Interferometric stabilisation of a fibre-based optical computer

Experimental study

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ECOLE
POLYTECHNIQUE
DE BRUXELLES

Outline

Introduction

- The development of next generation technological computation paradigm is investigated
- Optical computers use light as information carrier $\longrightarrow$ *fast*
- Optical computers do not need to rely on boolean logic as classical computers do, new computation paradigms based on specific physical properties of light can be implemented
- *Photonic reservoir computing* is one of such implementation

Outline

Reservoir computing

- Special kind of artificial neural network
- State of the art performances for:
  - Real-time data processing
  - Chaotic time series prediction
  - Speech-recognition
  - Nonlinear communication channel equalisation
  - Financial forecasting
- Machine learning computationally lighter than the majority of artificial neural networks
- Scheme imposes very few constraints
  $\Longrightarrow$ implementation in physical systems possible !

Mathematical model

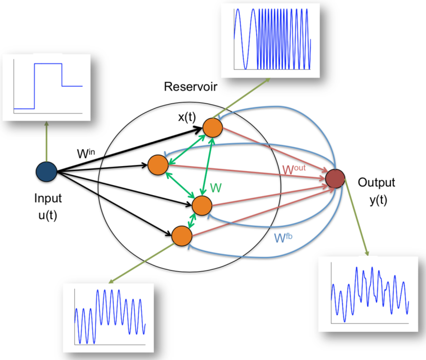
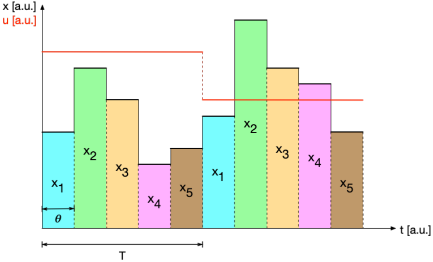


Figure: [BFP12]

- $\mathbf{x}$: state vector (activation levels of the neurons)
- u : input signal
- y : output signal
- $\mathbf{W}^{\text{in}}$: input matrix
- $\mathbf{W}$: connection matrix
- $\mathbf{W}^{\text{out}}$: output matrix

$$\mathbf{x}(n+1) = \mathbf{f}\left(\mathbf{W}^{\text{in}} u(n+1) + \mathbf{W}\mathbf{x}(n)\right)$$
$$y(n+1) = f^{\text{out}}\left(\mathbf{W}^{\text{out}}\mathbf{x}(n+1)\right)$$

Photonic reservoir computing



- So far in optical systems, only **Time Division Multiplexing** of the neurons
- Two main families of optical encoding of the neurons:
  - In the phaser of the electric field : $x_i = E_i$
  - In the intensity of the light : $x_i = |E_i|^2$

Numerical simulations - NARMA10

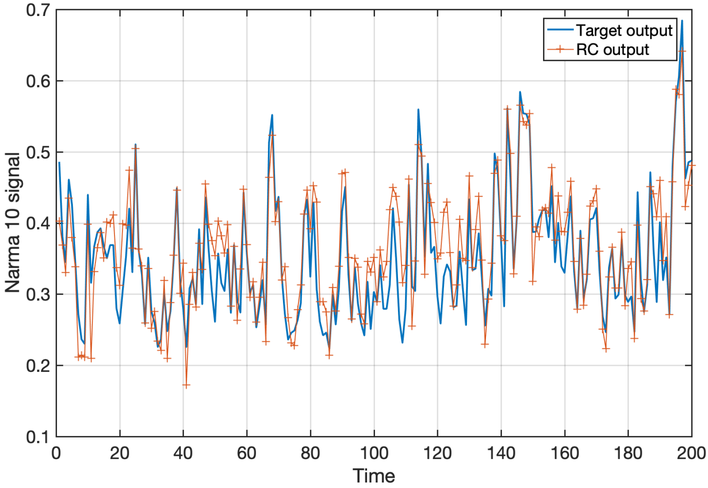


Figure: Simulation with 50 neurons. Normalised Mean Square Error of 0.1541.

Numerical simulations - nonlinear channel equalisation

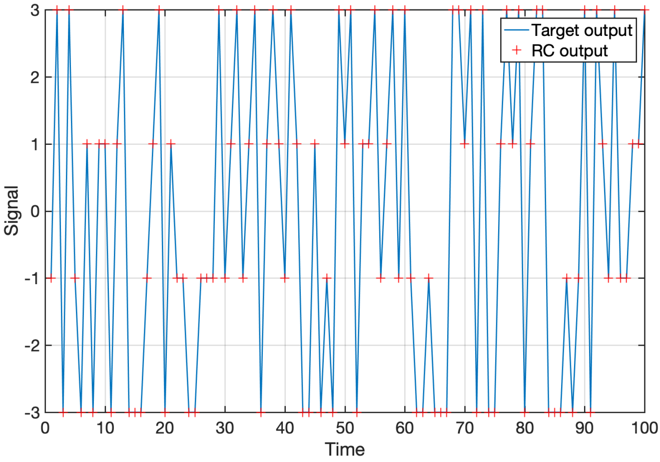


Figure: Simulation with 50 neurons. Signal-to-Noise Ratio of 32 dB. Signal Error Rate of 5×10^{-4}.

Outline

Working principle

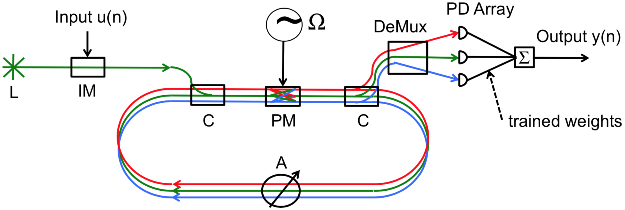


Figure: [Akr+16]

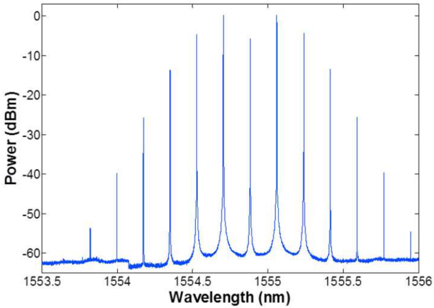
- **Wavelength Division Multiplexing** of the neurons
- Input: Monochromatic light source modulated in amplitude (data)
- The reservoir is the **ring cavity**
- Wavelength coupling handled by an intra-cavity **phase modulator**
- Output : wavelength demultiplexing and linear combination

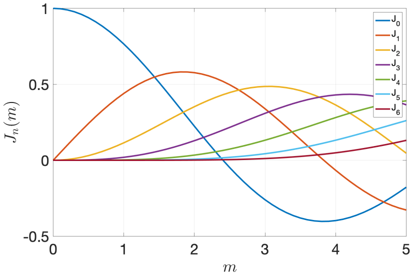
Frequency coupling of the neurons

- Transfer function of a phase modulator

$$Ee^{i\omega t} \xrightarrow{\Omega} Ee^{i\omega t}e^{im\sin(\Omega t)} = E\sum_{n=-\infty}^{\infty} J_n(m)e^{i(\omega+n\Omega)t}$$

- J_n : Bessel function of order n
- m : modulation depth ($m \leq 2$ experimentally)
- **Drawback : limited number of usable neurons $\Longrightarrow$ 13 neurons**





Mathematical model

- Neurons encoded in complex phaser representation of the electric field
- State vector :

$$\mathbf{x} = \sum_{i=-\eta}^{\eta} x_i \hat{\mathbf{e}}_i$$

- Basis vectors :

$$\hat{\mathbf{e}}_n = e^{i\omega_n t} = e^{i(\omega + n\Omega)t}$$

- Phase modulator frequency coupling transfer matrix :

$$\mathbf{J} = \begin{bmatrix} J_0(m) & J_{-1}(m) & \dots & J_{-\eta}(m) & \dots & J_{-2\eta}(m) \\ J_1(m) & J_0(m) & \dots & J_{-\eta+1}(m) & \dots & J_{-2\eta+1}(m) \\ \vdots & \vdots & & \vdots & & \vdots \\ J_{2\eta}(m) & J_{2\eta-1}(m) & \dots & J_{\eta}(m) & \dots & J_0(m) \end{bmatrix}$$

Mathematical model

- Acquired phase factor matrix :

$$\Phi = \begin{bmatrix} e^{i\phi_{-\eta}} & 0 & \dots & 0 \\ 0 & e^{i\phi_{-\eta+1}} & & 0 \\ \vdots & & \ddots & \\ 0 & 0 & \dots & e^{i\phi_{\eta}} \end{bmatrix}$$

- α and β : feedback and input gains

Dynamics and output of the reservoir

$$\mathbf{x}(n+1) = \alpha \Phi \mathbf{J} \Big(\mathbf{x}(n) + \beta u(n+1)\ \hat{\mathbf{e}}_0 \Big)$$

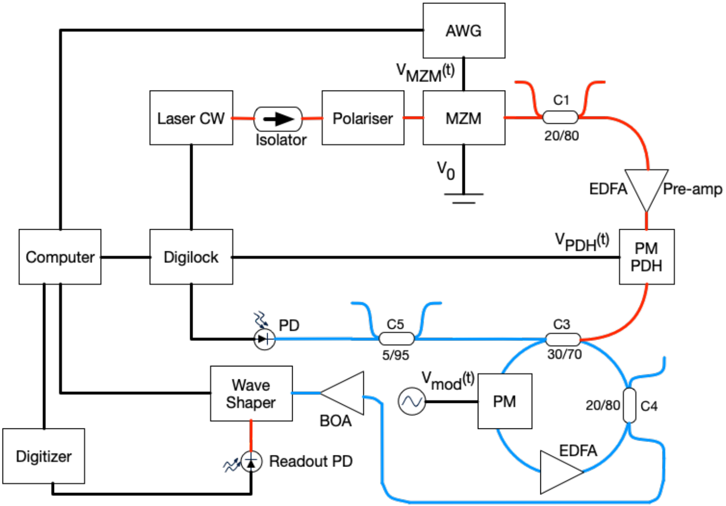
$$y(n+1) = \sum_{i=-\eta}^{\eta} W_i^{\text{out}}\ |x_i(n)|^2$$

$\hookrightarrow$ Linear reservoir with quadratic output

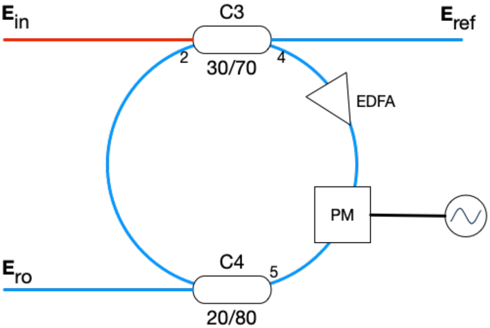
Outline

Interferometry

Experimental setup



Transfer function of the cavity



- **Transfer matrix** of the cavity :

$$\mathbf{E}_{\mathrm{ref}} = \mathbf{R}\ \mathbf{E}_{\mathrm{in}}$$

$$\mathbf{R} = \varepsilon_1 \mathbf{I} - (1-\varepsilon_1^2)\varepsilon_2 e^{-\gamma L}\left(\mathbf{I} - \varepsilon_1\varepsilon_2 e^{-\gamma L}\Phi_{1-\xi}\mathbf{J}\Phi_\xi\right)^{-1}\Phi_{1-\xi}\mathbf{J}\Phi_\xi$$

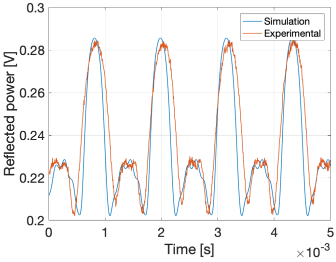
Transfer function of the cavity

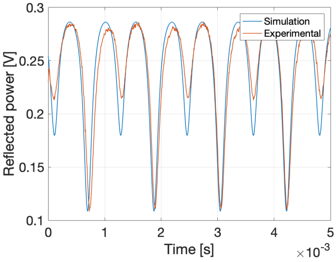
- Reflected field for a monochromatic input field:

$$\mathbf{E}_{\text{ref}} = E_0 \sum_{n=-\eta}^{\eta} R_{n,0}\hat{\mathbf{e}}_n \Longrightarrow |\mathbf{E}_{\text{ref}}|^2 \approx |E_0|^2 \sum_{n=-\eta}^{\eta} |R_{n,0}|^2$$

- Reflectivity :

$$\mathcal{R}(\omega) = \sum_{n=-\eta}^{\eta} |R_{n,0}(\omega)|^2$$





Classical cavity stabilisation

Pound-Drever-Hall technique

Pound-Drever-Hall technique for the reservoir cavity

Cavity stabilisation performances

Results

Rank	A_{PDH} [V_{PP}]	ν_{PDH} [kHz]	ε^* [a.u.]	ϕ [rad]	Challenger [mrad^2]
#1	0.4	781	400	1.3	291.5
#2	0.2	781	-300	-1.43	327
#3	0.4	781	700	1.45	337.25
#4	0.3	781	500	1.31	362.25
#5	0.4	781	600	1.39	376.5

- Overall best modulation frequency $\nu_{\text{PDH}} = 781\,\text{kHz}$
- However, measurements of modulation amplitudes are inconsistant
  - Should not depend on the stabilisation position
  - Most probable explanation : software developed to post-process raw data not working properly

Outline

Erratum

- Appendix A : All the values should be divided by two except ε^* and ϕ, and Challenger which should be divided by four.

Conclusion

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References

[Akr+16] A. Akrout et al. “Parallel photonic reservoir computing using frequency multiplexing of neurons”. In: *arXiv preprint arXiv:1612.08606* (2016).

[BFP12] A. Bernal, S. Fok, and R. Pidaparthi. “Financial Market Time Series Prediction with Recurrent Neural Networks”. In: (2012). URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.278.3606&rep=rep1&type=pdf.