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Integrated Delay Based Photonic Reservoir Computing

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We have analyzed the performance of a reservoir computing system based on a semiconductor laser with delayed optical output feedback on timeseries prediction and bit parity tests. Both laser and feedback section are fully integrated on an InP based photonic chip fabricated on the Jeppix platform. We have studied how the system parameters affect the performance and found that this reservoir computing chip reaches processing speeds of 0.9GSa/s with comparable performances as obtained by other non-integrated RC setups based on delayed feedback as well as RC setup on passive silicon photonic chips.

Introduction

The concept of reservoir computing (RC), a paradigm within neuromorphic computing, offers a framework to exploit the transient dynamics within a recurrent neural network for performing useful computation. It has been demonstrated to have state-of-the-art performance for a range of tasks that are notoriously hard to solve by algorithmic approaches, e.g., speech and pattern recognition and nonlinear control. RC rekindled neuromorphic computing activities in photonics [1]. Today, multiple photonic RC systems show great promise for providing a practical yet powerful hardware substrate for neuromorphic computing. Not all reservoirs are neural networks, i.e. based on discrete nonlinear optical nodes (neurons). Any high dimensional nonlinear dynamical system can be exploited for RC. The concept of delay line-based RC, using only a single nonlinear node with delayed feedback, was introduced some years ago by Appeltant et al. [2] as a means of minimizing the expected hardware complexity in photonic systems. The first working prototype was developed in electronics in 2011 by Appeltant et al. [2] and several performant optical systems followed quickly after that [1], one of which based on a semiconductor laser with external optical feedback [3].

Delay-based RC offers a simple technological route to implement photonic neuromorphic computation. Its operation boils down to a time-multiplexing with the delay limiting the resulting processing speed. As most optical setups end up to be bulky employing long fiber loops or free-space optics, the processing speeds are limited in the range of kSa/s to tens of MSa/s. In this work, we focus on external cavities which are far shorter than what has been realized before in experiment. We present an experimental validation of reservoir computing based on a semiconductor laser with an 10.8cm delay line, both integrated on an active/passive InP photonic chip built on the Jeppix platform [4].

Practical setup

A schematic of the chip is shown in figure 1, consisting of the laser, two spirals comprising the delay line, two semiconductor optical amplifiers (SOA1 and SOA2) integrated in the delay line to compensate for the losses as well as tune the feedback strength and lastly a Distributed Bragg Reflector (DBR) mirror to complete the feedback loop. The laser consists of an active section sandwiched between two DBR mirrors,

Figure 1 Schematics of the integrated photonic chip used in the experiments. A Distributed Bragg Reflector (DBR) laser connected to two consecutive spirals, comprising the delay line. The semiconductor optical amplifiers (SOA) compensate for the losses in the delay line and the DBR on the far right completes the feedback loop.

comprising the laser cavity and also enabling the tuning of the lasing wavelength. The single mode laser operates around 1550nm with a side mode suppression larger than 20dB. The in- and output waveguides are connected to the chip facet under an angle of 7 degrees to avoid reflections from the side coupled fibers.

A three level mask with 23 nodes separated by 50ps is employed, which corresponds to a delay time of 1150ps, slightly shorter than the delay time 1170ps. The total length of the mask corresponds to a computation speed of 0.87GSa/s.

The dataset is multiplied with the mask and fed to the arbitrary waveform generator (AWG). The AWG has a sampling speed of 60GSa/s, which means 3 samples per nodes, ensuring a fairly accurate signal compared to what is expected. The RF signal from the AWG is fed to a Mach-Zehnder modulator that modulates the data unto the output of an external tunable laser. The modulated optical signal is coupled into the laser on the chip. The output of the laser is isolated using a circulator and analyzed with an oscilloscope sampling at a speed of 40GSa/s, corresponding to two output samples per node. The output is captured over a timeframe of 34 times the total masked data length, such that the time traces can be averaged out to minimize read out noise.

Task and performance indicator

The performance is tested by one-step-ahead prediction of a timeseries generated by a far-infrared laser operating in a chaotic state[2], also known as the Santa-Fe timeseries. This time series has 9000 points of which we only use the first 5000. A five-fold cross-validation is performed, using a 33-66% split for training and testing respectively. The best performance out of these five is chosen as the performance for that particular measurement. The performances are indicated by the Normalized Mean Square Error (NMSE). The performance is also tested by the bit-parity recognition task, but the results are not presented in this paper.

Results

The performance of our setup is studied as some important system parameters are scanned. The left plot in figure 2 illustrates how the performance relates to the pump current of the reservoir laser. At higher pump strength the performance improves

significantly. As the pump current increases so does the optical power that is coupled into the delay line, leading to feedback induced memory in the system. This is expected behavior if compared to simulations we have performed. The performance cannot improve endlessly as the pump current is increased, as the system will go into a chaotic regime once the feedback strength gets too strong. We could not go to higher pump currents, as the laser gets saturated. At lower feedback strength the system is not chaotic because of injection locking.
In the middle plot we put the injection wavelength along the abscissa. The lowest NMSE or the best performance is observed at 1549.96nm, which is also the point where injection locking is achieved. It is clear that as we move away from the injection locking wavelength, that our RC setup performance degrades. This is because the system goes into a chaotic regime and loses its consistent behavior, degrading the performance.
The last plot has the sum of the currents applied to the two feedback SOA's placed along the abscissa. The sum of these currents give an indirect indication of the amplification achieved in the delay line and hence an indication of the feedback strength. We see that the performance generally improves as feedback increases, with some outliers that we attribute to changes in feedback phase. As currents are increased, the optical path length of the delay line changes due to thermal heating. These changes could be the cause of the outliers we see in our graphs.

The best experimental performance reached here, is an NMSE of 0.13 with 23 nodes at 0.87GSa/s. Which is similar to the 0.12 reached by Larger et. al. [5] with an optoelectronic setup with 400 virtual nodes at a processing speed of 48kSa/s. Brunner et al. [3] achieved a prediction error as low as 10.6%, at a speed of 13MSa/s employing a fiberloop. The advantage of our system being clearly the size and the speed.
We also benchmarked the setup on Bit parity tests at speeds of 0.9Gbit/s, of which the results are not shown here. We get similar performances as Vandoorne et al. [6] with a passive silicon chip reservoir with speeds of 12.5Gbit/s.

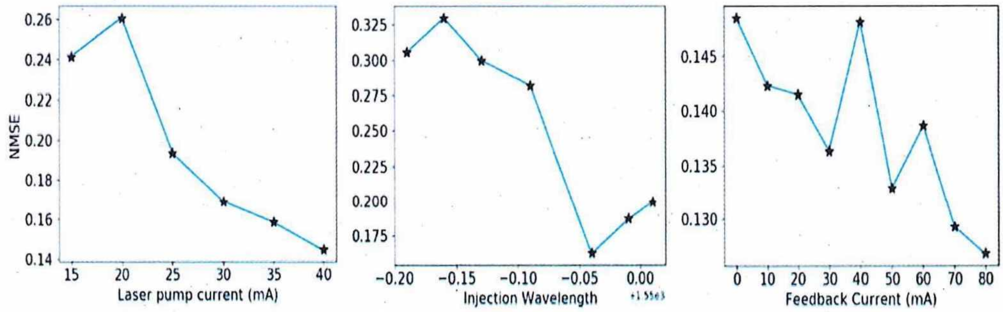

Figure 2 The performance indicated by the NMSE as a function of the reservoir laser pump current (left), Injection wavelength (middle) and combined current applied to the two SOA's in the delay line (right). Measurement results are shown as black stars. The lines connecting the experimental points are to guide the eye.

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