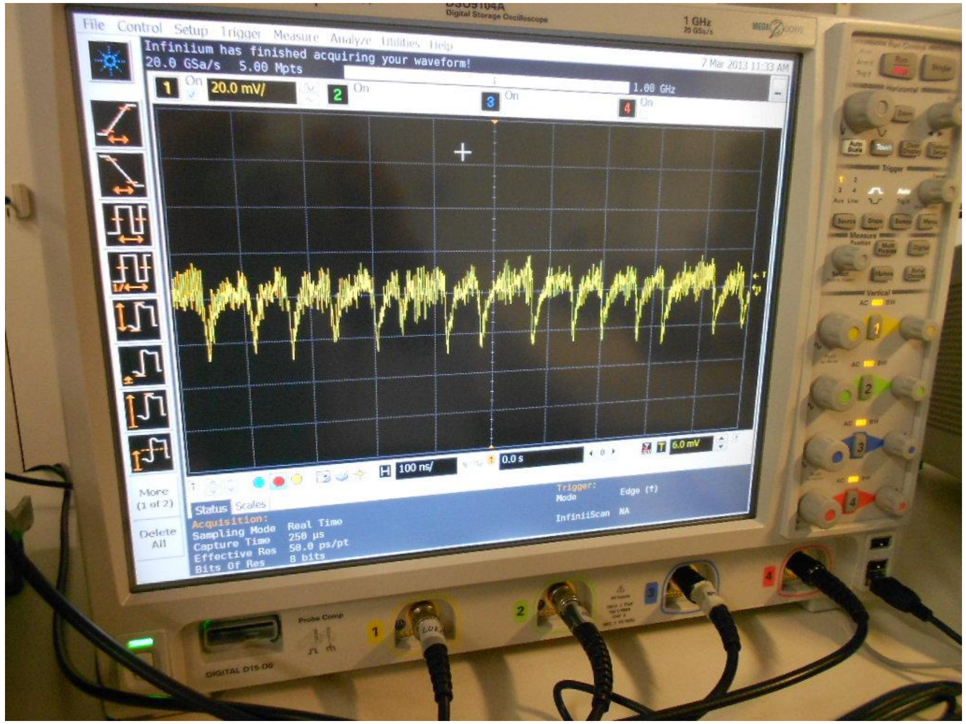

WP4: Neural Inspired Information Processing

C. Masoller, A. Pons, M.C. Torrent, J. García Ojalvo
UPC, Terrassa, Barcelona, Spain

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NETT Fellows' Induction
Nottingham, UK, April 2013

Two fellows in WP4: ESR 9 & ESR 10

- **ESR9** (to be recruited) will develop semiconductor laser networks that mimic the information processing capabilities of small neuronal networks.
- To be recruited may 2013
- Supervised by C. Masoller, M. C. Torrent and J. Garcia Ojalvo

- **ESR10** (Maciej Jedynak) will model at a mesoscopic level neuronal activity.
- Supervised by A. Pons and J. Garcia Ojalvo
- A focus of the study will be the effect of noise and the relation with coordination malfunctions that modify normal patterns of synchronized behaviour, which in turn lead to neurological disorders.

Internships and secondments

- **ESR 9**: From neuronal to photonic networks and back
  - Internship: Cairn
  - Secondments: CNR or UNOTT

- **ESR 10**: Stochastic effects in neuronal tissue at the mesoscopic level
  - Internship: INRIA
  - Secondments: CNR

Tasks and deliverables

ESR9

- Relating structural coupling with dynamical correlation in laser networks (Deliverable number 9.1, Month 30)
- Information processing capabilities in lasers and neuronal networks (9.2, M48)

ESR10

- Understanding sources of noise in neural mass models (10.1, M10)
- Ordering effects of random fluctuations at the mesoscopic level (10.2 M36)

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ESR 9 time table and work plan

- Characterize semiconductor lasers (SCLs) as optical neurons (first and second year)
- Coupled lasers: neuro-inspired laser networks (3rd year)
- Characterization of optical spikes and comparison with neuronal spikes via *symbolic ordinal analysis.*
- Relating coupling directionality with dynamical correlation in laser networks via *symbolic ordinal analysis* (9.1, M30)
- Quantifying information transmission (via a small modulation of the laser pump current) in coupled lasers (9.2, M48)
- Explore the road back to neuronal networks

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ESR 9 lab

- Experimental and numerical work will be carried out at the semiconductor laser laboratory in Terrassa, Barcelona

- In collaboration with Andres Aragoneses, PhD student finishing his third year.

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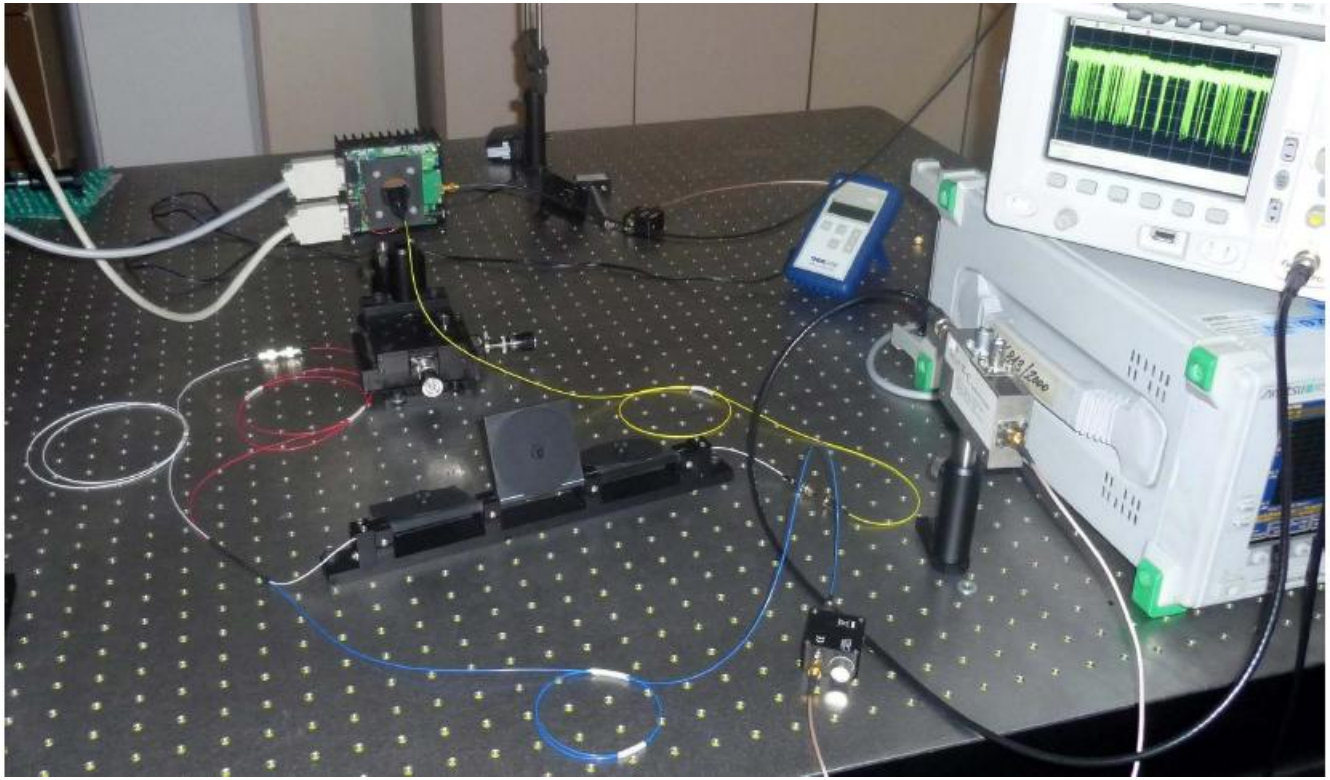
Semiconductor lasers lab



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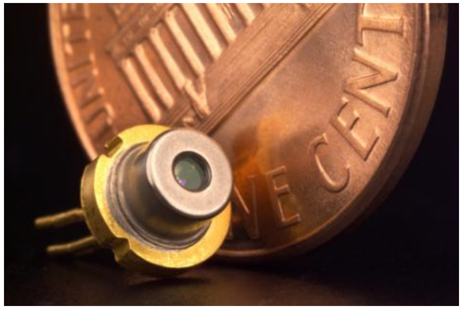
Outline

- Why semiconductor lasers?
- Coupling schemes
- Method of analysis: ordinal patterns
- On going and future work
- Concluding remarks

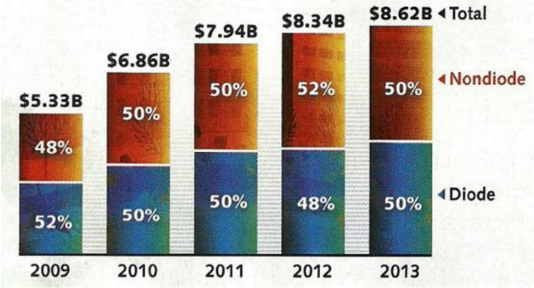
Semiconductor lasers

- Semiconductor lasers are compact, reliable and inexpensive.



- Mainly used for fiber optics communications and optical data storage (CDs, DVDs).

- Also in printers, bar-code scanners, sensors, etc.

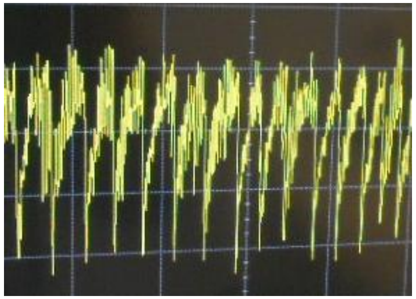


- Recent developments include Green and Blue lasers for applications in the life sciences (opto-genetics, biomedical imaging, etc).

Semiconductor lasers

- "solitary" (free-running) semiconductor lasers emit a stable output intensity.

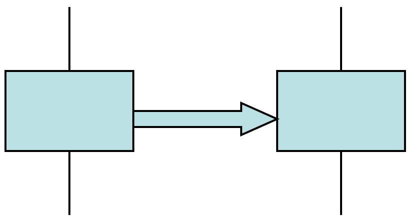
- Under optical feedback (self coupling) or with optical coupling (to another laser) these lasers display various types of dynamical outputs, that can resemble neuronal spikes.



- A range of coupling schemes provides access to different types of dynamical outputs.

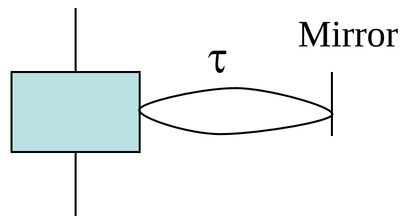
Coupling schemes

Coherent coupling



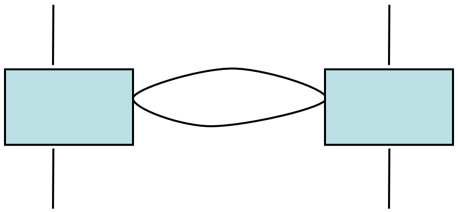
Optical Injection

$x_0 \rightarrow x$



Optical Feedback

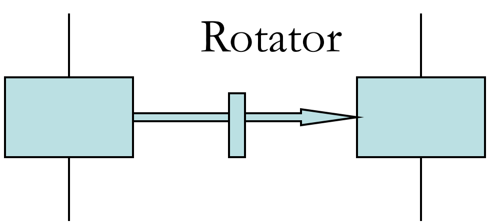
$x(t-\tau) \rightarrow x$



Two SCLs mutually coupled

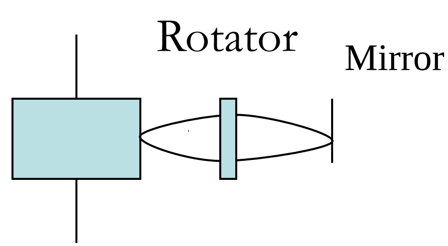
$x_1 \leftrightarrow x_2$

Orthogonal coupling



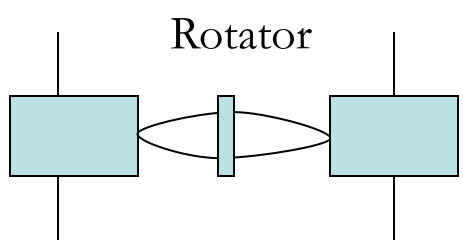
Orthogonal Injection

$x_0 \rightarrow y$



Orthogonal feedback

$y(t-\tau) \rightarrow x$



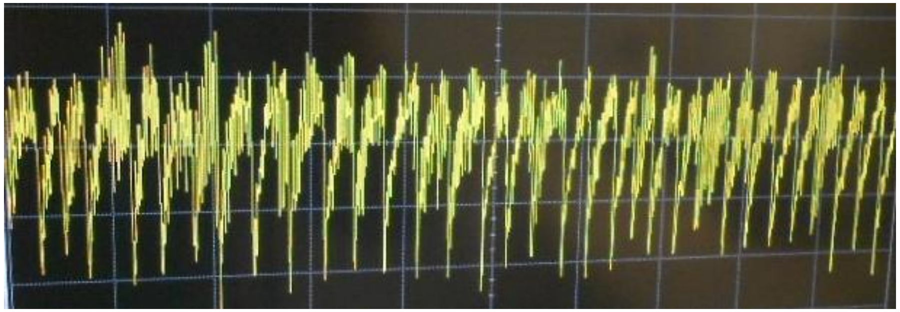
Orthogonal coupling

$y_1 \rightarrow x_2$
$y_2 \rightarrow x_1$

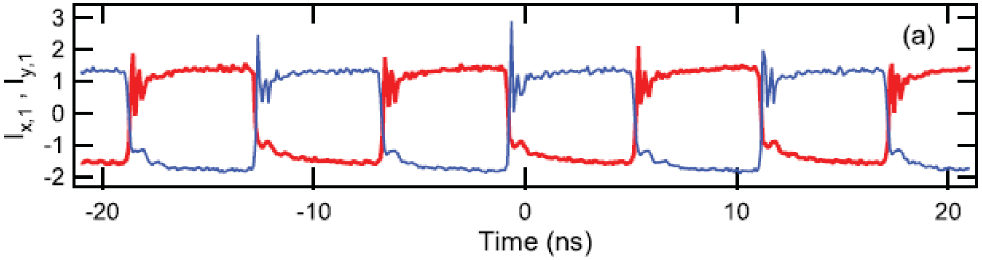
(Adapted from A. Gavrielides, AFOSR, US)

Two types of dynamical output

- With *coherent* optical feedback or coupling: spikes



- With *orthogonal* feedback or coupling: switching



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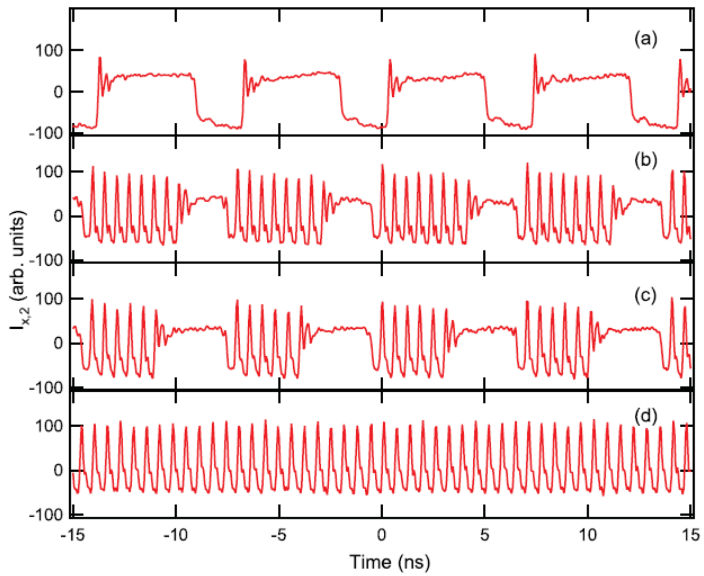
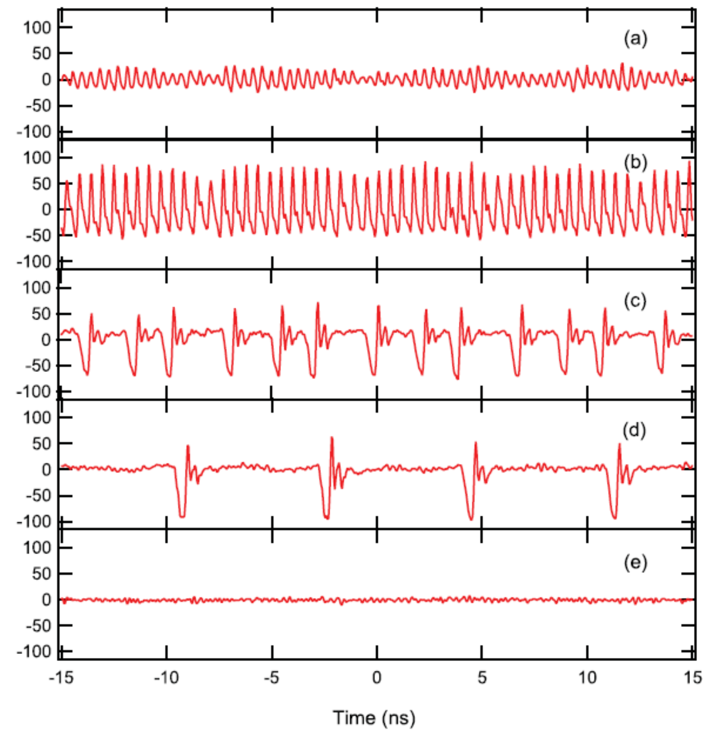
And also more complex behaviours





Prof. Coombes' presentation: Complexity, the NETT glue

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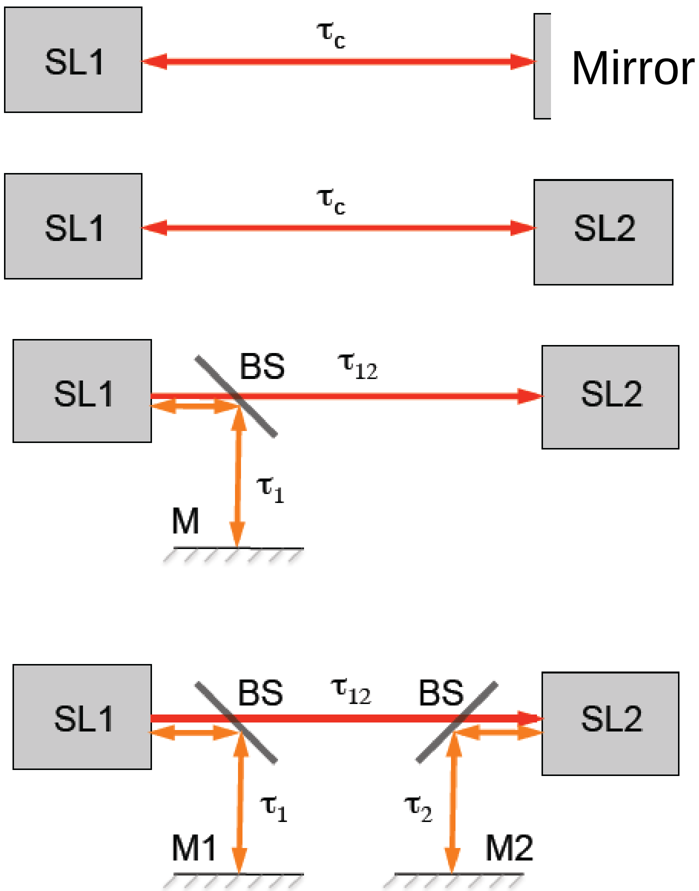
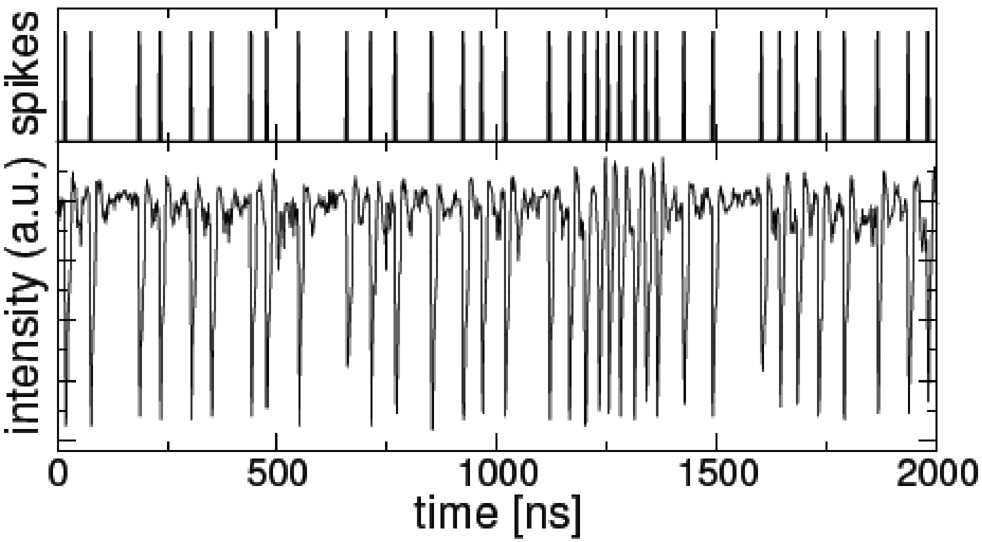
Optical spikes



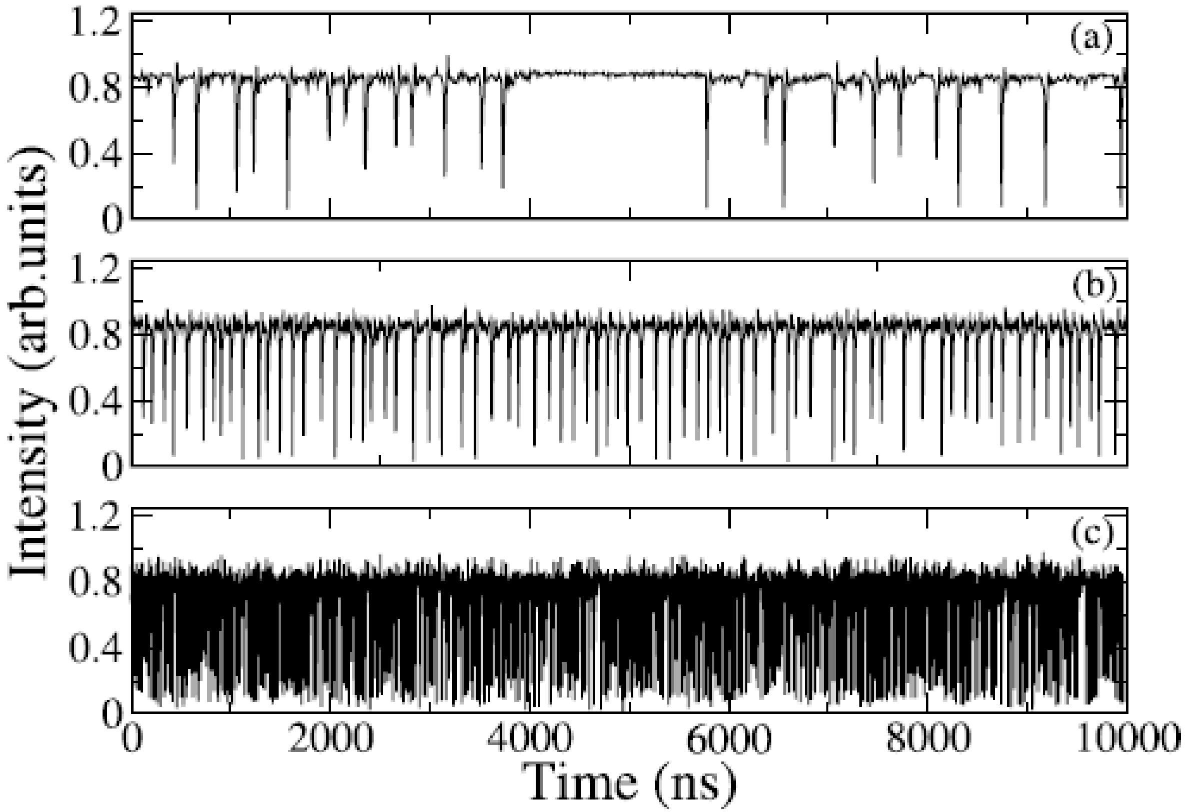
Laser output and detected spikes
(J. Tiana PhD thesis, UPC 2011)



Huge difference in the time scales of the "optical neuron" and of biological neurons
5 orders of magnitude (ns vs ms)

These setups induce a similar type of spiking optical output

The spike rate can be controlled by the laser parameters

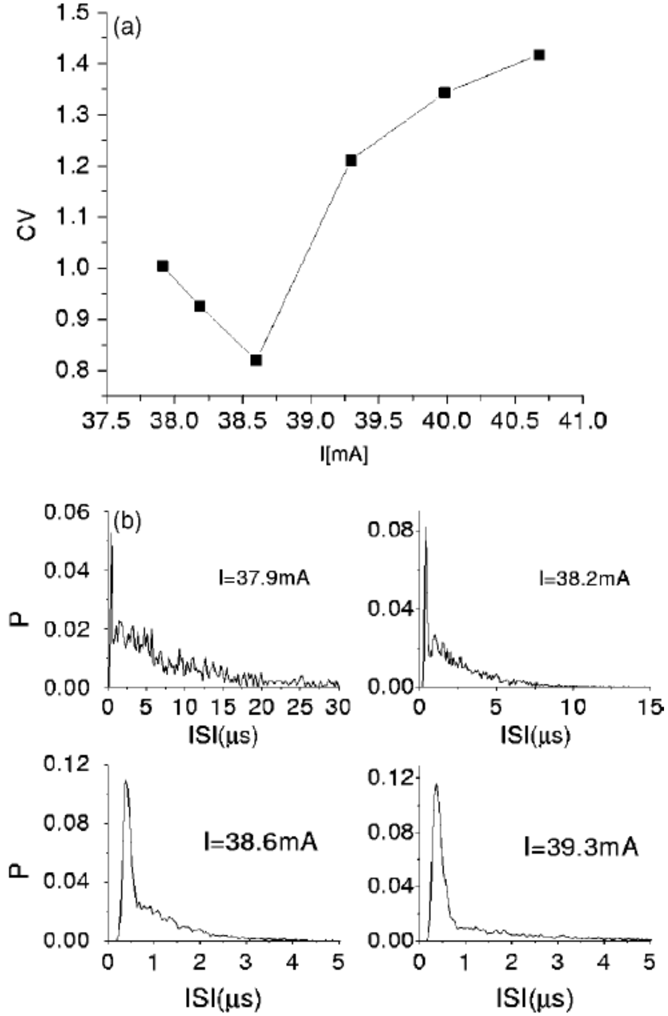


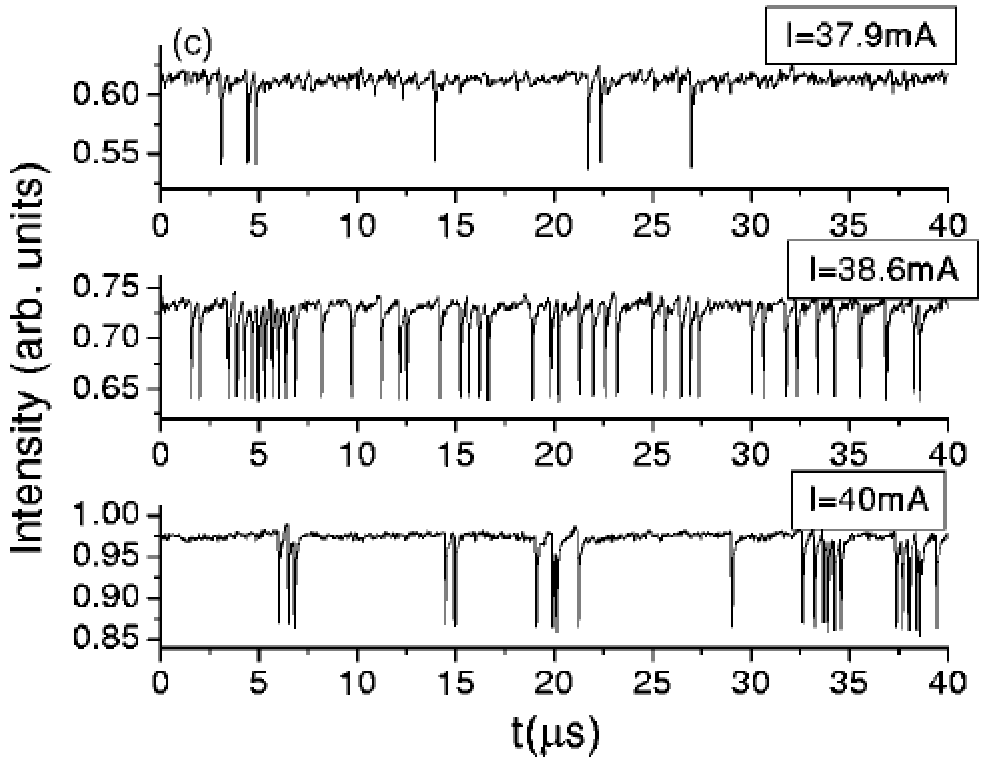
This dynamics is explained by a simple laser model (stochastic delay differential rate equations)

Laser output for increasing pump current (adapted from J. Tiana PhD thesis, UPC 2011)

Optical spikes: excitability

Normalized standard deviation





J. M. Mendez et al, PRE 2005

Optical spikes: coherence and stochastic resonance

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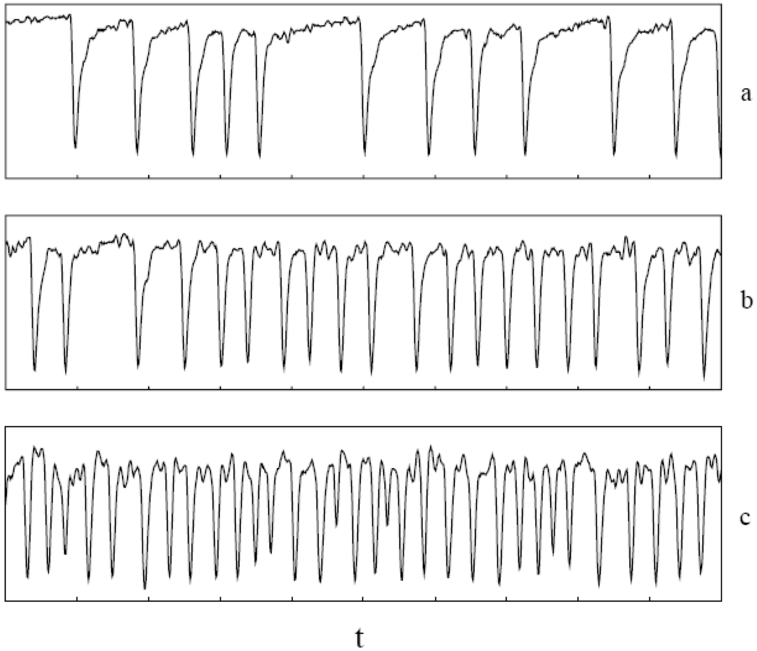

FIG. 1. Temporal behavior of the laser intensity for increasing input noise amplitude. From top to bottom: noise = −60.8 dBm/MHz (a), −52.5 dBm/MHz (b), and −44.3 dBm/MHz (c). The horizontal scale is 100 ns/div. The vertical scale is the same for the three plots.

Giacomelli et al, PRL 2000

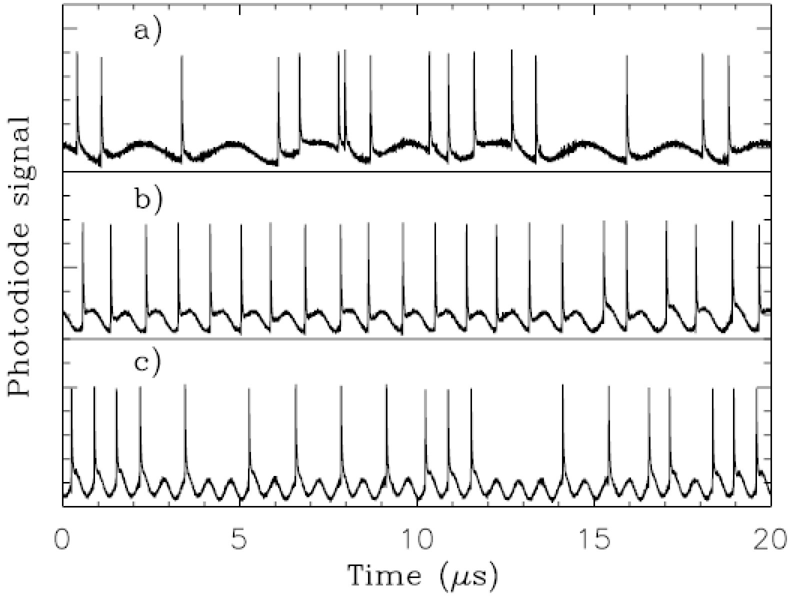

FIG. 1. Time traces of the laser output for a fixed noise level (−60.8 dBm V MHz$^{-1/2}$) and forcing frequency 0.4 MHz (a), 1.1 MHz (b), and 1.8 MHz (c). The vertical scale is the same for the three plots.

Marino et al, PRL 2002

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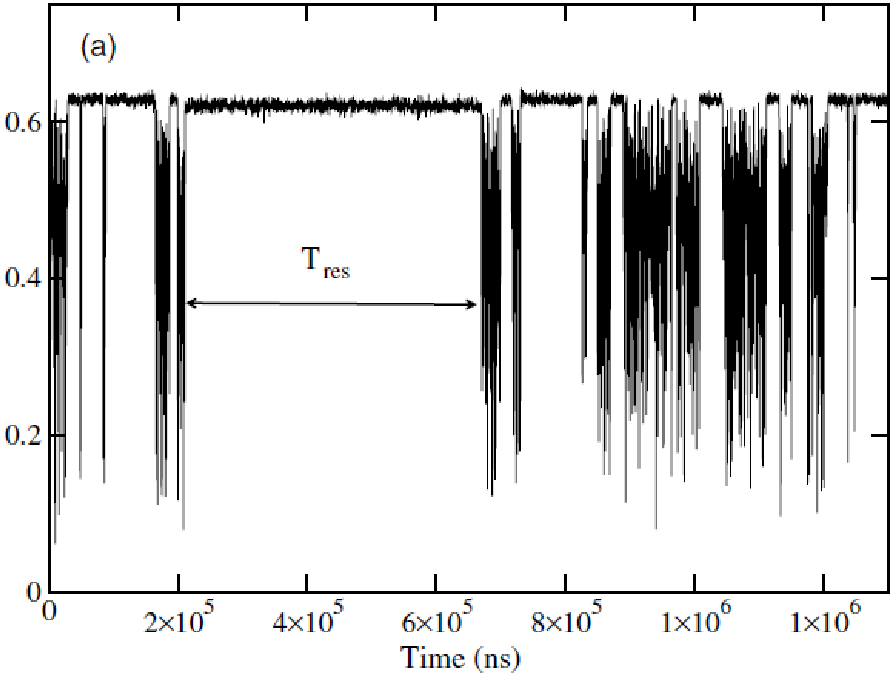
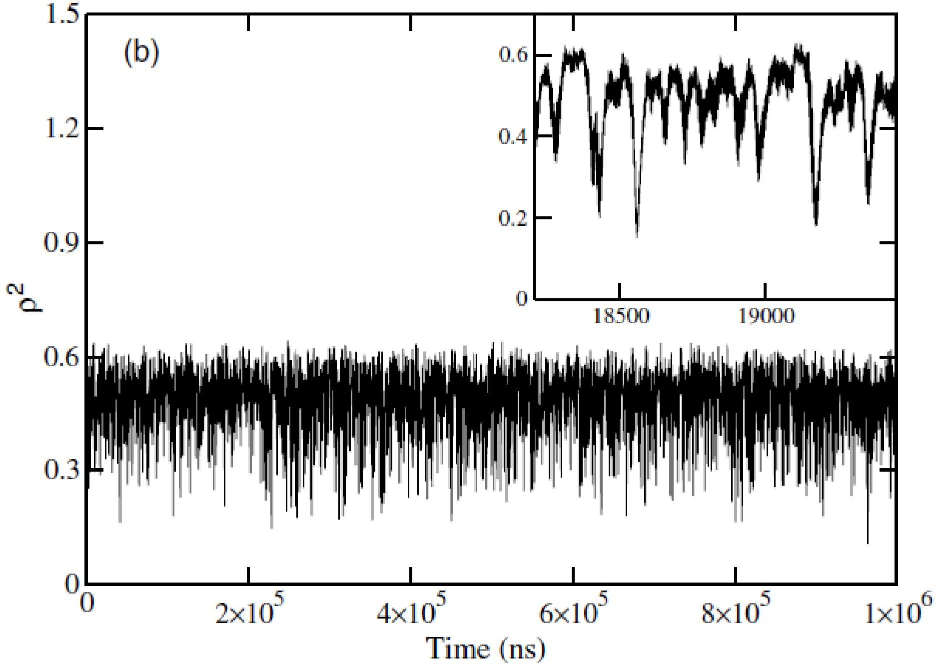
Optical spikes: bistability or noise-sustained transient dynamics

- Weak noise
- Stronger noise





A. Torcini et al, PRA 74, 063801 (2006)

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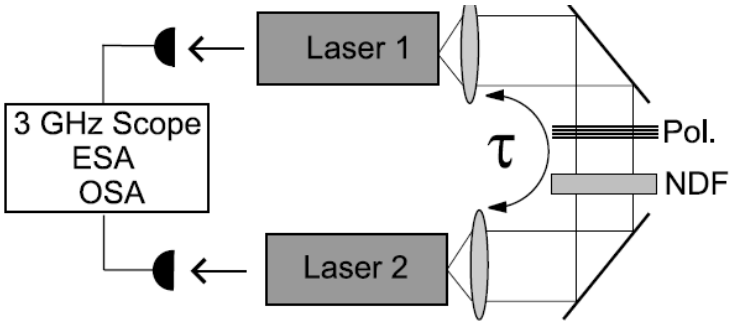
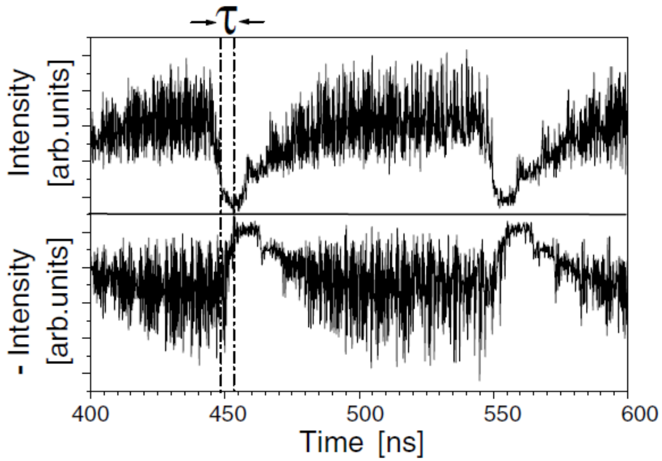
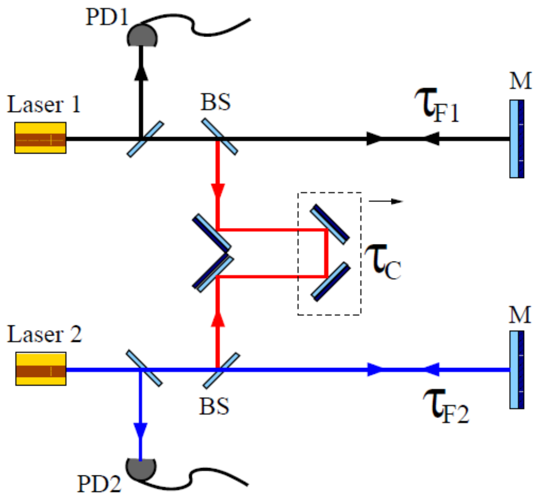
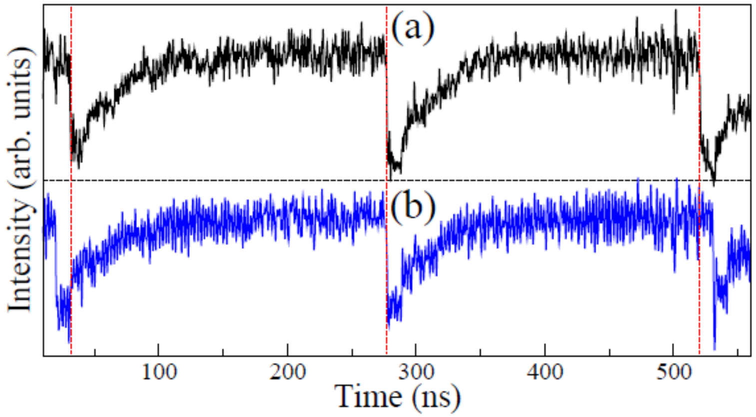
Two coupled lasers: lag-synchronization





T. Heil et al, PRL (2001)





J. F. Martinez Avila and J. R. Rios Leite, Opt. Express (2009)

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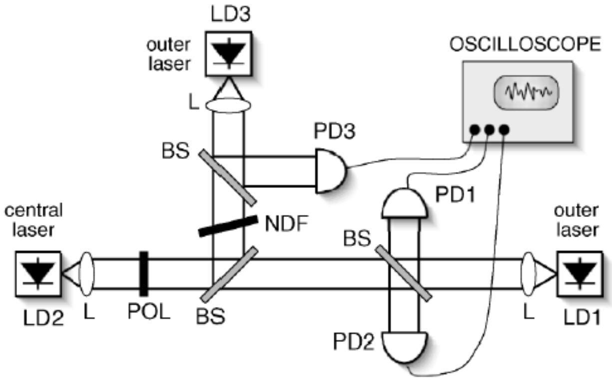
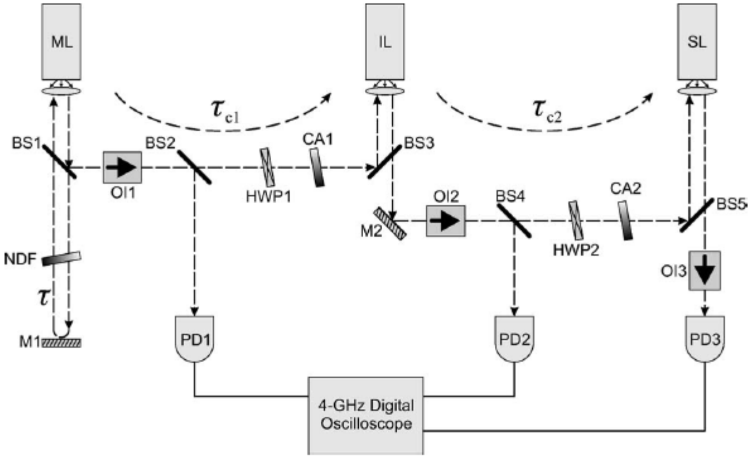
Towards optical neural networks: three coupled lasers

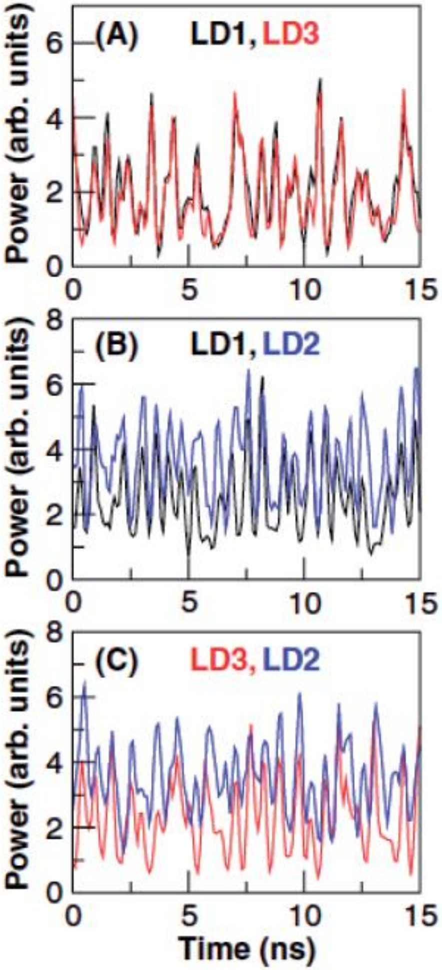


I. Fischer et al, PRL 2006



M. W. Lee et al, JOSAB 2006

zero-time-lag synchronization



I. Fischer et al, PRL 2006

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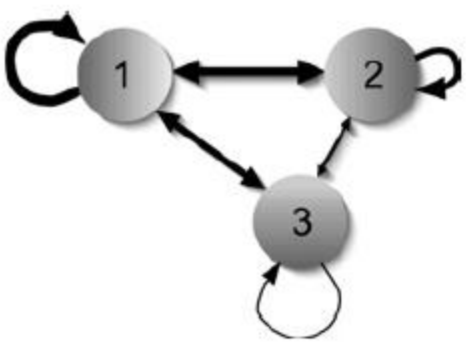
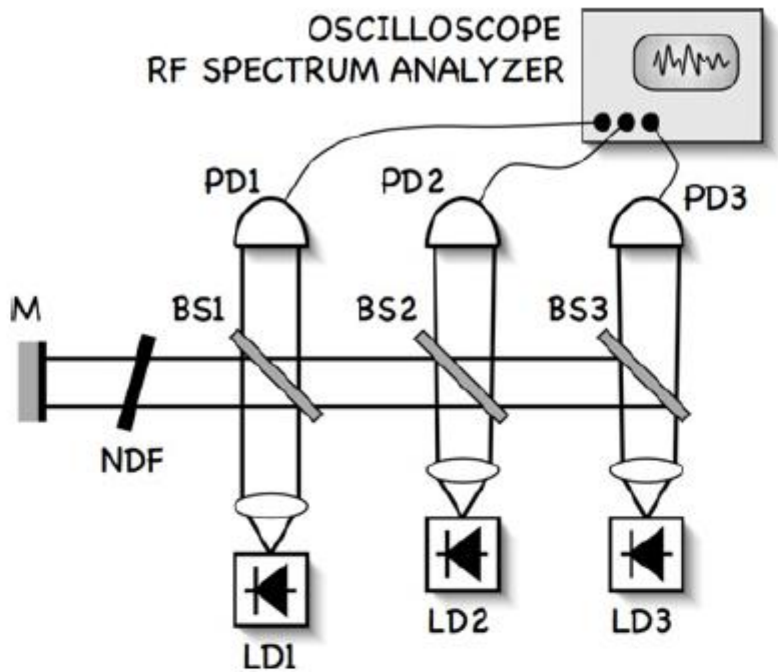
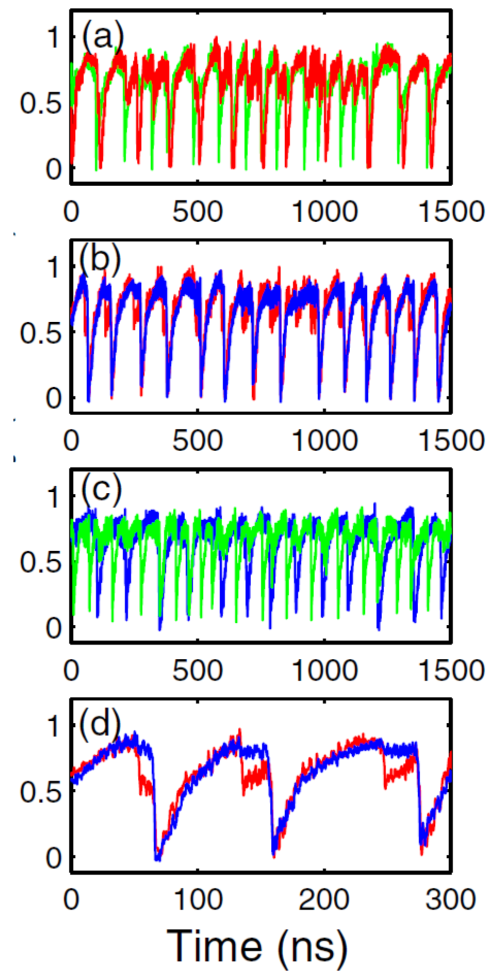
Clustering in a small laser network







C. Martinez, C. Masoller, M. C. Torrent and J. García Ojalvo, EPL 2007

Complex and stochastic dynamics

In these configurations (self-feedback or coupling) the laser spiking dynamics results from the interplay of

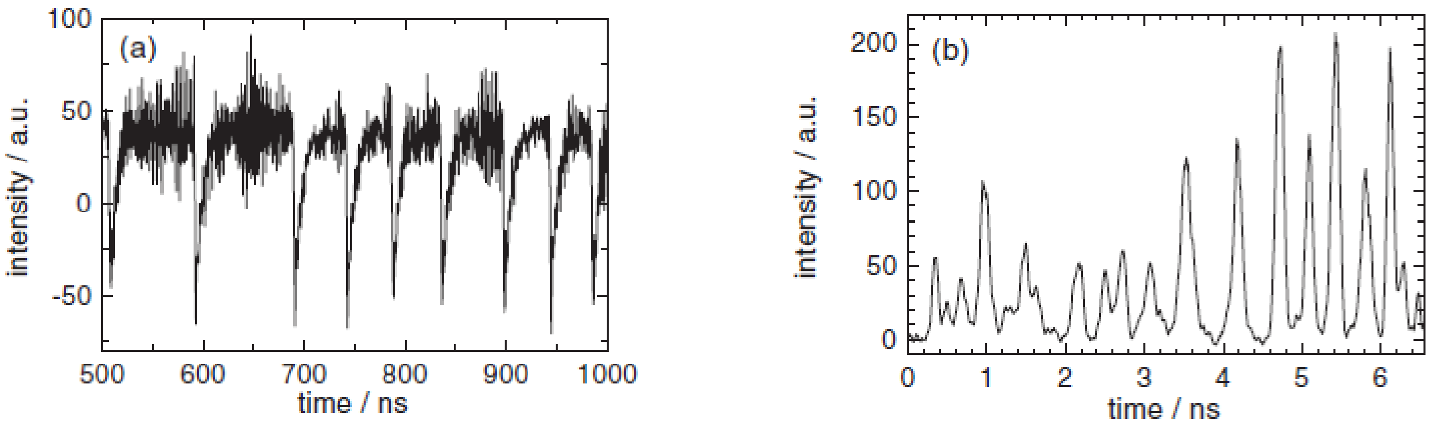
- Intrinsic nonlinear light-matter interactions
- Internal and external noise (optical, electrical, thermal, mechanical)
- Time-delay effects (light propagation time)

$\Longrightarrow$ We have a stochastic and high-dimensional complex system (the phase space is infinite due to the delay)

Problems

- Main problem: we can measure only one "output" variable (the intensity)

- Also a problem: the measure system (photodiode, oscilloscope) has a finite resolution bandwidth that gives low temporal resolution.



I. Fischer et al, PRL 1996

Time-series analysis

To characterize the underlying dynamics and test for determinism and nonlinearity, the two popular approaches are

- Phase-space reconstruction
  - Time-delay coordinates
  - Derivative coordinates
- Symbolic analysis
  - Phase space partition

They allow for model verification, forecasting, characterization, classification, etc.

Ordinal analysis

- Ordinal analysis is a form of symbolic analysis that was proposed by Bandt and Pompe in 2002 (Phys. Rev. Lett. 88, 174102).

- It has been successfully applied to many complex systems (biological, physics, socio-economics, geoscience, etc)
  - To distinguish stochasticity and determinism
  - To classify dynamical behaviours
  - To quantify complexity

- Suitable for event-level description of dynamical systems (e.g., for the analysis and classification of spike trains)

Symbolic analisys

- We consider a time series $\{x_1, x_2, x_3, \ldots\}$ that describes a dynamical system
- The time series is transformed (using an appropriated rule) into a sequence of symbols $\{s_1, s_2, \ldots\}$
- Which are taken from an "alphabet" of possible symbols $\{a_1, a_2, \ldots\}$

Symbolic words and "language"

- Next we consider "blocks" of symbols ("patterns" or "words")
- All the possible words form a "dictionary"
- And we can then analyze the "language" of the symbolic dynamics, i.e.,
  - the probabilities of the words,
  - missing/forbidden words,
  - transition probabilities,
  - symbolic information measures (entropy, mutual information, etc).

Examples

- Binary transformation. Consider a time series $\{x_1, x_2, x_3, \ldots\}$. The rule

  $$\text{if } x_i > x_{th} \Rightarrow s_i = 0; \text{ else } s_i = 1$$

  transforms the time-series into a sequence of 0s and 1s

- Ordinal transformation. The rule

  $$\text{if } x_i > x_{i-1} \Rightarrow s_i = 0; \text{ else } s_i = 1$$

  also transforms the time-series into a sequence of 0s and 1s

Construction principle of ordinal patterns (OPs) of length D

Computers in Biology and Medicine 42 (2012) 319–327

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

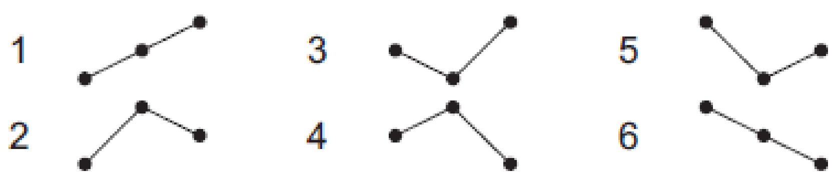
ELSEVIER

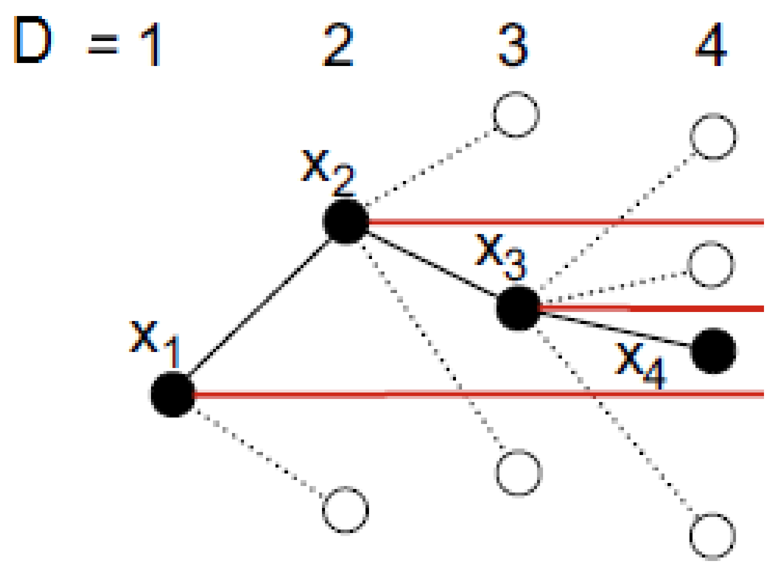
Classifying cardiac biosignals using ordinal pattern statistics and symbolic dynamics

U. Parlitz[a,b,*], S. Berg[c], S. Luther[a,b,d], A. Schirdewan[e], J. Kurths[f,g], N. Wessel[f]

For D=2 there are only two possible directions from x_1 to x_2: up (pattern 01) or down (pattern 10)

For D=3 there are 6 OPs:

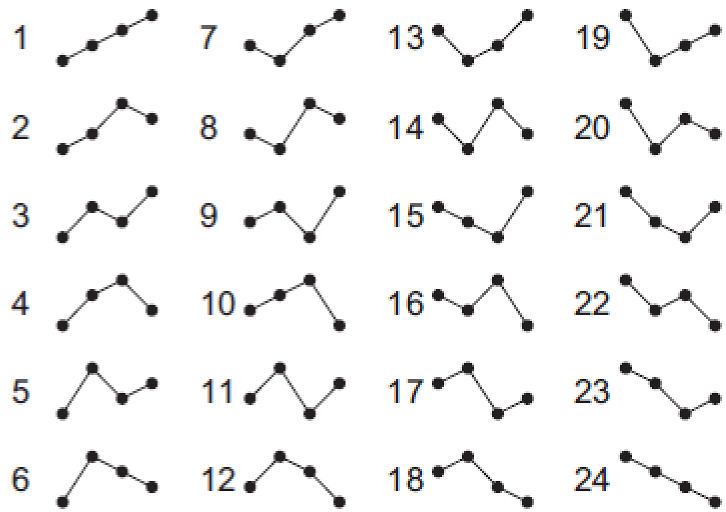




Ordinal patterns

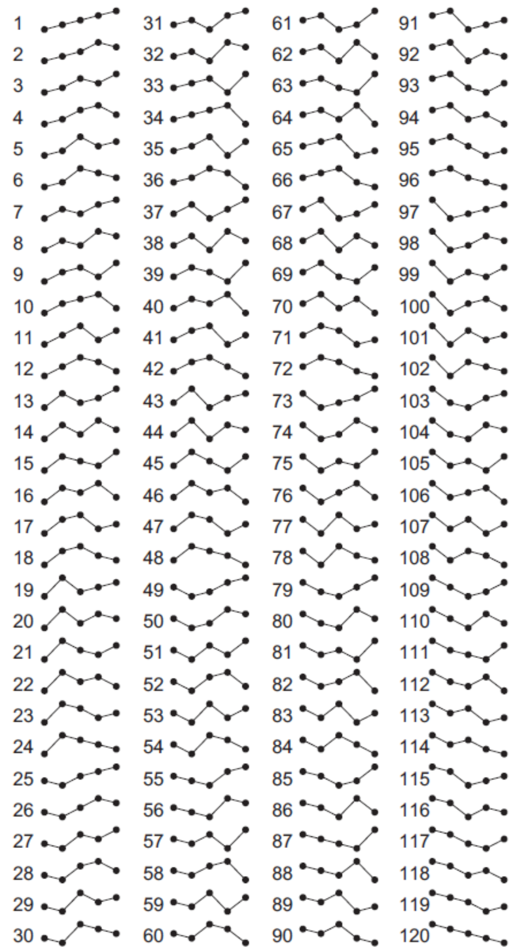
- For OPs of length D there are D! possible patterns

D=4

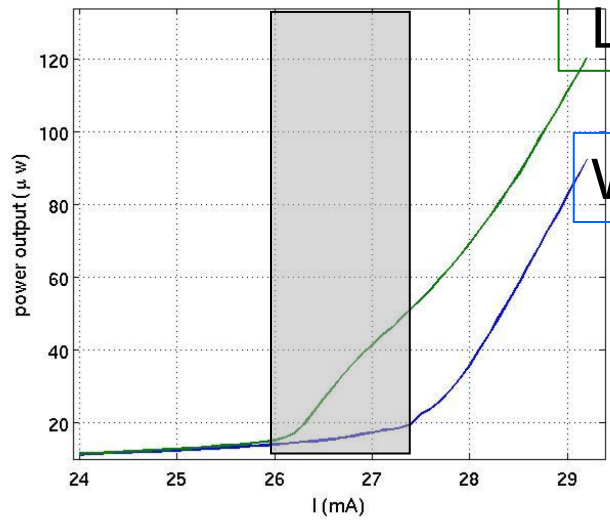


U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

D=5



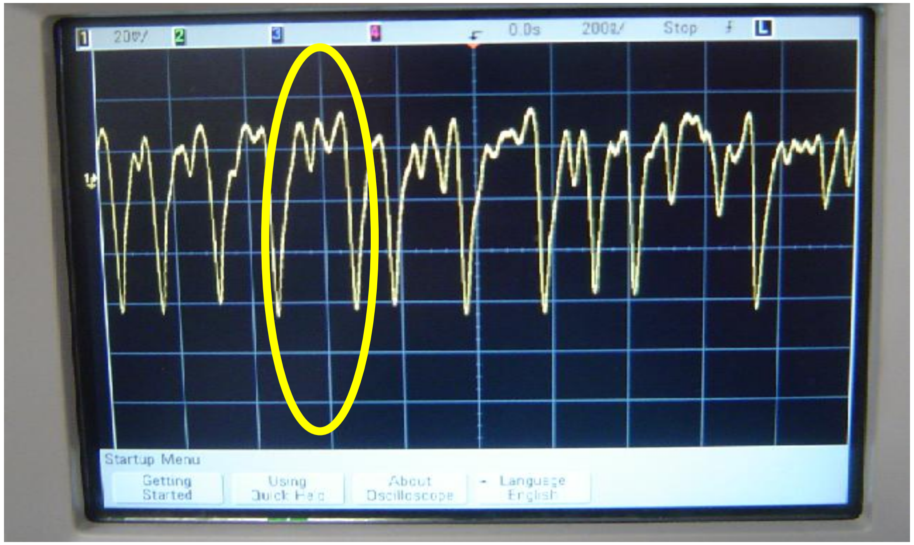
Ordinal analysis of optical spikes



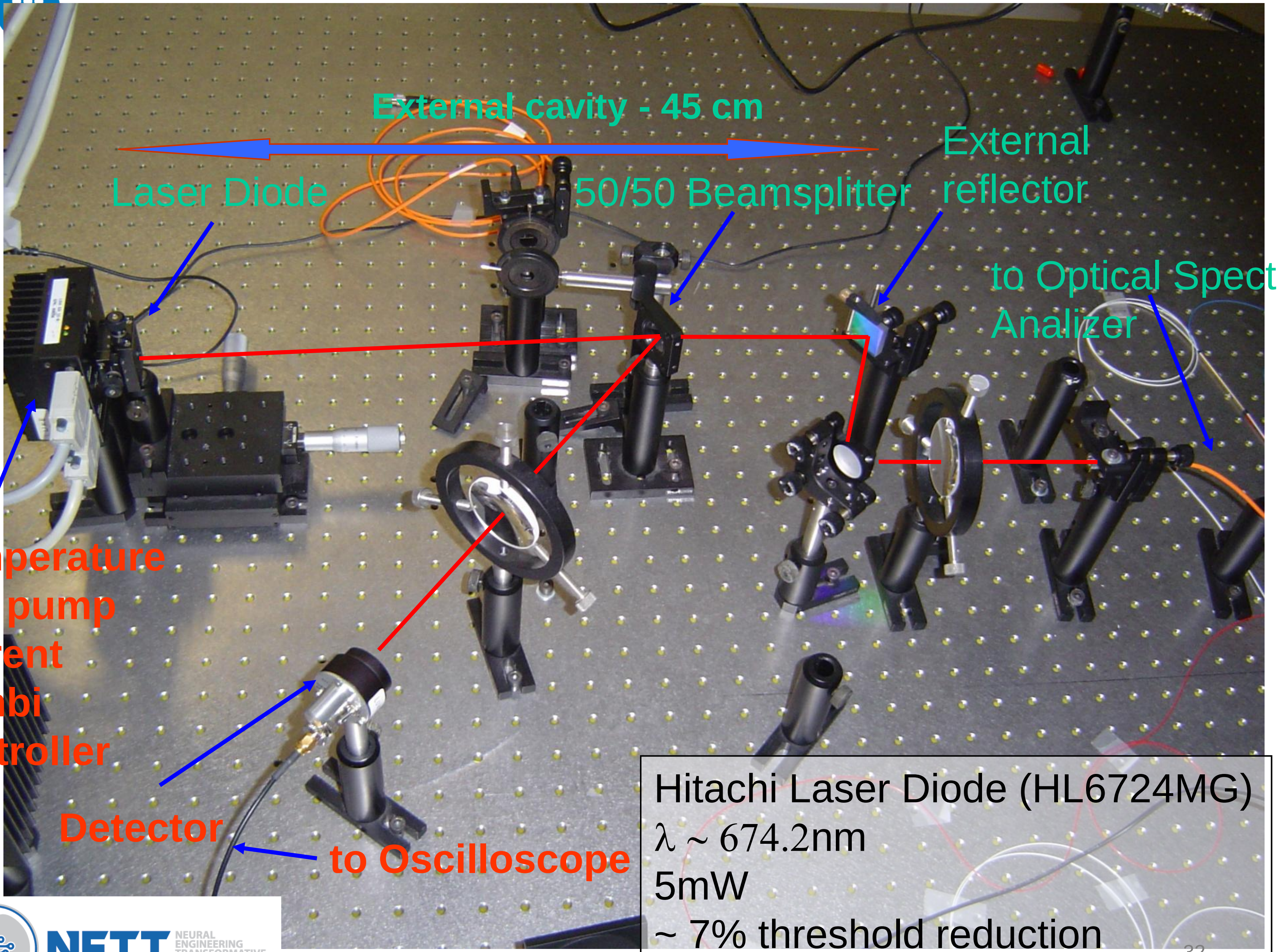
Laser with feedback

Without feedback

Laser output



IDI = Inter Dropout Interval (ΔT_i)



Hitachi Laser Diode (HL6724MG)
λ ~ 674.2nm
5mW
~ 7% threshold reduction

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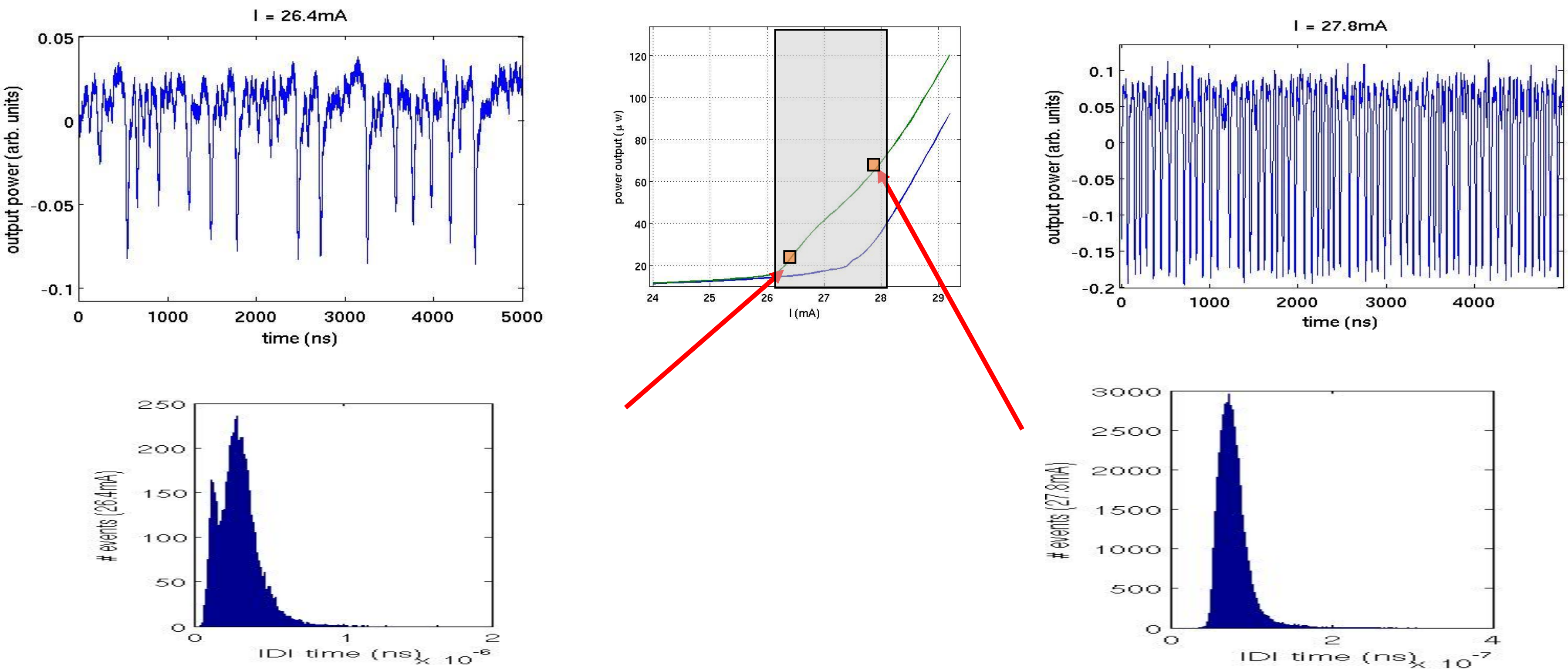
Statistics of the inter-dropout-intervals



Is there any information in the IDI sequence?
(analogy with foreign text as in Prof. Russell's presentation)

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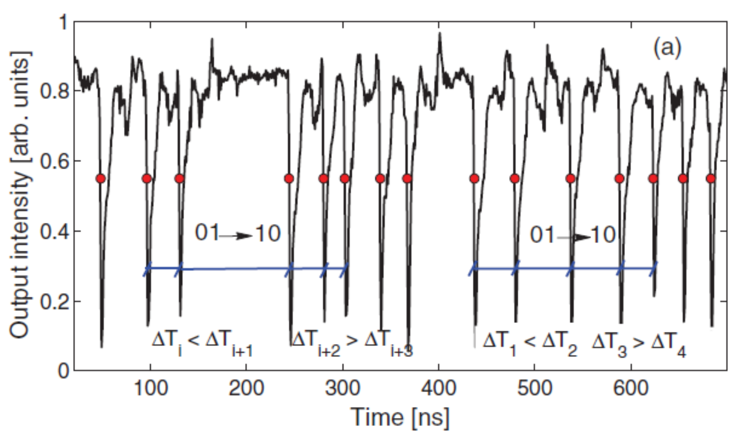
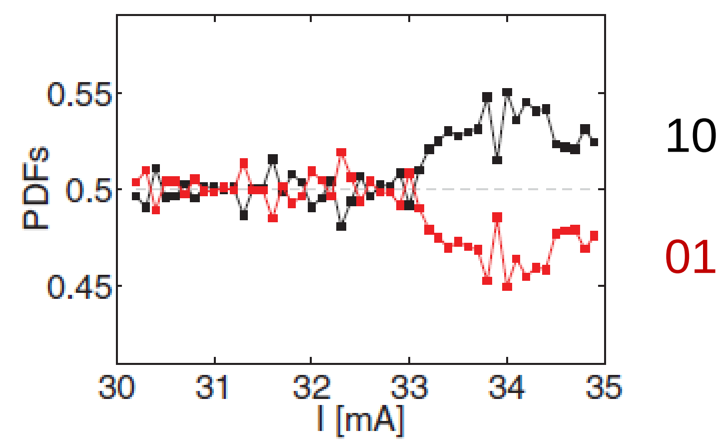
"language" analysis: word probabilities

PHYSICAL REVIEW E **84**, 026202 (2011)

Language organization and temporal correlations in the spiking activity of an excitable laser: Experiments and model comparison

Nicolas Rubido,[1] Jordi Tiana-Alsina,[2] M. C. Torrent,[2] Jordi Garcia-Ojalvo,[2] and Cristina Masoller[2]





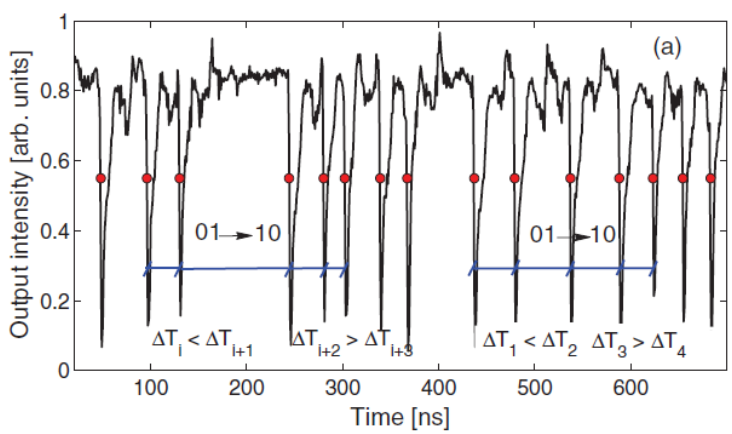
Consistent with stochastic dynamics at low pumps, but signatures of determinism at higher pump currents

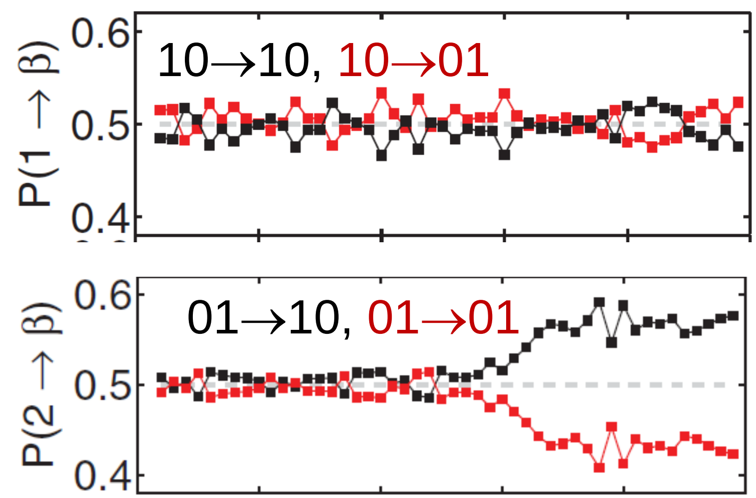
“language” analysis: transition probabilities

PHYSICAL REVIEW E **84**, 026202 (2011)

Language organization and temporal correlations in the spiking activity of an excitable laser: Experiments and model comparison

Nicolas Rubido,[1] Jordi Tiana-Alsina,[2] M. C. Torrent,[2] Jordi Garcia-Ojalvo,[2] and Cristina Masoller[2]





Consistent with stochastic dynamics at low pumps, but signatures of determinism at higher pump currents

At low pump currents: inter-dropout-intervals not fully random

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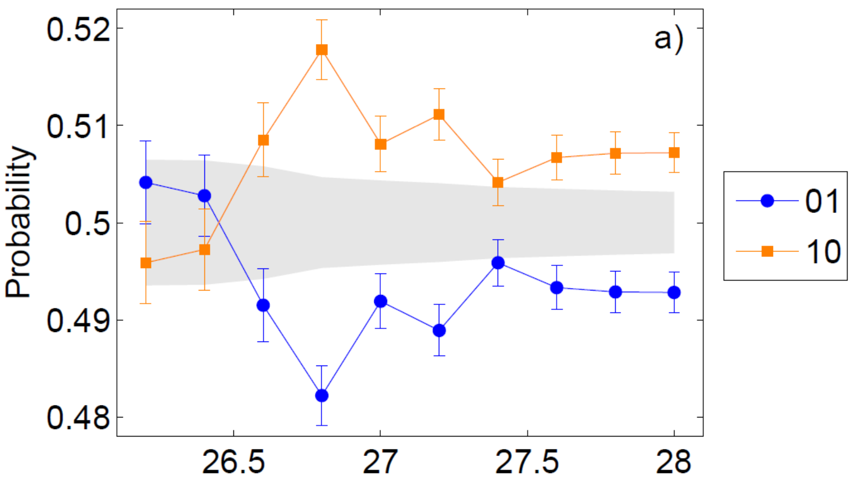
D=2



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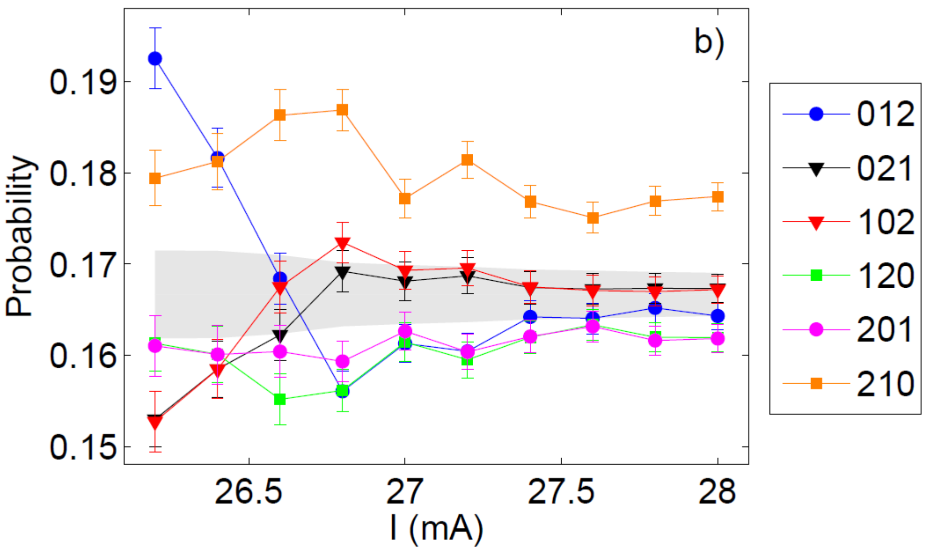

NETT NEURAL ENGINEERING TRANSFORMATIVE TECHNOLOGIES

A. Aragoneses, et al submitted (2013)

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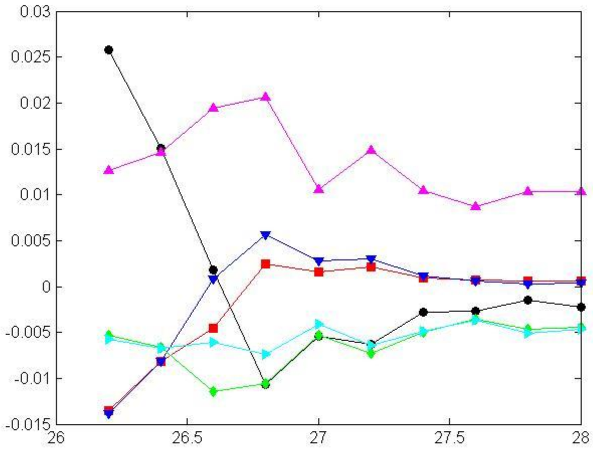
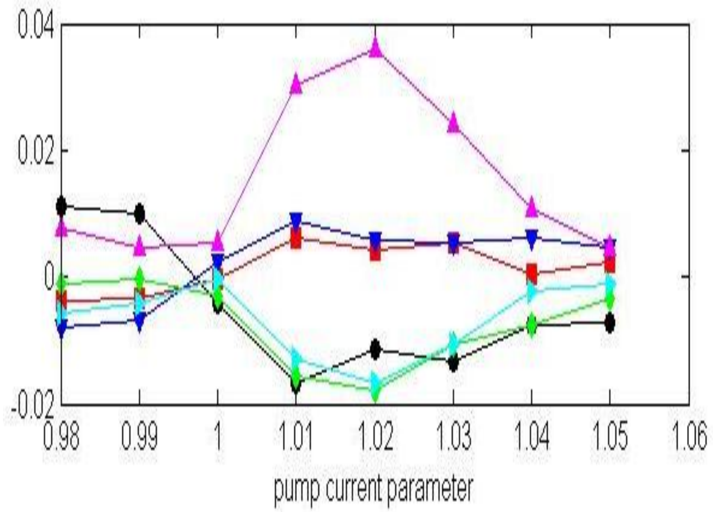
Ongoing work: model comparison

Experiments



Simulations



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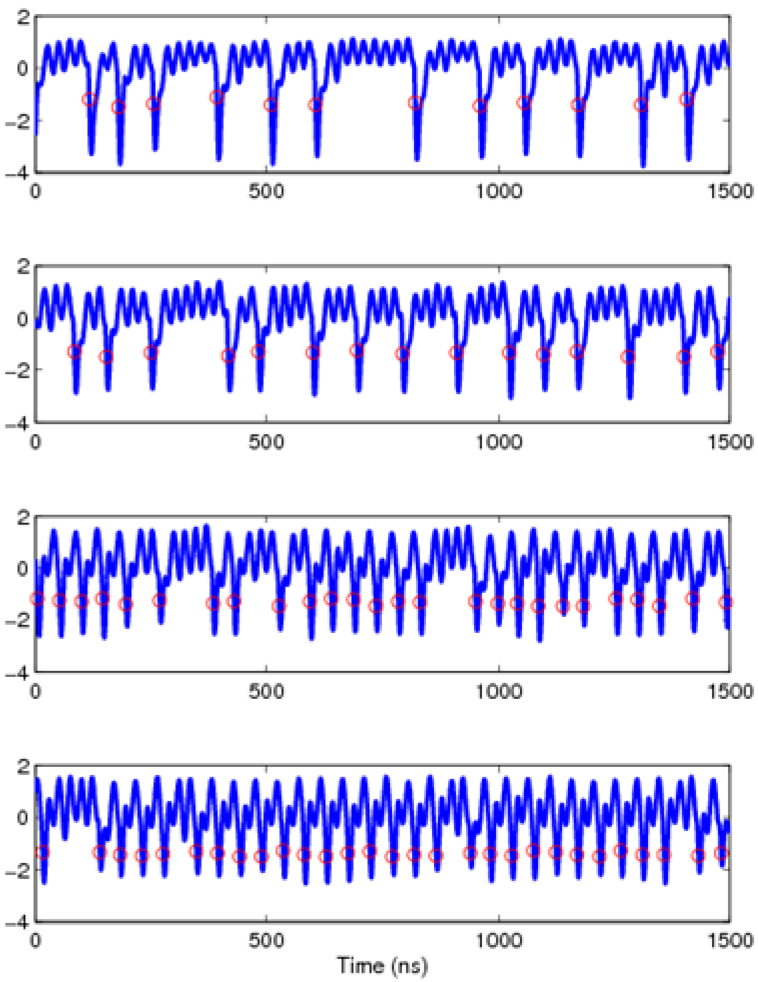
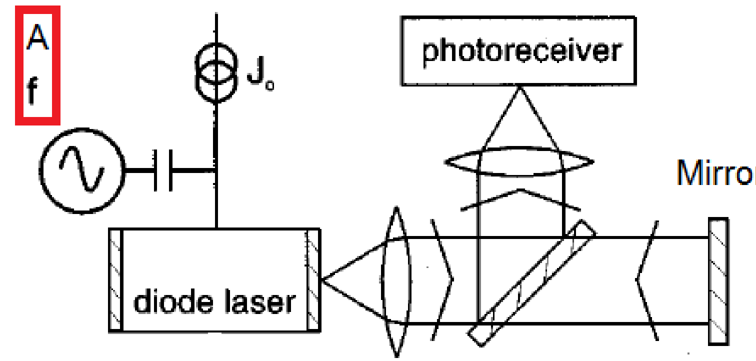
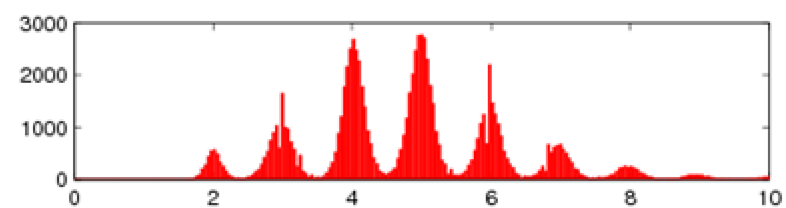
Ongoing work: spiking under the influence of a periodic forcing





Histogram of inter-dropout-intervals



IDIs (in units of the modulation period)

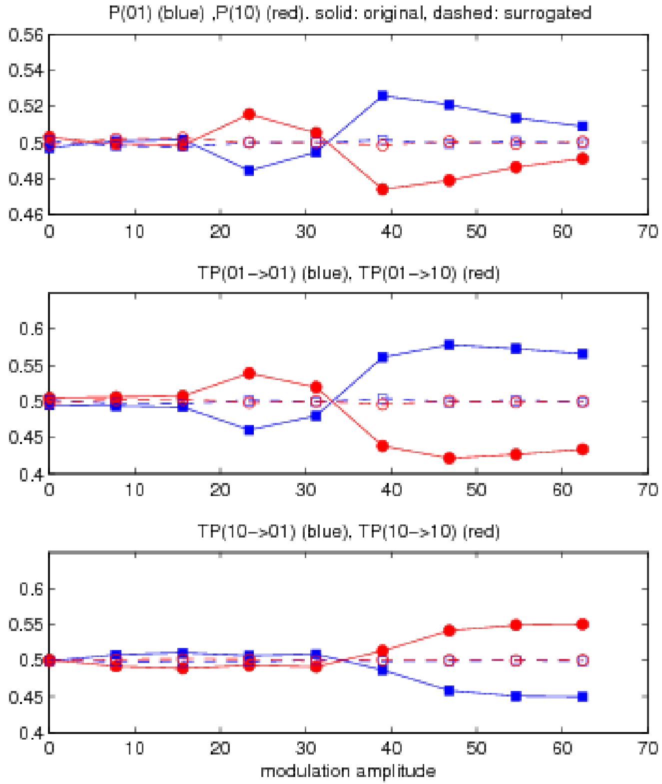
Ongoing work: influence of forcing parameters

Experiments

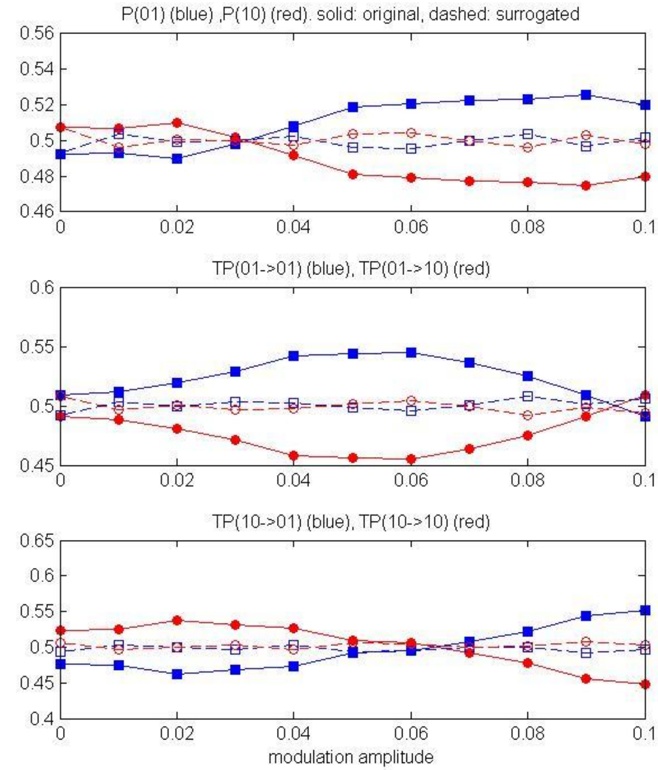
P(10)
P(01)

TP(01→10)
TP(01→01)

TP(10→10)
TP(10→01)



Simulations



OP probabilities and transition probabilities depend on the modulation amplitude (A) and frequency (f)

Concluding remarks

- Ordinal analysis is a powerful technique for classifying different types of dynamics.

- It allows inferring signatures of determinism and stochasticity.

- Our goal is to use this tool for
  - characterizing and classifying optical spikes (single unit, coupled units) and
  - comparing with spikes of biological neurons (via ordinal analysis of inter-spike-intervals).

- Potential application: building optical neurons for all-optical ultra-fast neuro-inspired information processing

Thank you for your attention!