Interferometric stabilisation of a fibre-based optical computer

Experimental study

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Outline

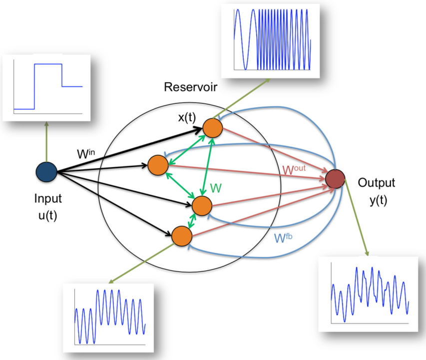
Introduction

- Limits of Moore's law slowly reached
- Optical computers can be **fast**
- Optical computers $\longrightarrow$ ~~boolean logic~~
- Development of photonic reservoir computing

Reservoir computing

- Special kind of artificial neural network
- Applications in :
  - Real-time data processing
  - Chaotic time series prediction
  - Speech-recognition
  - Financial forecasting
  - ...
- Machine learning computationally light
- Few constraints $\Longrightarrow$ implementation in physical systems !

Mathematical model



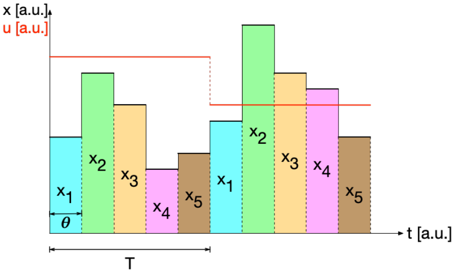
Bernal, Fok, and Pidaparthi 2012

- $\mathbf{x}$: 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

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

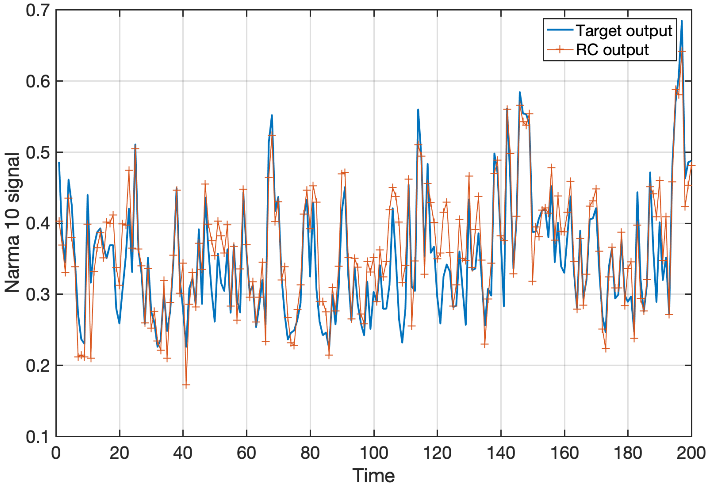
Photonic reservoir computing

- **Time Division Multiplexing** of the neurons



- Encoding of the neurons :
  - **Intensity** of the light : $x_i = |E_i|^2$ (Paquot et al. 2012)
  - **Phaser** of the electric field : $x_i = E_i$ (Vinckier et al. 2015)

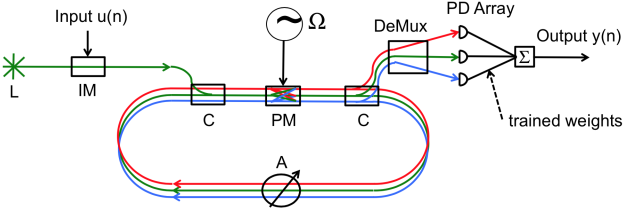
Numerical simulations - NARMA10



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

Outline

Wavelength division multiplexing of the neurons



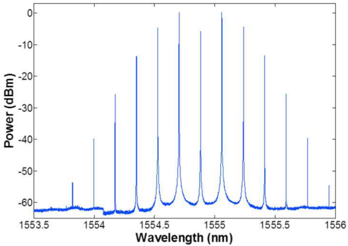
Akrout et al. 2016

- Input : monochromatic laser modulated in amplitude $\rightarrow u(n)$
- Optical cavity stabilisation with intra-cavity phase modulation
- Output : wavelength demultiplexing and linear combination

Frequency coupling of the neurons - phase modulator

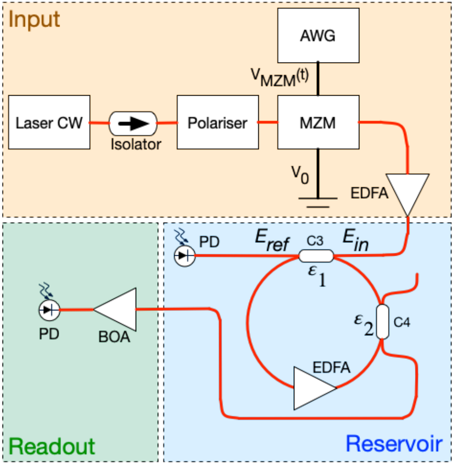
$$Ee^{i\omega t} \xrightarrow{\Omega} Ee^{i\omega t}e^{i m \sin(\Omega t)} = E \sum_{n=-\infty}^{\infty} J_n(m)e^{i(\omega + n\Omega)t}$$

- J_n : Bessel function of order n
- m : modulation depth
- Ω : modulation frequency $\approx 20\,\text{GHz}$



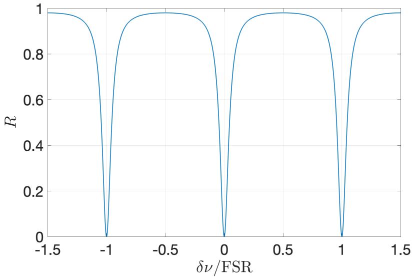
$\hookrightarrow$ Only 13 neurons !

Cavity transfer function **without** phase modulation



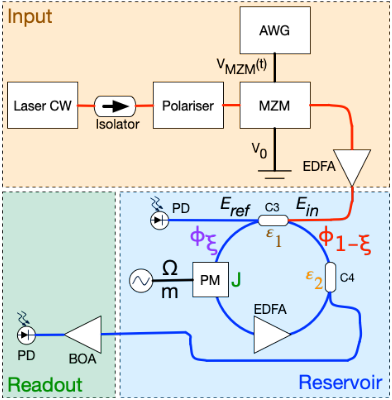
- Reflectivity :

$$\mathcal{R}(\omega) = 1 - \frac{1}{1 + \mathcal{F}\sin^2\left(\frac{\omega}{\mathsf{FSR}}\right)}$$



$\hookrightarrow$ Symmetric

Cavity transfer function **with** phase modulation

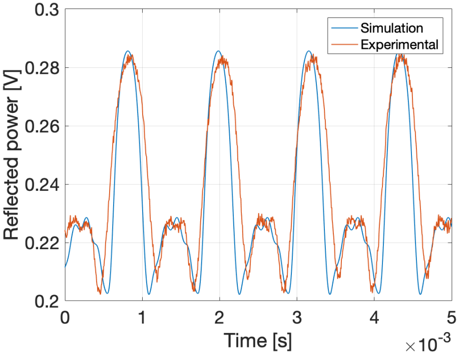


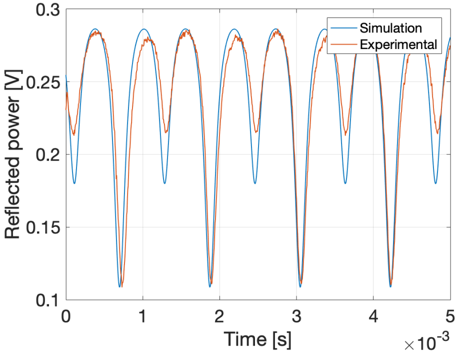
Transfer matrix

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

Cavity transfer function **with** phase modulation

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

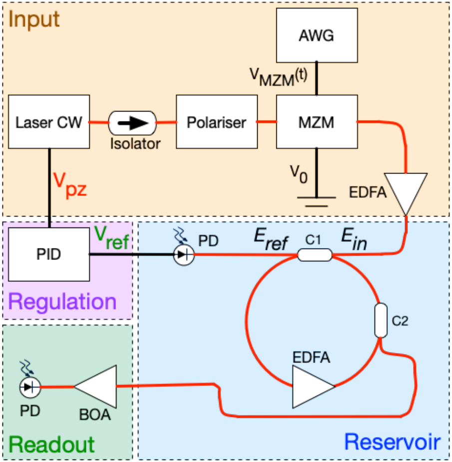


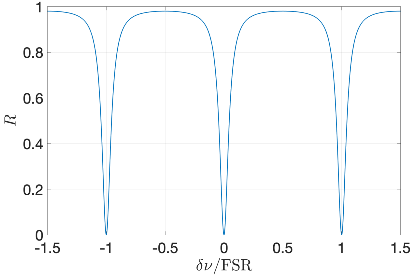


$\hookrightarrow$ More complex $\Rightarrow$ hard to stabilise !

Outline

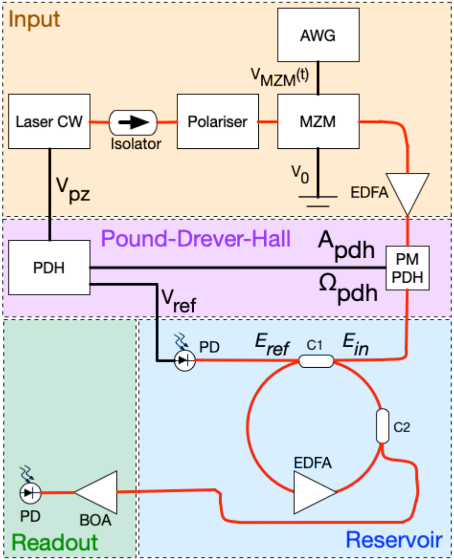
Classical cavity stabilisation

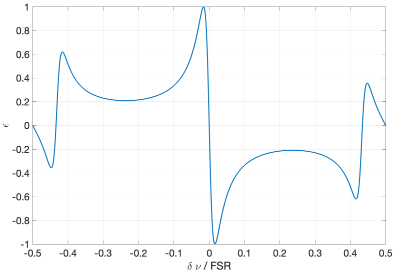




- Stabilisation of V_{ref} using V_{pz}
- Limitation : **symmetry**

Pound-Drever-Hall technique

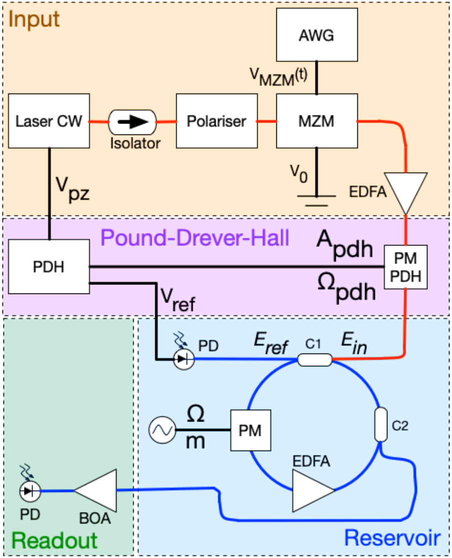


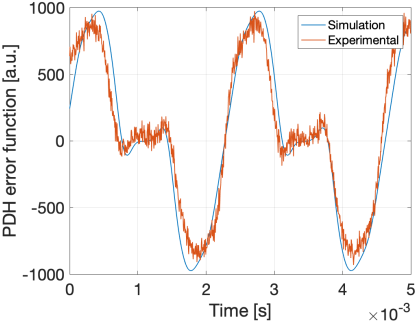


- Phase modulation + lock-in amplification
- Error function **anti-symmetric**

  $\hookrightarrow$ Better performances !

PDH technique for reservoir cavity **with** phase modulation





- Linear regions with steep slopes

$\hookrightarrow$ PDH error signal can be used !

Cavity stabilisation performances

- PDH parameters to explore
- Reservoir computer performances degraded by **phase noise** and **modulation amplitude** $\Rightarrow$ tradeoff !
- Figure of merit : Challenger $= \sigma_{\text{PDH}} \cdot \Delta\varphi$

$\hookrightarrow$ Should be minimised !

Results

Rank	A_{PDH} [V_{PP}]	ν_{PDH} [kHz]	ε^* [a.u.]	ϕ [rad]	Challenger [$mrad^2$]
#1	0.4	781	400	1.3	292
#2	0.2	781	-300	-1.43	327
#3	0.4	781	700	1.45	337
#4	0.3	781	500	1.31	362
#5	0.4	781	600	1.39	377

- Best modulation frequency $\nu_{PDH} = 781\,\text{kHz}$
- However, measurements not very reproducible so far...
- Not possible to use the cavity as a reservoir computer
  $\Rightarrow$ **still too much noise**

Outline

Conclusion

- Wavelength division multiplexed optical reservoir computer
- Optical cavity stabilisation **with intra-cavity phase modulation** $\longrightarrow$ **Pound-Drever-Hall technique**
- Experimental exploration of PDH settings $\longrightarrow$ optimal tradeoff for stabilisation performances[1]

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

Appendix : Pound-Drever-Hall (with details !)