10 GHz bandwidth nonlinear delay electro-optic phase dynamics for ultra-fast nonlinear transient computing

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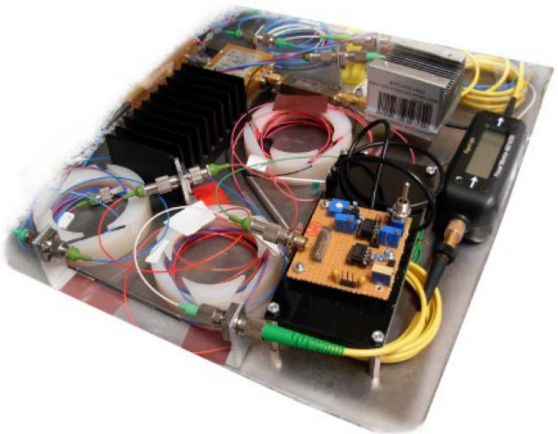

CLEO / Europe IQEC 2013, CD-10: Optical Devices for Data Processing

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Outline

- **Introduction**
  - Background, Motivations
  - Reservoir Computing using delay dynamics
  - High Complexity Delay Dynamics Reservoir with EO
- **RC with Ultra-fast Photonic Nonlinear Delay Dynamics**
  - EO phase Dynamics as a reservoir
  - Operating Conditions of the reservoir
  - Spoken digit recognition test
- **Conclusion, Perspectives**

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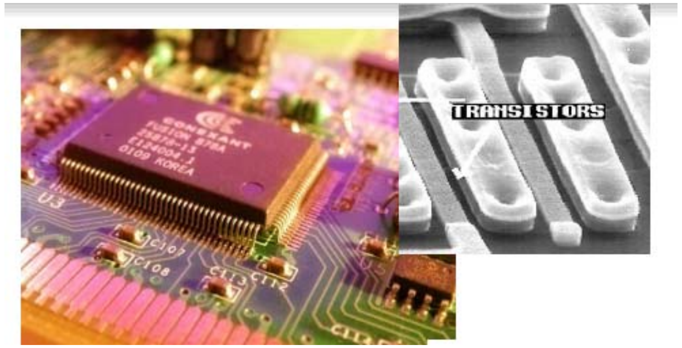
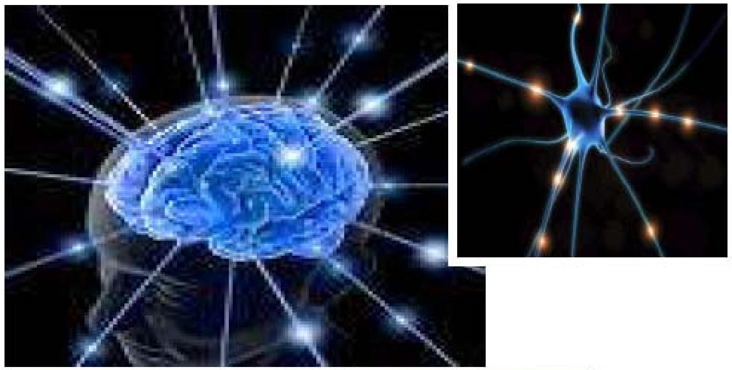
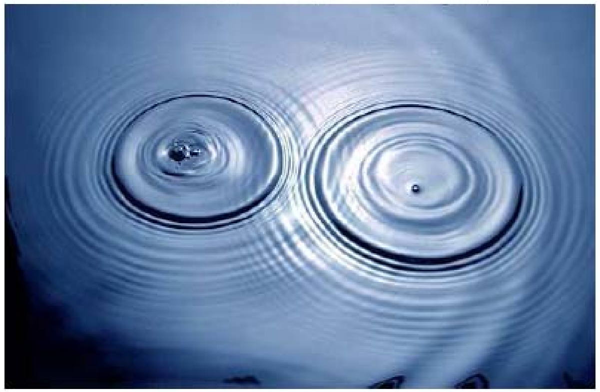
Background, motivations



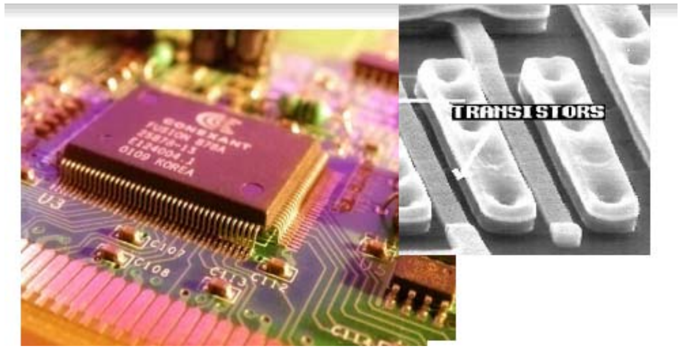


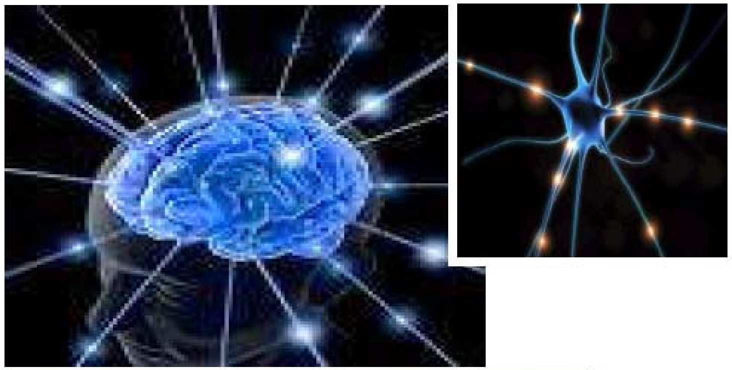


- Digital electronics, standard computers are still limited :
  - ✓ Complex tasks : classification, prediction
  - ✓ Information processing at ultra high speeds.

- Experimental implementation of Reservoir Computing (RC) or Nonlinear Transient Computing (NTC)
- To generate transient states for processing the information

Background, motivations





- **Neural Network Computing**
  - Artificial intelligence, network of coupled oscillators, learning, actual demonstration via "conventional computer" simulations

- **Cognitive brain research, bio-inspired computing principles**
  - biologic neural network, time trajectories corresponding to pulse train solutions

- **Echo State Network (ESN), Liquid State Machines (LSM), Reservoir Computing (RC)**
  - Novel architecture exhibiting universal computational potential

H. Jaeger and H. Haas, "Harnessing Nonlinearity : Predicting Chaotic Systems and Saving Energy in Wireless Communication" Science 304, 78 (2004)

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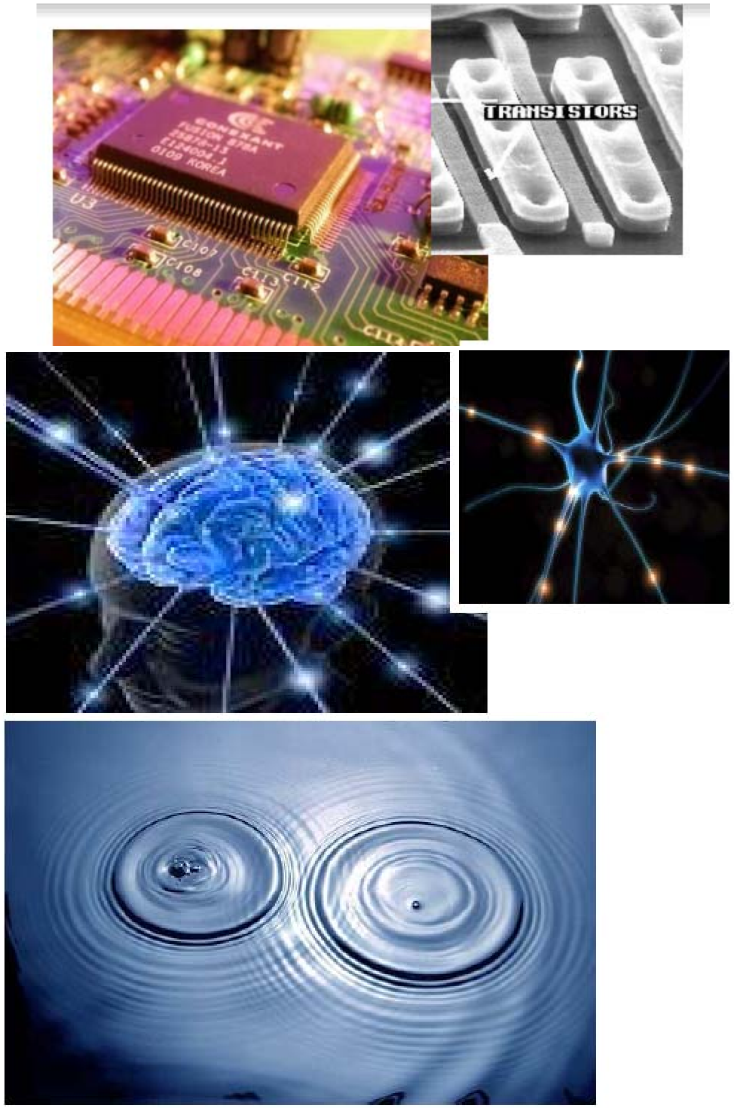
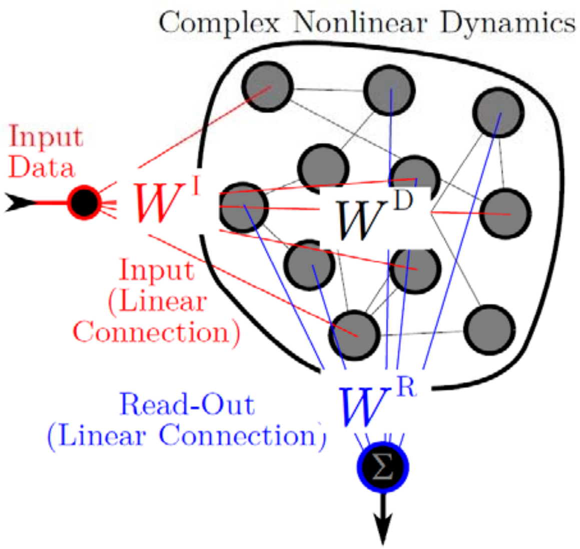
From Neural Networks to RC



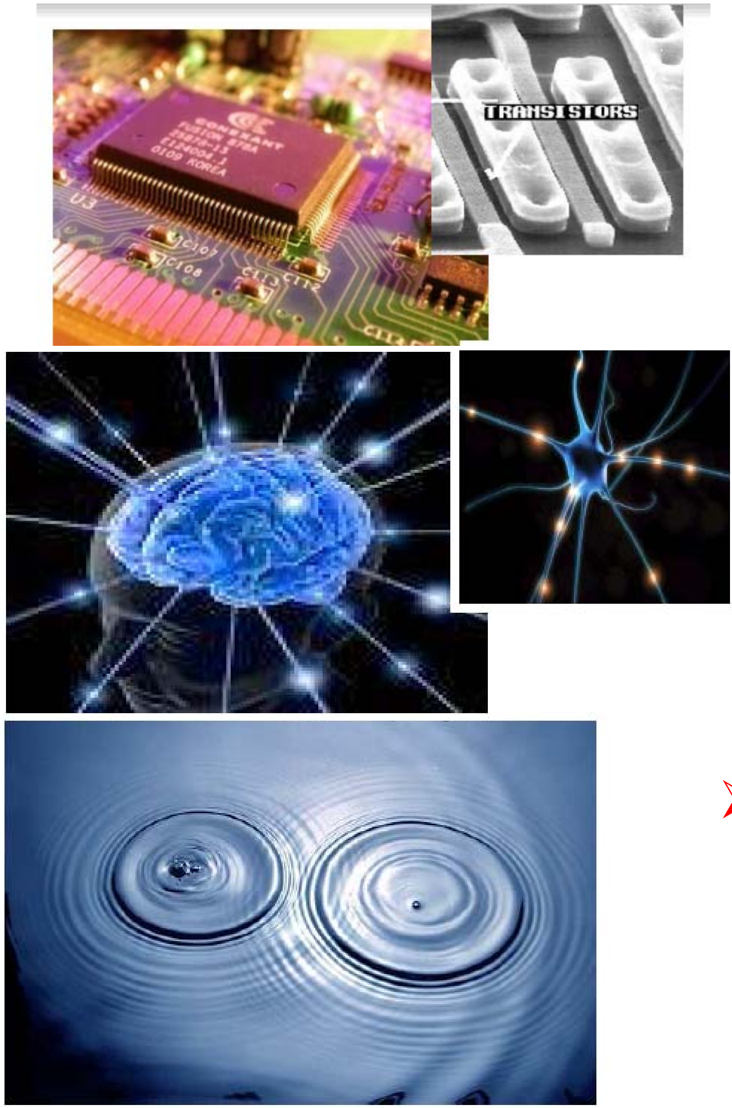
- **Basic architecture**



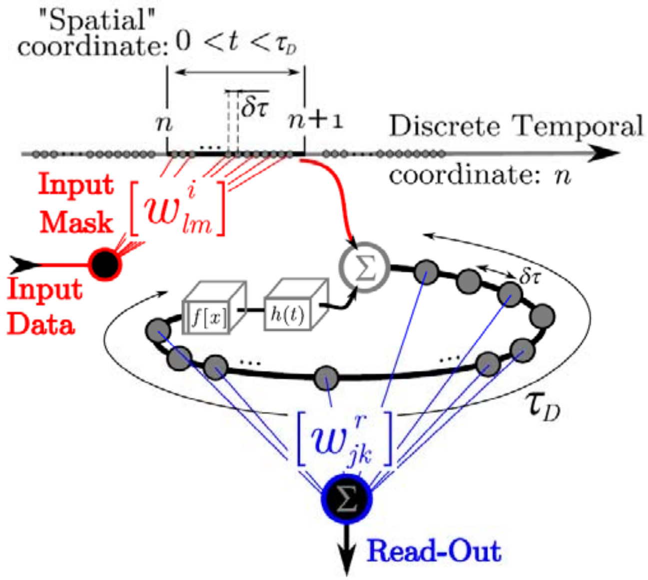
- **Towards a parallel photonic reservoir :**

K.T Vandoorne, J. Dambre, D. Verstraeten, B. Schrauwen, P. Bienstman, “Parallel reservoir computing using optical amplifiers”, IEEE Transactions on Neural Networks, 22(9), 1469-1481 (2011)

Our approach : harnessing delay dynamics



- **Spatio-Temporal viewpoint of a DDE**



- **Towards a reservoir computing experimental setup using delay dynamics :**

L. Appeltant, M. C. Soriano, G. Van der Sande, J. Danckaert, S. Massar, J. Dambre, B. Schrauwen, C. R. Mirasso, and I. Fischer, "Information processing using a single dynamical node as complex system," Nature Commun. 2, 468 (2011).

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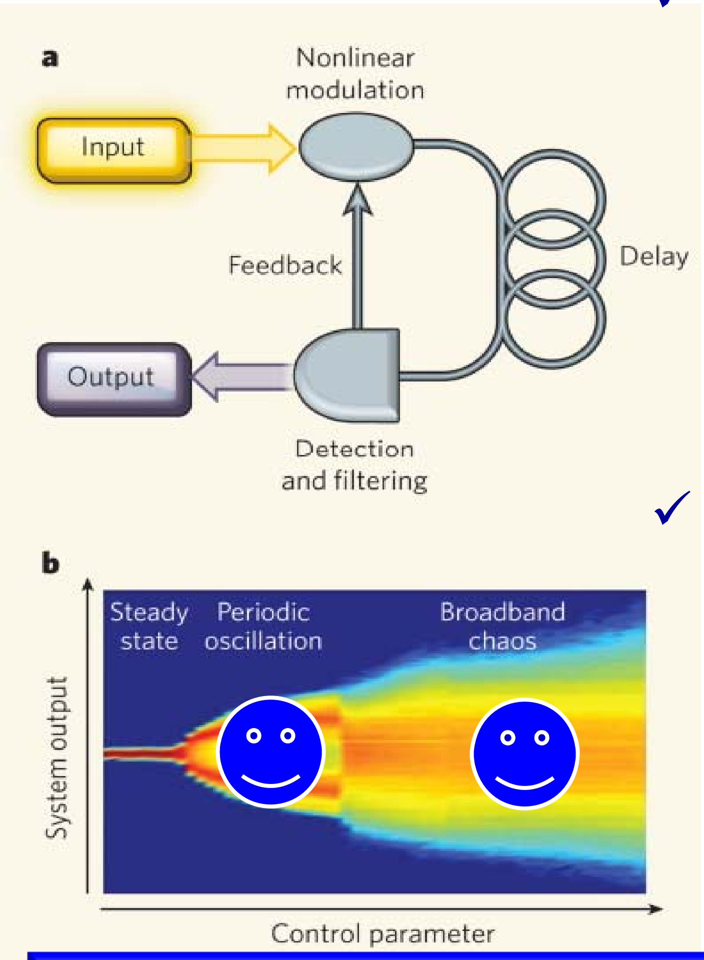
Delay Dynamics with optoelectronic systems



L. Larger, J. M. Dudley, Nonlinear dynamics: Optoelectronic Chaos, Nature 465, 41-42 (2010)

✓ **Ikeda dynamics:** linearly filtered nonlinear delayed feedback

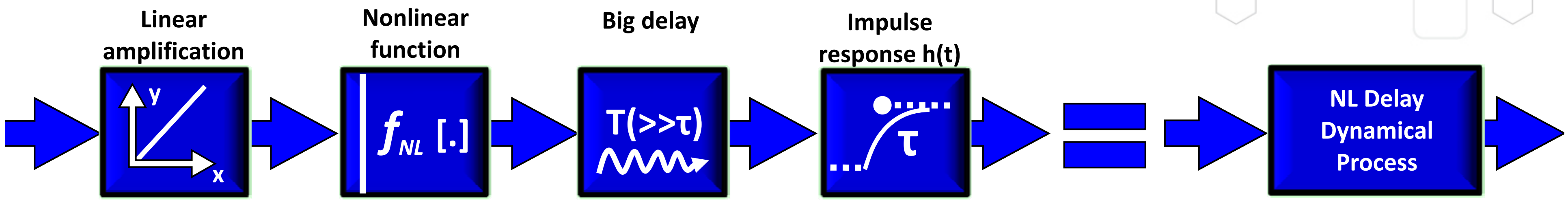
- infinite dimensional dynamics
- very high practical attractor dimension
- highly nonlinear realization
- optoelectronic solution with telecom devices
- high reliability and controllability

✓ **Two Main applications & various regimes vs feedback gain:**

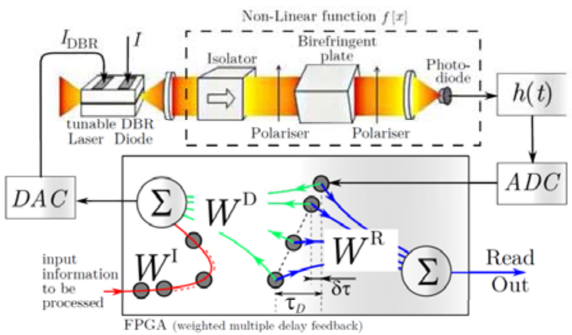
- Optical Chaos Communications
- High spectral purity micro-wave oscillator

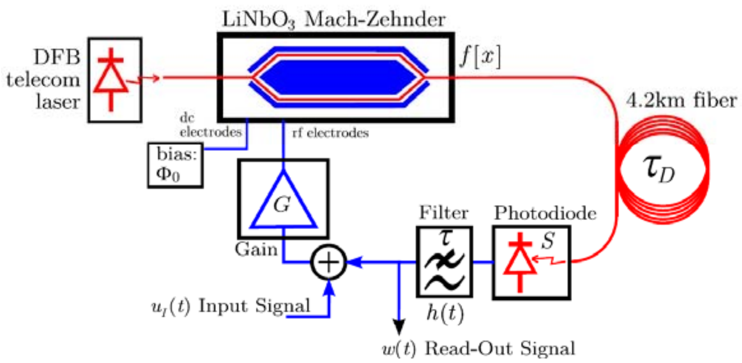
Existing optoelectronic systems

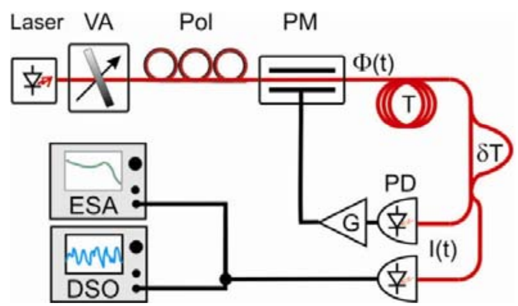
- **Nonlinear Delay Dynamical Process**

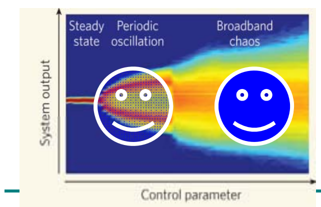


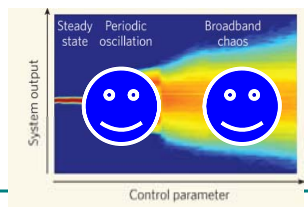
- **Various existing experimental setups**

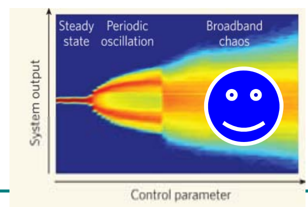












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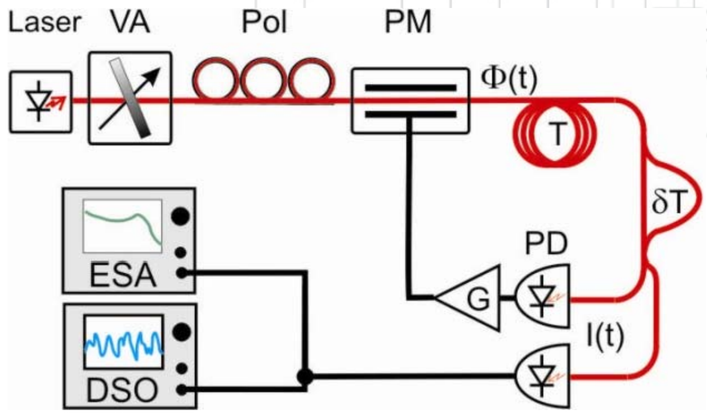
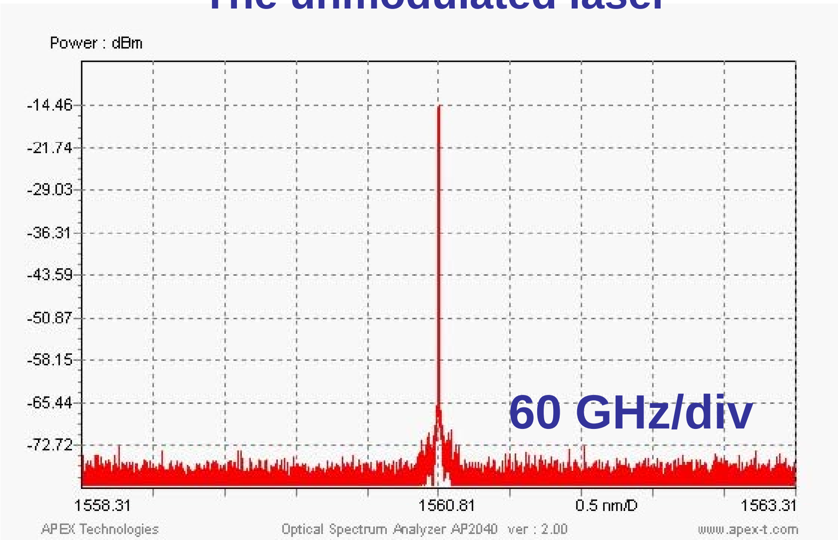
10 GHz bandwidth EO Phase dynamics system

- Picking ideas from efficient coherent communications principles

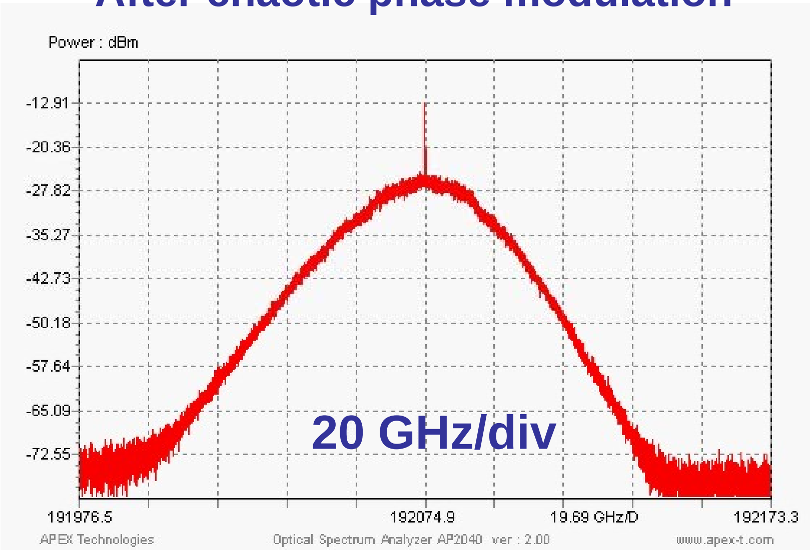
  Imbalanced Mach-Zehnder (typ. DPSK demodulator) for PM to IM conversion:
  - ca. 3cm unbalancing
  - 10Gb/s E/O O/E devices



The unmodulated laser



After chaotic phase modulation

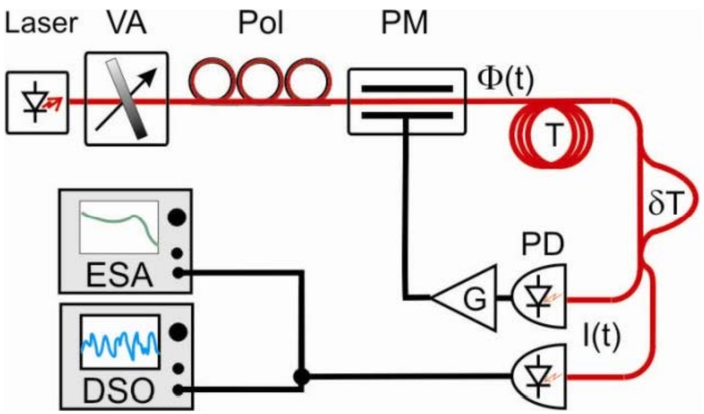


EO Phase Dynamics

- The phase dynamics exhibits an additional temporal coupling term δT
  - Nonlinear delay integro-differential equation

$$\frac{1}{\theta}\int_{t_0}^{t}\varphi(\xi)\mathrm{d}\xi + \varphi(t) + \tau\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \beta\cdot[f_{(t-T)}(\varphi^{\star}) - f(0)]$$

  - Imbalanced interferometer: Temporally nonlocal non linearity



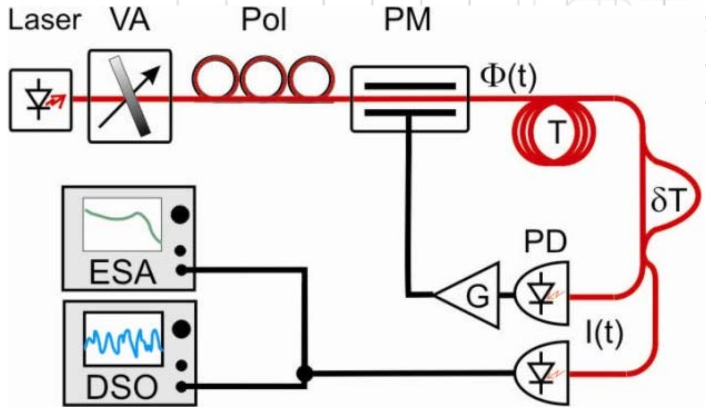
* Standard DPSK demodulator:

$$f_t(\varphi) = \{1 + \cos[\varphi(t) - \varphi(t-\delta T) + \phi_0]\}$$

* Generalized multiple wave interferometer:

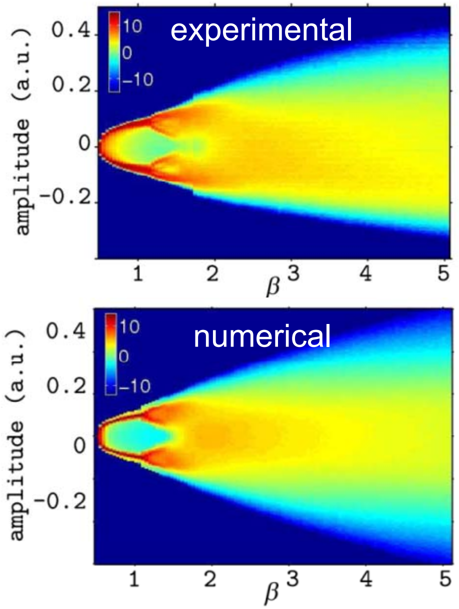
$$f_t(\varphi) = F_0\left|1 + \sum_k \alpha_k\, e^{i[\varphi(t)-\varphi(t-\delta T_k)]}\, e^{i\phi_k}\right|^2$$

EO Phase dynamic system, undriven system



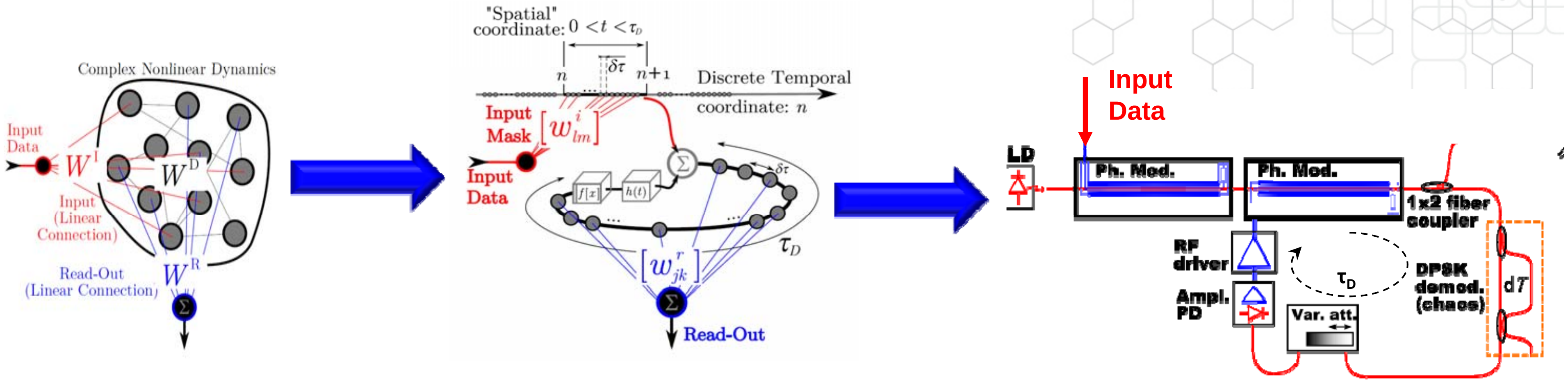
- Control parameters (feedback gain β, static phase shift ϕ_0) allows to reach complex regime,

- experimental / numerical bifurcation diagrams



Single delay electro-optic phase dynamics, driven system

- <u>**Basic architecture**</u>



✓ Photonic setup with a phase dynamic with a bandpass feedback

✓ Input Driven Nonlinear Delay Dynamics (DDE):

$$\phi(t)+\tau\dot{\phi}(t)+\frac{1}{\theta}\int_{t_0}^{t}\phi(s)ds=\beta\sin^2\left[\phi(t-\tau_D)-\phi(t-\delta T-\tau_D)+\rho u_i(t-\tau_D)-\rho u_i(t-\delta T-\tau_D)+\phi_0\right]$$

✓ Physical variable : response time τ ↔ to keep the system far from steady state, δτ=0,2τ

feedback strength β ↔ overall feedback loop gain; input data weight ρ; NL operating point ↔ Φ_0

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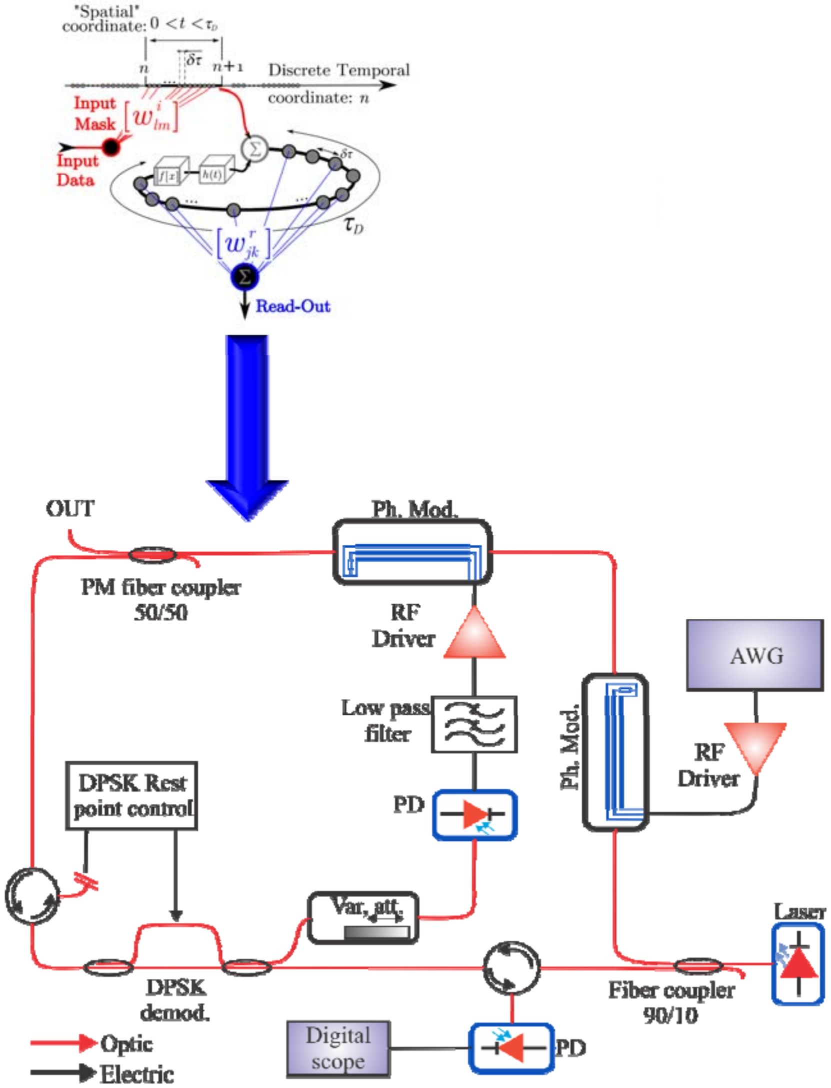
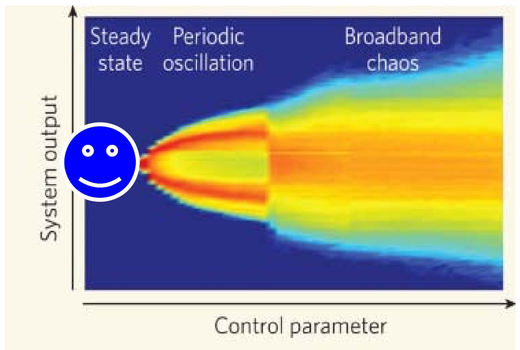


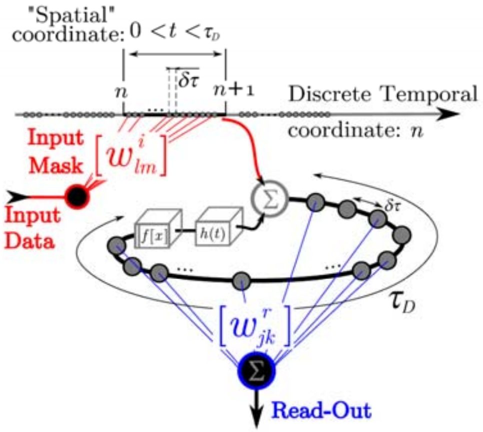
Practical values : phase dynamics

- **Amplitude parameters :**
  - ✓ Feedback strength $\beta \simeq 0.5$
  - ✓ Offset phase Φ_0: NL operation "close to an extremum"
  - ✓ Large input data weight, ρu_i close to π

- **At the edge of chaos. . . stable steady state**
  - ✓ Not too small feedback strength β (allowing NL mixing)
  - ✓ Not too close to the instability threshold (too slow response)

- **Nonlinear Transient Computer (NTC)**





Practical values : phase dynamics

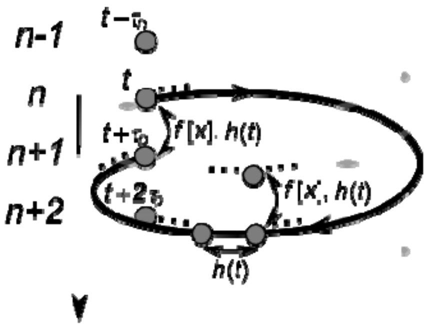
➢ **Number of nodes N typically 100 < N < 1000**

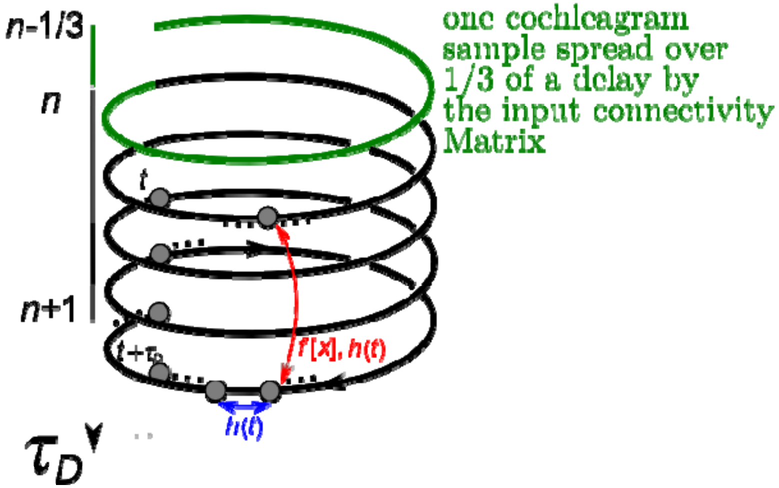
✓ to keep the system far from steady state during its dynamical response, we choose δτ=0,2τ and it gives the number of nodes :

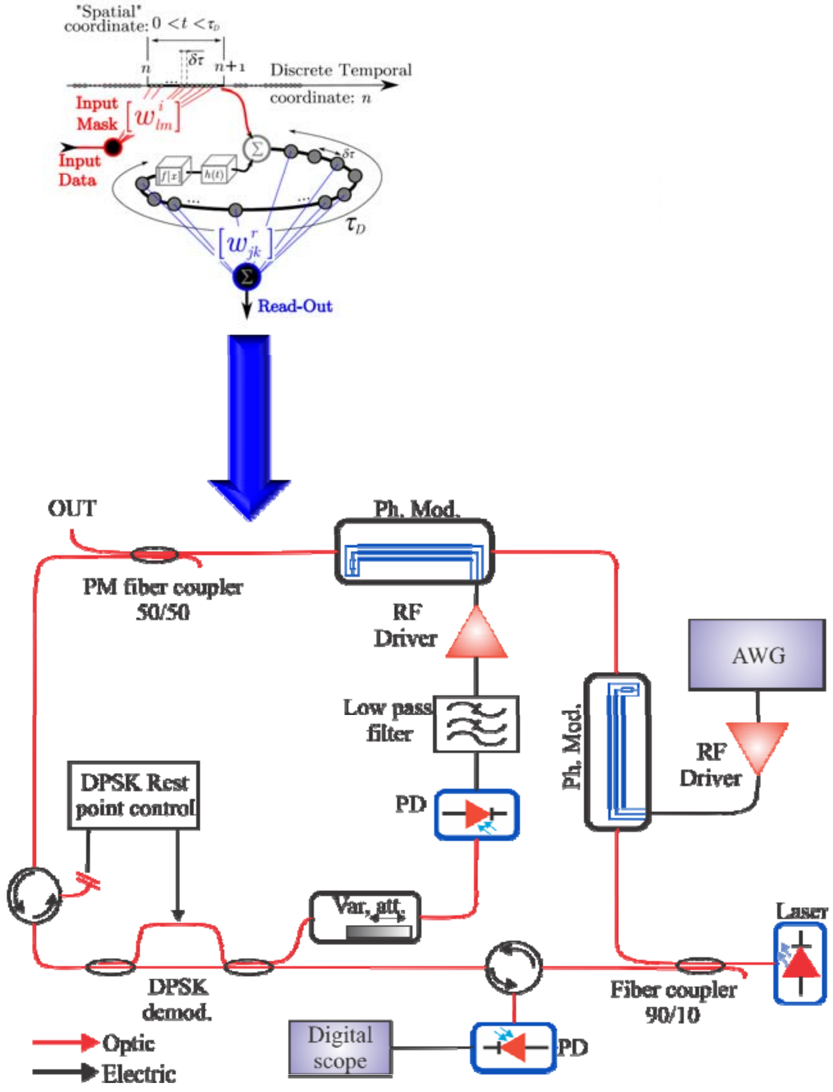
$$N = \tau_D / \delta\tau$$

✓ But EO phase system τ = 284 ps , we obtain N> 1000, or τ = 20 ps and gives N > 15000

To operate with tractable number of Nodes, the input data is spread over 1/3 of the delay (increases the memory): $N = \tau_D / 3\delta\tau = 428$ (τ = 284 ps)







Practical values : phase dynamics

➢ **Temporal parameters** :

➢ Fixed delay : $\tau_D \simeq 63{,}2$ ns

➢ Two different possible low pass filters

1) <u>Intermediate feedback bandwidth 560 MHz / τ = 284 ps</u>

✓ Large delay condition, $\tau_D/\tau \simeq 220$, **we fix : $\tau_D/3N = 0.2\tau$**

✓ N = 428 nodes separated by ca. 0.2τ : required input and read-out resolution $\simeq$ **20 GSamples/s)**

2) <u>Intermediate feedback bandwidth 7,73 GHz / τ = 20 ps</u>

✓ Large delay condition, $\tau_D/\tau \simeq 3200$, too large !

✓ N = 428 nodes separated by ca. 0.2τ (required input and read-out resolution $\simeq$ 250 GSamples/s !!!

✓ **NOT POSSIBLE WITH OUR AWG and DSO limited to 24 GS/s (AWG) and 45 GHz (DSO),**

but possible in unsynchronized regime (Y. Paquot et al, scientific reports, 2012)

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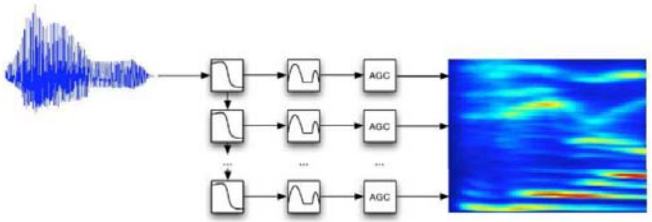
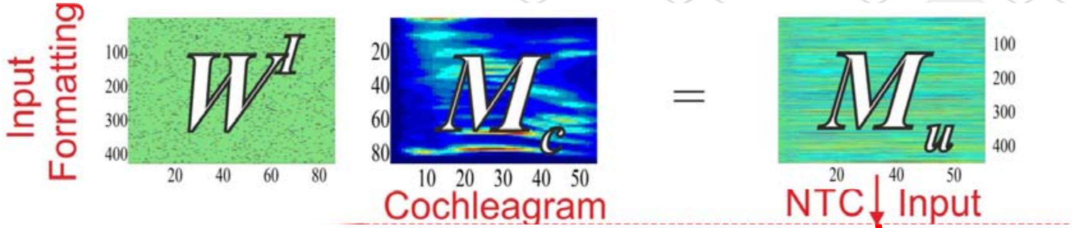
Dynamical Processing of Spoken Digits

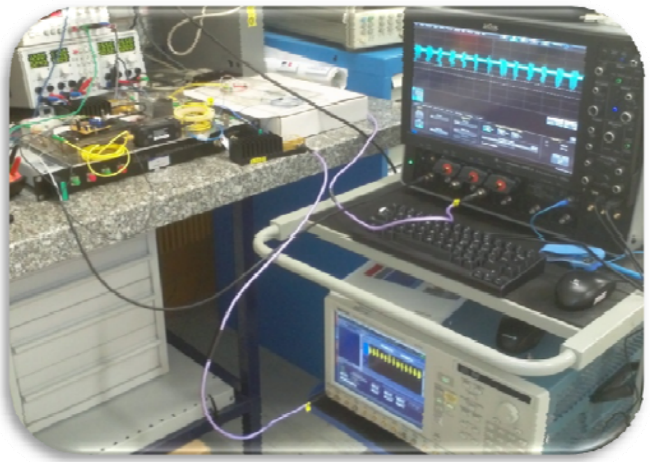
➢ **Input pre-processing :**

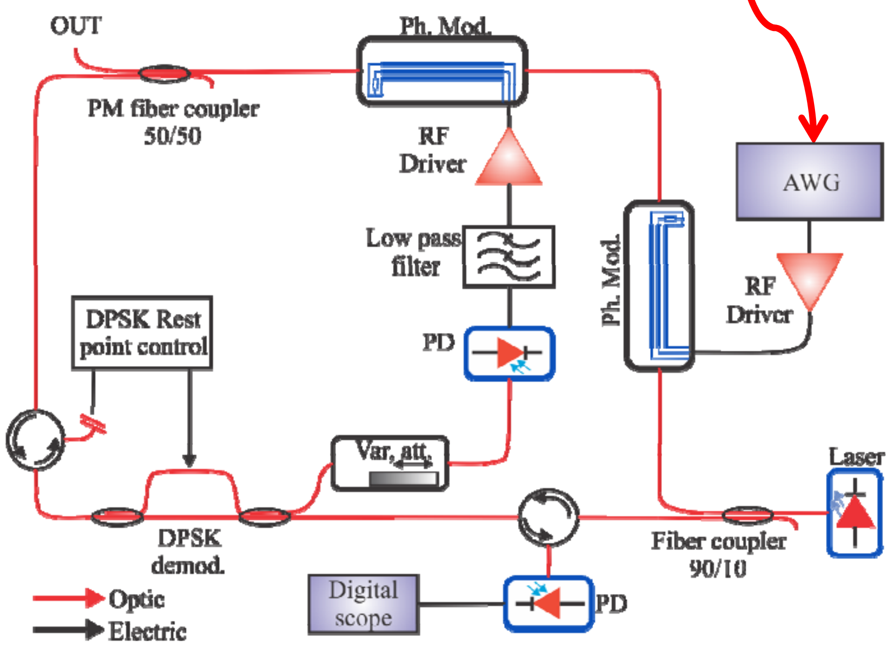




Lyon Ear Model transformation (Time & Frequency 2D formatting, 32 to 130 Samples x 86 Freq.channel)

Sparse "connection" of the 86 Freq. channel to the N nodes : random connection matrix

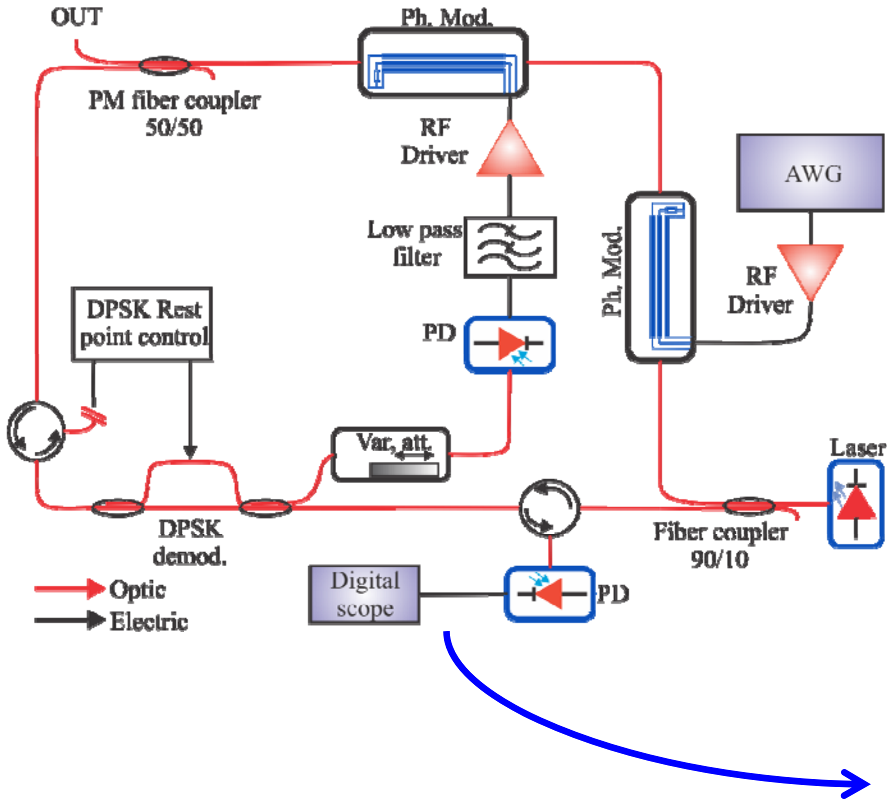


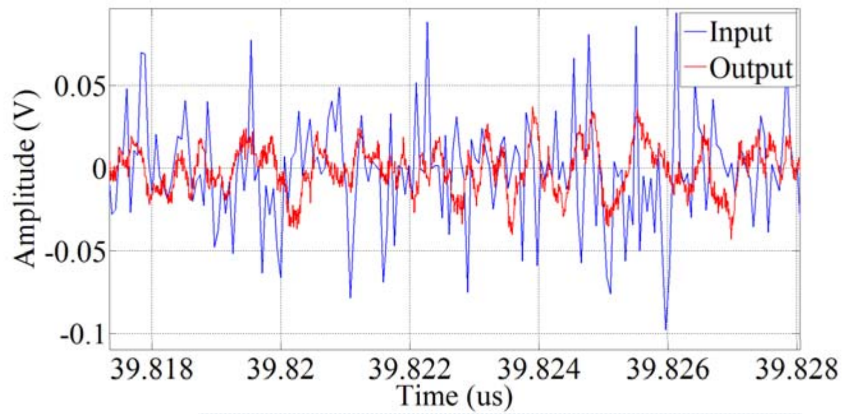


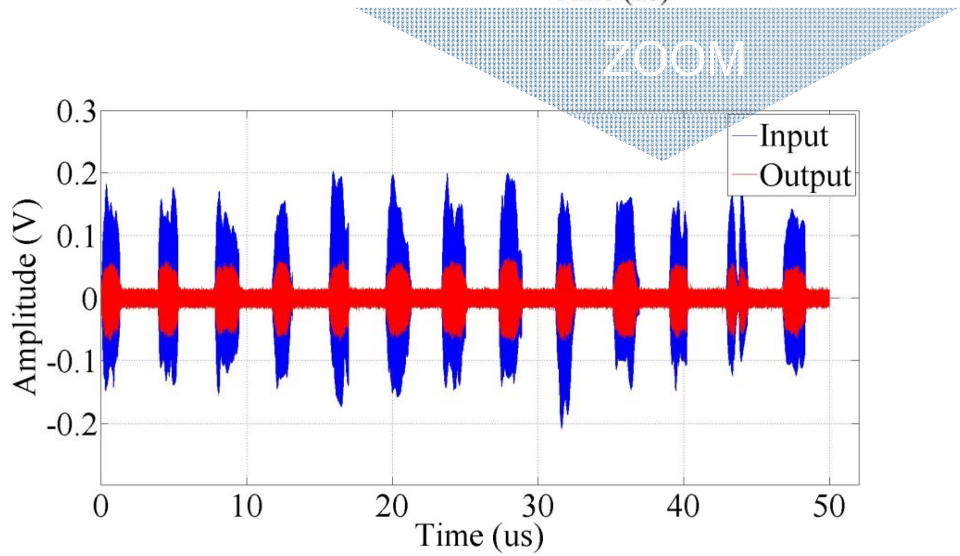
Reservoir state : experimental results

➢ **Phase dynamics :**

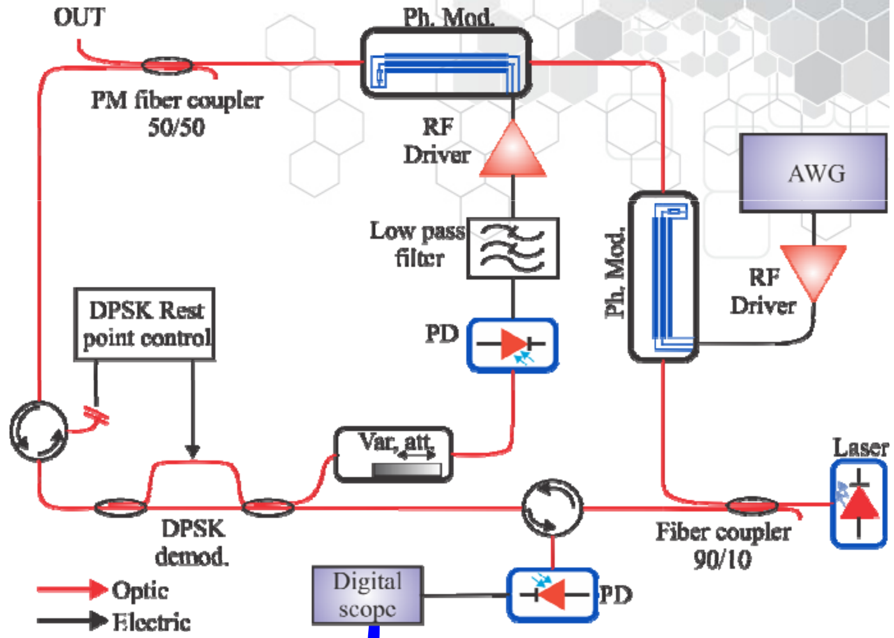
Time series recorded for Read-Out post-processing







Read-Out, Training, and Testing

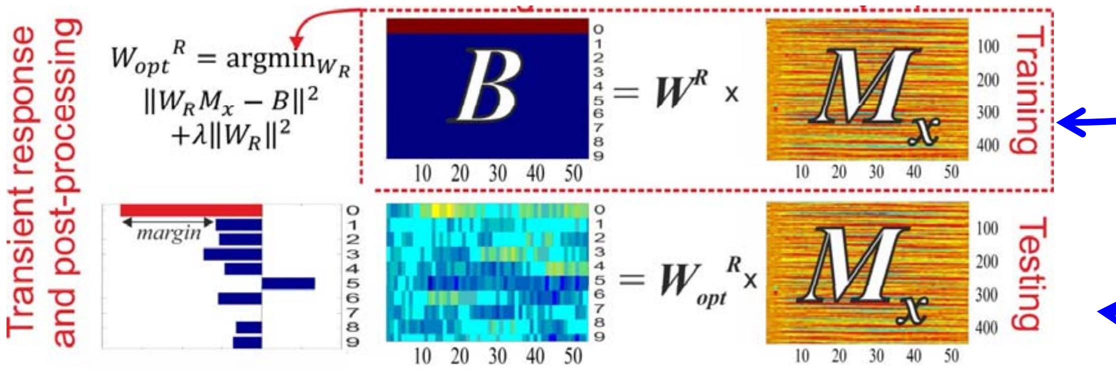


- **<u>Training of the Read-Out with target output function</u>**

  Learning: optimization of the W matrix, for each digit

  Regression problem

- **<u>Testing with training-defined Read-Out</u>**



Results : Word Error Rate (WER) < 0.02% at 20GS/s

We process 1 200 000 spoken digit per second !

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Conclusion, perpectives

- **Simple electro-optic architecture with a bandwidth higher than 10 GHz**

- **Pre- and post-processing performed externally**

- **Excellent first results at ultra-fast data rate on a classification benchmark test**

Spoken Digit Recognition with **Word Error Rate (WER) < 0.02% at 20GS/s, 1.2MDigit/s** (set size limited, 500 spoken digits data base)

Other benchmark test in process (chaotic time series prediction,…)

- **Many remaining degrees of freedom for optimization**