Photonic information processing using multi-mode semiconductor lasers with delayed feedback

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Optical implementations of reservoir computing systems have shown great promise. They can be implemented using semiconductor lasers subject to delayed feedback. Currently, these systems rely on long delay lines, which are hard to integrate on chip. We propose to use semiconductor lasers with multiple longitudinal modes to distribute the computational power over more than one optical wavelength. As such, both the delay line can be shortened and the processing speeds will increase. Due to complex modal interactions, better computational performance on several benchmark tasks are obtained compared to single mode systems and this for a wide range of mode separations.

General introduction

The brain is indisputably the most intriguing organ we possess. It has barely the size of a small ball and a power-consumption of 20 Watts, but still is able to manage physical, hormonal, cognitive and other bodily functions, simultaneously. At the base of this immense (parallel) computing power of the brain lies a large and complex neural network. Not surprisingly, lots of research has been done to imitate the brain by developing artificial neural networks (ANN). These ANN consists of thousands, if not millions, of artificial neurons, which have a certain activation function, and are (pseudo-)randomly linked to each other. Each of the links has a certain weight, that determines how much one neuron couples to the other. During the training procedure, a certain signal is fed into the network and the output layer is observed. If the output is not matching with the expected value, then the weights of the links are tuned, so that an acceptable output is observed for all training data-points. One can imagine that this training procedure becomes very time-consuming and demanding as the number of links increase.

Reservoir computing

Reservoir computing (RC) [1] is a relatively new paradigm in brain-inspired computing techniques. In RC the output layer of the ANN is explicitly split from the rest of the network, effectively creating a reservoir and the output layer, as shown in Figure 1. The links and their corresponding weights in the reservoir are kept fixed for all purposes. Only the links leaving from the reservoir to the output layer are considered during training. This drastically simplifies the training-procedure, because it boils down to solving a least square problem for a single set of equations.
The reservoir can be regarded as a complex dynamical system and as such can be implemented in various physical systems, such as a bucket of water [2] or a VLSI chip [3]. The advantage of implementing the reservoir in a physical system is that there is no need for a CPU to simulate the neurons, which may prove to be more energy-efficient. In 2008 Vandoorne *et al.* [4] were the first to suggest a photonic implementation of RC. This caused a lot of research to be started in optical domain reservoir computing.

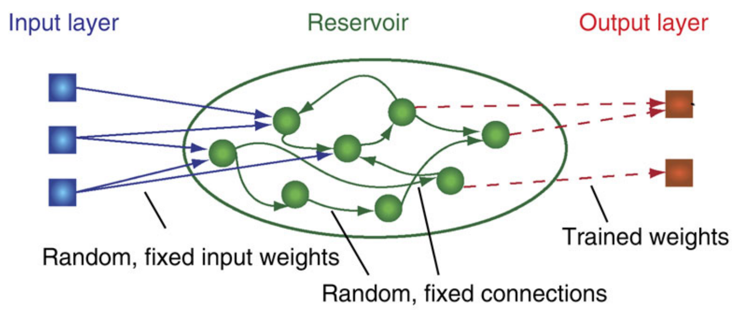

Figure 1: Network topology of a Reservoir computer. Adapted from [5]

RC based on delayed feedback

A compact implementation of RC is based on delayed feedback from a single dynamical node [5]. Instead of having multiple neurons randomly connected to each other as shown in Figure 1, there is only one neuron that feeds its output back to itself, as shown in Figure 2. The input stream to this single nonlinear node needs to be preprocessed in a way such that the single node can perform as multiple nodes. The input-stream is first made to be piecewise constant for an interval τ, which is the time needed to traverse the feedback loop. Then it is multiplied with a periodic mask that is piecewise constant over N intervals of duration θ, which we call the node-separation. Finally this preprocessed signal is fed into the nonlinear node. The piecewise constant character of the mask assures that the nonlinear node will have a different response for each interval. This creates virtual nodes in the feedback loop, whose values can be accessed by sampling the output response at a rate which corresponds to the node-separation θ. These virtual node values can be combined in a last output layer. It is clear that Figures 1 and 2 are in fact very similar, the difference only lies in the fact that in Figure 1 the neurons are functioning parallel, whereas in Figure 2 one neuron generates different node-values sequentially.
This technique is well suited for an optical implementation and recently experimental results were obtained for an optoelectronic implementation [6]. Brunner *et al.* [7], however, experimented with a fully optical reservoir computer, where a single-mode semiconductor laser (SL) is used as nonlinear node and is subjected to feedback. As the cavity also forms a part of the feedback loop, we get a very rich interaction between injected and feedback data through the optical fields as well as the carrier distribution. In their experiment, Brunner *et al.* used a mask that creates $N = 388$ nodes with $\theta = 200$ps node-separation, which corresponds to a fiber-loop of 16m. This is fairly long and needs to be reduced drastically, if we want to move towards on-chip reservoir computers. Nguimdo *et al.* [8] showed that the node separation can be reduced further down to 20ps, if phase dynamics are also taken into consideration.
In order to look for other methods of reducing the loop-length, we suggest to use a multi-mode semiconductor laser (SL) as single nonlinear node. We explore whether it is possible to distribute the computational power over the different modes or wavelengths.

RC-model with two-mode SL

To simulate the two-mode semiconductor laser, we have used the rate equation model as described by Lenstra and Yousefi [9]. This model not only considers the complex modal

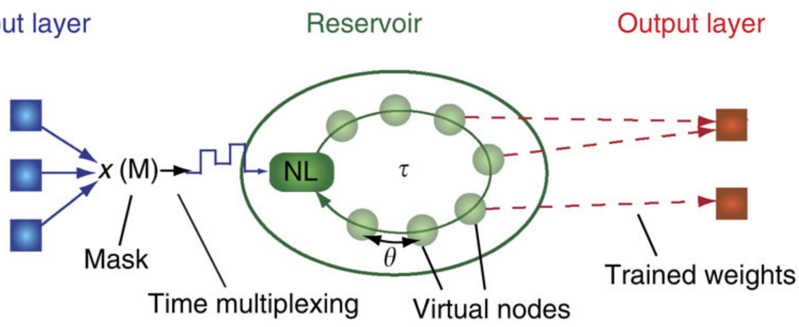

Figure 2: Schematic depiction of a reservoir computer based on delayed feedback. Adapted from [5]

fields, but also takes into account the periodic gratings induced in the carrier distribution by spatial hole burning. The model can easily be extended to higher number of modes, as well as extended to include optical injection and feedback.

The performance of this RC-model is tested using the Santa Fe laser generated time-series [10]. The task is to do a one-step-ahead time-series prediction. The performance is measured using the Normalized Mean Square Error (NMSE), which can take up any positive value, where a lower NMSE denotes a better performance.

The performance of the RC-model as a function of injection current improves as the injection current rises, until the SL goes into a chaotic regime, then the performance worsens drastically. This behavior is in accordance with that observed in the RC-model with a single-mode SL. The performance as a function of the the intermode spacing, which is depicted in Figure 3, shows that there is an optimal window of mode-spacing where the performance is good, namely between 1 and 100GHz. If the intermode spacing is under this interval, then the interaction between the modes gets too strong and destabilizes the system. On the other hand if the intermode spacing is too big, then the modes start behaving as two independent lasers.

We consider an RC with $N = 200$ nodes and a node separation of $\theta = 20$ps. The best performance observed in the two-mode RC-model has an NMSE of 0.0048, which is one magnitude of order smaller than the best performance of the single-mode RC-model (NMSE$= 0.067$). This drastic improvement in performance allows to decrease the number of nodes. When the number of nodes for the two-mode RC-model is decreased from 200 to 50, the performance is still better than that what can be achieved by the single-mode RC-model. This means that the feedback loop can be shortened by a factor four, without degrading the RC performance.

Conclusion

The results obtained from our simulations show that a reservoir computer based on optical feedback from a two-mode semiconductor laser has a significant improvement when compared to a single-mode RC-model. The delay line can be shortened by a factor four, which is needed if we want to move towards on-chip implementations. Further reductions can be achieved by introducing more longitudinal modes in the cavity. One can even expect the elimination of the feedback loop.

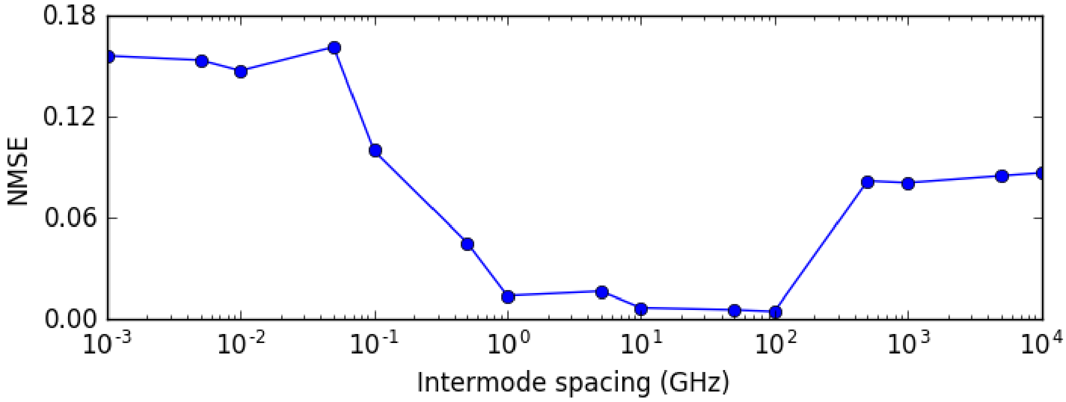

Figure 3: The performance of an RC-model based on a two-mode SL as a function of the intermode spacing.

Acknowledgements

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