to explore this potential, we implemented a scheme using a single laser with a modified data injection scheme, emulating identical, yet uncoupled, reservoirs. To that end, we divide the delay time in multiple sections as depicted in Fig. 4. Therefore, when emulating multiple reservoirs, we keep the total number of (virtual) nodes in the reservoirs fixed. To emulate two uncoupled reservoirs, we injected information for the first 194 nodes of the delay, while leaving the remaining 194 empty. After all data of the first reservoir was injected, the procedure was repeated a second time. In the second step, however, the first half of the delay was kept empty, with data now being injected into the second half of the nodes. The injection mask was similarly split into multiple sections. We performed such experiments for two and four uncoupled reservoirs. In particular, we divide the delay in equal sections for the emulation of two or four uncoupled reservoirs. Since all of the emulated reservoirs are embedded using the same laser diode and setup, parameter variations within the reservoirs should be small.

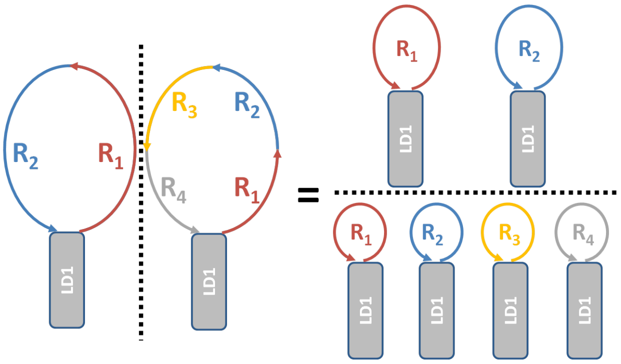


Figure 4: Emulating multiple uncoupled delay-reservoirs using one delayed feedback system.

In these experiments, the laser bias current was set to I_{bias}=7.7 mA, the feedback attenuation was chosen as 20 dB. Results of these experiments are depicted in Fig. 5. Using a single reservoir only, we obtain a word error rate approaching 0%. This performance remained unchanged for two uncoupled reservoirs. This means that by using two uncoupled reservoirs the overall processing speed can be doubled. For four uncoupled reservoirs the error increased from 0% to about 1%. Analyzing the distribution of the readout weights showed that in the case of multiple reservoirs, the training procedure of the system resulted in a significant suppression of one or multiple reservoirs. But overall, these results demonstrate that a trade-off between processing speed and hardware complexity can be achieved.

3. Conclusions

Using a semiconductor laser system with delayed optical feedback, fast and parallel information processing can be realized. Excellent performance in terms of accuracy and speed have been achieved for tasks comprising spoken digit recognition, time series prediction and vector and matrix operations. By combining multiple reservoirs, we showed that the processing speed of the system can be further significantly increased. This potential is further highlighted by several other optical schemes implementing optical reservoir computing. These comprise optoelectronic systems [4,7], all-optical systems based on semiconductor lasers [5,6] or semiconductor optical amplifiers [8] and silicon photonics [9].

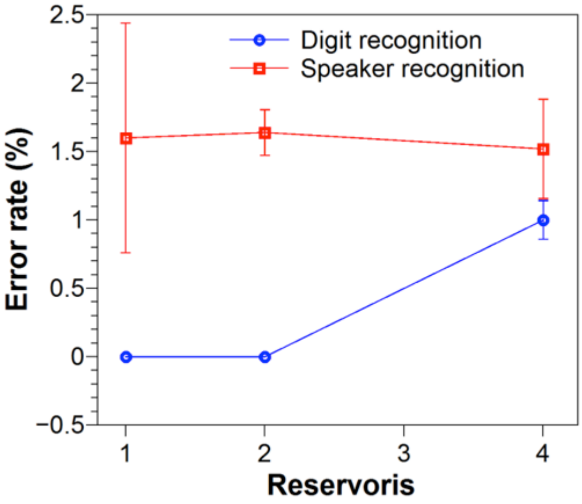


Figure 5: Digit and speaker recognition using multiple uncoupled reservoirs, embedded in one device. For more than 2 reservoirs, the error rate for spoken digit recognition increases significantly.

Acknowledgments

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