Marie Curie IEF NOVALIS, publishable summary

The Marie Curie IEF **NOVALIS** project (Project # 275840) aimed at realizing a Liquid-State-Machine (LSM) based on multiple semiconductor lasers serving as nonlinear nodes. The LSM represents a novel machine learning concept, also referred to as Reservoir-Computing (RC) or nonlinear transient computing. Central to the concept is the realisation of a network of nonlinear nodes, in which the information to be processed induces complex nonlinear transient dynamics. A linear weighted sum of the individual transients provide the result of the desired computation. The individual weights are adjusted in a training (learning) procedure. This novel concept has already proven to show impressive performance in a number of complex and computationally demanding tasks. Crucially, a machine learning concept was transferred highly successfully from software-emulation on digital-electronic computers to multiple real-world, physically realised systems. Surprisingly, regardless of the noise present in experimental systems, for some benchmark tests the hardware implementations outperformed their software based counterparts. The **NOVALIS** project was essentially involved in several of the first publications in this young and active field of science.

The first objective of the **NOVALIS** project was the realisation of a LSM based on multiple semiconductor lasers (SLs), forming a network via coupling by optical fibres. **The second objective** was to create a reservoir of multiple vertical-cavity surface-emitting lasers (VCSELs). **The third and final objective** was to demonstrate parallel information processing using a spatial-light-modulator (SLM) incorporated into the multiple-VCSEL setup.

The first step of this project was using a single SL subject to delayed feedback. Using a single laser diode, we were able to demonstrate impressive information processing capacity of SLs. We optically injected information into the system at an injection rate of 5 GSamples/s. Besides the highly successful demonstration of all optical spoken digit recognition[1], we were able to demonstrate chaotic timeseries prediction[1] and analytic vector operations[2] with great success. Using a modified data injection protocol, partitioning the injection into multiple sections, we emulated reservoirs of up to 4 uncoupled SLs. For two uncoupled devices (200 network nodes each), performance mirrored the one found for a single SL (400 nodes), achieving a Word-Error-Rate (WER) of only 0.014 %[1]. For the case of 4 SLs, the error increased, revealing an increased sensitivity to operating conditions. As a next step, we established coupling and feedback for a system of two SLs using polarisation maintaining optical fibres. In this experiment a strong and slowly varying (millisecond timescales) modulation of the output intensities (modulation amplitude approaching unity) was found. We were not able to identify the origin or to avoid this effect, hence reproducible computation-results would not be attainable.

As the next objective, a network of multiple lasers, here VCSELs, was envisioned. Until this day, the size of SL-networks used for characterising network dynamics or for utilizing their dynamical properties were limited to a maximum of four lasers - with the vast majority of experiments reported for no more than two SLs. As such, the realisation of a SL-network incorporating a significantly larger number of devices would represent a substantial progress for the implementation of an all-optical LSM, but also for the scientific community of complex laser-dynamics. During the **NOVALIS** project, a system allowing individual control of the bias current of up to 64 lasers was established. As a next step, we incorporated a chip with 63-VCSELs into an external-cavity. The cavity was formed via an imaging lens and an SLM, see Fig. 1a). For correct alignment, each laser therefore experiences delayed self-coupling. The interconnectivity between individual lasers, crucial for a complex network (the Reservoir), was established using a diffractive-optical-element (DOE). The DOE in our setup produced a 3x3 diffraction pattern for each laser. Based on this technique, we were able to establish a complex network with 24 laser diodes, achieving a significant threshold reduction of~ 2 % for the 24-laser network. Misaligning the angle between VCSEL-array and the DOE, Fig. 1 b), and consequently destroying the coupling, resulted in a

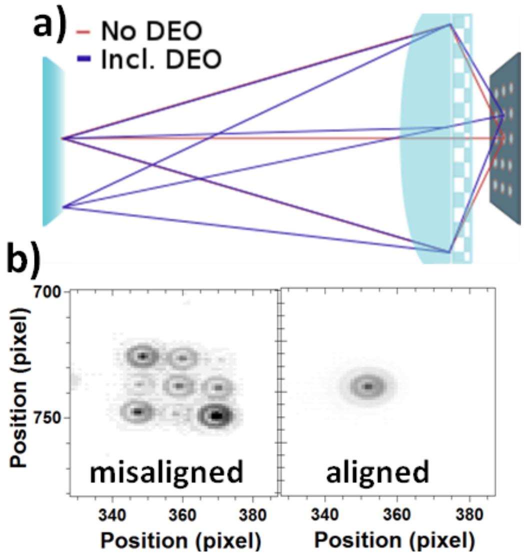

Figure 1 A network of VCSELs. Panel a) shows the principle mechanism of coupling between lasers. Without the DOE, each laser forms a single image on the SLM. Including the DOE (checker-board patterned element) results in the creation of multiple images per laser due to diffraction, overlapping for neighbouring lasers. Panel b) demonstrates the coupling for different angles (+6 and 0 degree), and an image of the intensity caused by the feedback coupling from

negligible threshold reduction. For larger network sizes, spherical aberrations resulted in significantly reduced coupling and feedback.
The final objective of the project was the demonstration of parallel information processing based on the SLM, plus characterising the reservoir dynamics using a high-time resolution imaging technique based on sampling. As reported in the first section, for the case of multiple fibre-coupled lasers we found a slowly varying amplitude variation of the induced transient dynamics. Such an effect would not be resolved using the originally intended network analysis technique, and therefore results would not reflect the true information processing capabilities. For that reason we modified the approach, realizing a different method, which is capable of representing the final requirement for a complete LSM: the realisation of the all-optical classifier. We used the Köhler-illumination principle for an all-optical spatial integrator.

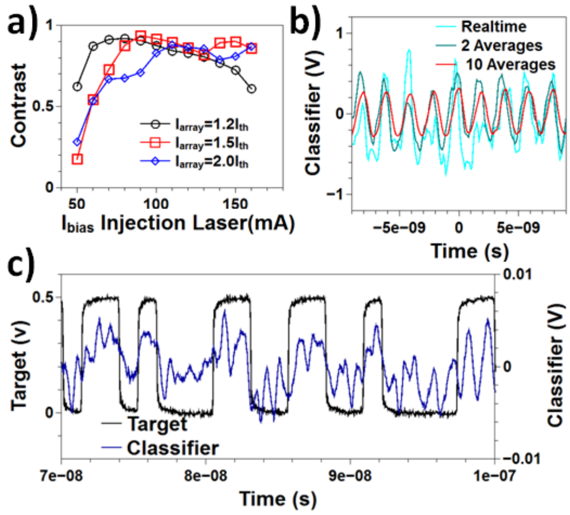

Figure 2 The left top panel shows the relative amplitude of the optical induced transients, a), and temporally resolved transients for different numbers of averaging, b). Panel c) demonstrates the deviation between the LSM classifier and its target values.

Based on this concept, we were able to localize the optical output of the entire VCSEL-network in an area smaller than 500 µm. Crucially, no slowly varying envelope as in the fibre-based network was found. Using an injection laser, we induced optical transients into 8 VCSELs. Relative transient amplitudes, as well as temporally resolved transients, are shown in panel a) and b) of Fig. 2. For certain bias-currents of the injection laser, the modulation amplitude approaches unity, indicating a strong reservoir response to the external optical stimulus. Using the SLM, we were able to scale the optical intensity of each individual laser with relative weights between 0.15...1, representing the readout weights of the classifier. Temporally resolved transients, shown in the top-right panel of Fig. 2, were detected with a fast photo-diode with an active area of 70x70 μm^2. Due to a detector area smaller than the size of the optical classifier output, a significant amount of the modulation amplitude was lost. In addition, the detector showed a noise level comparable to the amplitude of the induced transients. One major source of this noise was cross-talk from the SLM-control electronics, with multiple noise peaks for frequencies between ~10 MHz up to ~1 GHz. As a result, our efforts to implement an iterative training procedure for classifying square- and sine-waves did not lead to convergence. We associate this to a roundtrip error larger than the modification of the classifier response achieved in one training iteration, Fig. 2 b). In addition, the transients detected by the fast photo diode might not include all 8 modulated lasers, therefore not providing the required reservoir diversity. Panel c) of Fig. 2, however, shows that the classifier output reassembles the target value to some extent, demonstrating that for suitable injection parameters a successful classification should be achievable with our all-optical reservoir. Caused by this unforeseeable complication, we decided to demonstrate the true parallel computation capabilities of an all-optical LSM using a single delay coupled laser reservoir. We demonstrated parallel classification of spoken digits as well as the speaker of the digit.[1]
The NOVALIS project has therefore realised each individual section for implementing an all-optical LSM based on multiple laser reservoirs, representing a significant advancement of the field. Two central limitations remain noise in the classifier readout and the spherical aberrations in the resonator. However, those are not of a fundamental nature. Overcoming these hurdles would render all-optical laser reservoir with a significant number of lasers possible. Solving the detector noise problem and implementing the training procedure would establish an all-optical, stand-alone machine learning concept. Such a system would perform all-optical machine-learning computations at unprecedented speed and energy efficiencies. Hence, due to the importance of information processing and especially machine-learning algorithms to our modern way of life, economic and social impact could be significant. The NOVALIS project supported research in several aspect of physically implemented LSMs. Results were disseminated in five publications[1-5] as well as in four oral conference contributions, among those one invited oral presentation at CLEO/Europe 2013. Furthermore, the fellow organised a special session dedicated at experimental implementations of LSM/RC at the prestigious NOLTA 2013 conference.

1. D. Brunner et al., *Nat. Commun.* **4,**1364 (2013).
2. D. Brunner et al, *IEEE Photon. Technol. Lett.* **25**,1680–1683 (2013).
3. K. Hicke et al.. *IEEE Journal of Selected Topics in Quantum Electronics* **19**, (2013).
4. D. Brunner et al, *Scientific Reports* **2**, 732 (2012).
5. M. C. Soriano et al., *Optics Express* **21**, 12-20 (2013).