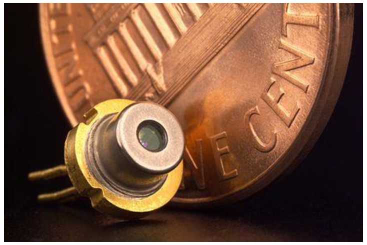
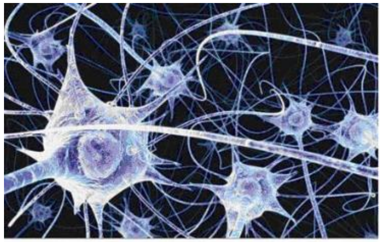


# Nonlinear laser and neural dynamics: fun and challenges of complex physical phenomena


Cristina Masoller
Departament de Física, Campus Terrassa, Barcelona
Universitat Politecnica de Catalunya


Photonics Meets Neuroscience @65
IFISC, October 31, 2025

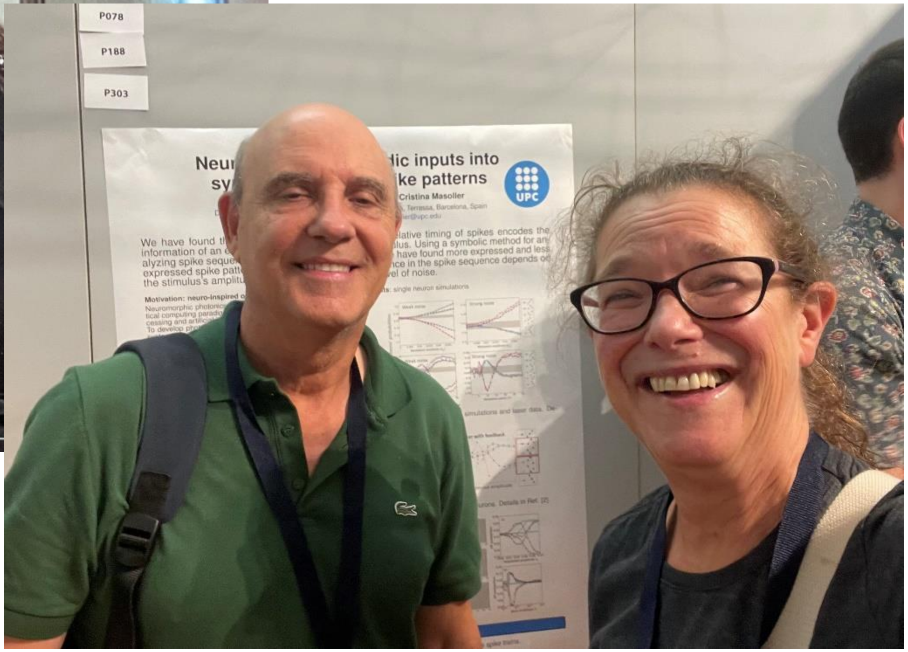
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

ICREA AGAUR GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN AIR FORCE OFFICE OF SCIENTIFIC RESEARCH UNITED STATES AIR FORCE

# Mallorca 2001


# Florence 2025






cristina.masoller@upc.edu @cristinamasoll1

# MEDYFINOL 2022




cristina.masoller@upc.edu @cristinamasoll1

# Claudio’s cloud


https://shiny.rcg.sfu.ca/u/rdmorin/scholar_googler/



cristina.masoller@upc.edu @cristinamasoll1

# Our first collaboration: synchronization of chaotic lasers for secure communications

456 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 14, NO. 4, APRIL 2002

# Chaos Shift-Keying Encryption in Chaotic External-Cavity Semiconductor Lasers Using a Single-Receiver Scheme

Claudio R. Mirasso, Josep Mulet, and Cristina Masoller

***Abstract*—In this letter, we numerically show that chaos shift-keying (CSK) encryption can be achieved by using a single receiver, thus providing a better performance when comparing with the traditional CSK scheme based on two receivers. We analyze the rate equation model for two unidirectionally coupled single-mode external-cavity semiconductor lasers operating in a chaotic regime. The message is encoded in the emitter by slightly varying its injection current. We find that under appropriate conditions, the receiver laser synchronizes to the chaotic emitter, filtering the encoded message and allowing message extraction.**

***Index Terms*—Injection-locked oscillator, nonlinear optics, semiconductor lasers (dynamics).**

scheme [2], [8], the carrier is modulated by the message. On the other hand, the CSK scheme [9] is based on the definition of two clearly separated states for bits “1” and “0,” while in the OOSK the system synchronized either to a bit “1” or “0” being unsynchronized for the other bit [10], [11]. In all these methods, the intensity of the message has to be small enough to avoid detection in the time or frequency domains. To the best of our knowledge, in the proposed CSK schemes the decoder consist of two replicas of the transmitting systems, each one configured for detecting either a bit “1” or “0” [9]. Although more secure, this scheme becomes more complicated to implement than the

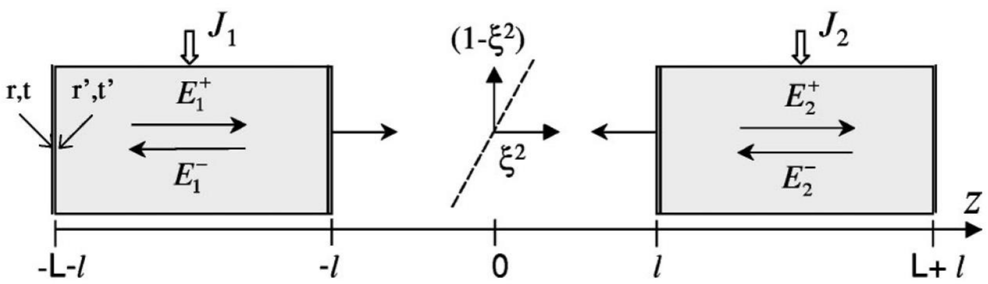


cristina.masoller@upc.edu @cristinamasoll1

PHYSICAL REVIEW A, VOLUME 65, 063815

# Modeling bidirectionally coupled single-mode semiconductor lasers

Josep Mulet,[1] Cristina Masoller,[2] and Claudio R. Mirasso[3]
[1]Instituto Mediterráneo de Estudios Avanzados, CSIC-UIB, E-07071 Palma de Mallorca, Spain
[2]Instituto de Física, Facultad de Ciencias, Universidad de la República, Igua 4225, Montevideo, Uruguay
[3]Departament de Física, Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain
(Received 15 January 2002; published 19 June 2002)




$$d_t A_{1,2}(t) = \mp i\Delta A_{1,2}(t) + \frac{1}{2}(1-i\alpha)\gamma[\mathcal{G}_{1,2}-1]A_{1,2}(t) + \hat{\kappa}_c A_{2,1}(t-\tau), \quad (31a)$$

$$d_t D_{1,2}(t) = \gamma_e[\mu_{1,2} - D_{1,2} - \mathcal{G}_{1,2}|A_{1,2}|^2], \quad (31b)$$

$$\mathcal{G}_{1,2} = \frac{a D_{1,2}}{1+\varepsilon|A_{1,2}|^2}, \quad (31c)$$



cristina.masoller@upc.edu @cristinamasoll1

# Anticipating the Response of Excitable Systems Driven by Random Forcing

M. Ciszak,[1] O. Calvo,[1] C. Masoller,[1,3] Claudio R. Mirasso,[1] and R. Toral[1,2]
[1]*Departament de Física, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*
[2]*Instituto Mediterraneo de Estudios Avanzados, CSIC-UIB, Edificio Mateu Orfila, Campus UIB, E-07122 Palma de Mallorca, Spain*
[3]*Instituto de Física, Facultad de Ciencias, Universidad de la República, Igua 4225, Montevideo 11400, Uruguay*
(Received 17 September 2002; published 22 May 2003)

We study the regime of anticipated synchronization in unidirectionally coupled model neurons subject to a common external aperiodic forcing that makes their behavior unpredictable. We show numerically and by analog hardware electronic circuits that, under appropriate coupling conditions, the pulses fired by the slave neuron anticipate (i.e., predict) the pulses fired by the master neuron. This anticipated synchronization occurs even when the common external forcing is white noise.

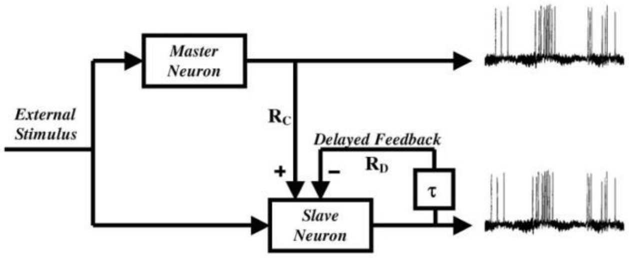
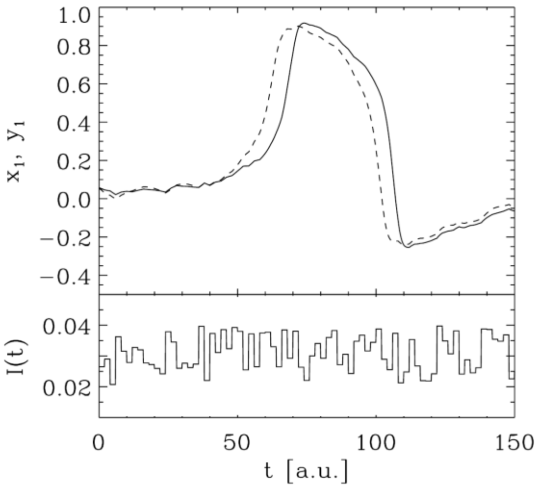



FIG. 1. Schematic diagram of two model neurons coupled in a unidirectional configuration, subjected to the same external forcing and with a feedback loop (with a delay time $\tau$) in the slave neuron.






cristina.masoller@upc.edu @cristinamasoll1

11 March 2002

PHYSICS LETTERS A

Physics Letters A 295 (2002) 39–43

www.elsevier.com/locate/pla

# Anticipating the dynamics of chaotic maps

Emilio Hernández-García [a,*], C. Masoller [b,c], Claudio R. Mirasso [c]

[a] *Instituto Mediterráneo de Estudios Avanzados, IMEDEA (CSIC-UIB), Campus Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain*

[b] *Instituto de Física, Facultad de Ciencias, Universidad de la República, Iguá 4225, Montevideo 11400, Uruguay*

[c] *Departament de Física, Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain*

Received 6 November 2001; received in revised form 28 January 2002; accepted 31 January 2002

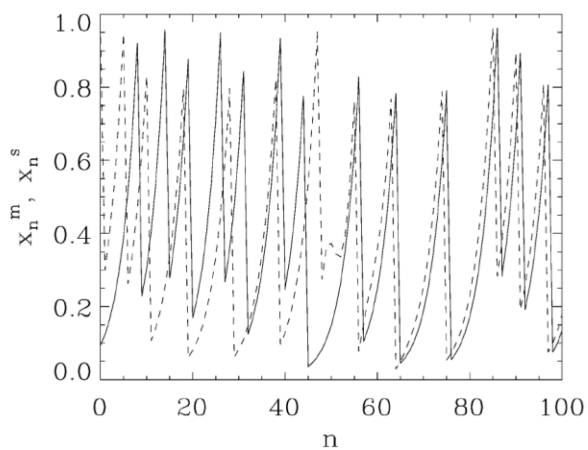



Fig. 4. Time series of the 2D Baker map ($x_n^m$ solid line, $x_n^s$ dashed line) for $a = 1.333$, $b = 0.777$, $\gamma = 0.7$, and $M = 1$. The coupling is set on at $n = 30$, leading to anticipated synchronization.



cristina.masoller@upc.edu @cristinamasoll1

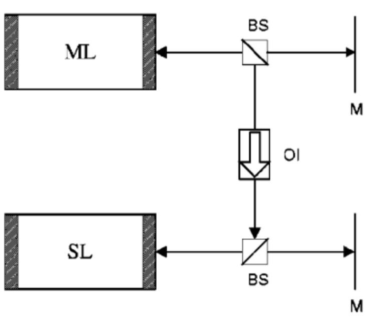
PHYSICAL REVIEW E, VOLUME 65, 056205

# Synchronization regimes of optical-feedback-induced chaos in unidirectionally coupled semiconductor lasers

A. Locquet,[1] C. Masoller,[2] and C. R. Mirasso[3]
[1]*GTL-CNRS Telecom, UMR CNRS 6603, Georgia Tech Lorraine, 2-3 rue Marconi, 57070 Metz, France*
[2]*Instituto de Física, Facultad de Ciencias, Universidad de la República, Igua 4225, Montevideo 11400, Uruguay*
[3]*Departament de Física, Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain*
(Received 5 January 2002; published 29 April 2002)

We numerically study the synchronization of two unidirectionally coupled single-mode semiconductor lasers in a master-slave configuration. The master laser is an external-cavity laser that operates in a chaotic regime while for the slave laser we consider two configurations. In the first one, the slave laser is also an external-cavity laser, subjected to, its own optical feedback and the optical injection from the master laser. In the second one, the slave laser is subject only to the optical injection from the master laser. Depending on the operating conditions the synchronization between the two lasers, whenever it exists, can be either isochronous or anticipated. We perform a detailed study of the parameter regions in which these synchronization regimes occur and how small variations of parameter yield one or the other type of synchronization or an unsynchronized regime.

DOI: 10.1103/PhysRevE.65.056205 PACS number(s): 05.45.Xt, 42.55.Px, 42.65.Sf




95 WOS citations



cristina.masoller@upc.edu @cristinamasoll1

# Almost 20 years later.

## Characterizing signal encoding and transmission in class I and class II neurons via ordinal time-series analysis

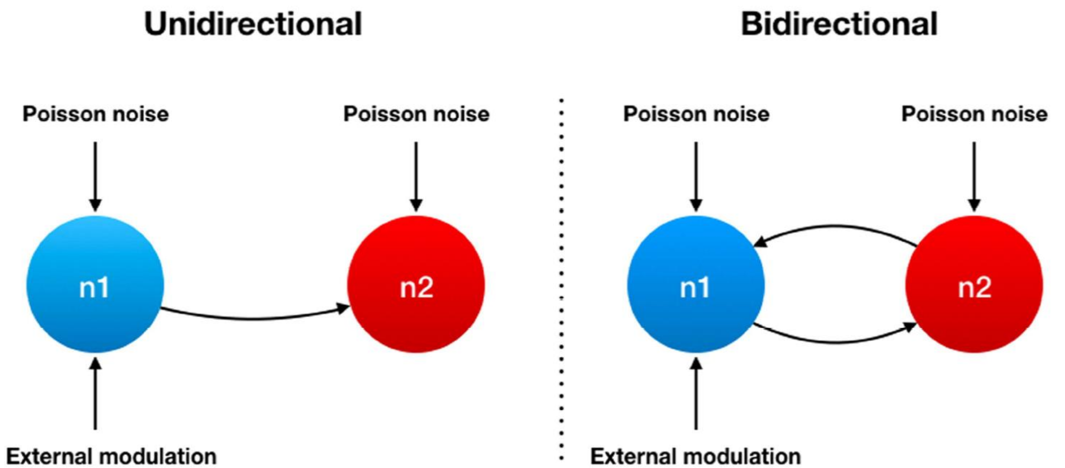
Cite as: Chaos **30**, 013123 (2020); doi: 10.1063/1.5121257
Submitted: 24 July 2019 · Accepted: 30 December 2019 ·
Published Online: 16 January 2020

View Online Export Citation CrossMark

C. Estarellas,[1,a)] M. Masoliver,[2,a)] C. Masoller,[2] and Claudio R. Mirasso[1]

**AFFILIATIONS**

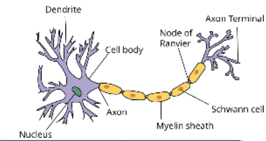
[1]Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC, UIB-CSIC), Campus Universitat de les Illes Balears E-07122, Palma de Mallorca, Spain
[2]Departament de Física, Universitat Politècnica de Catalunya, Terrassa 08222, Spain

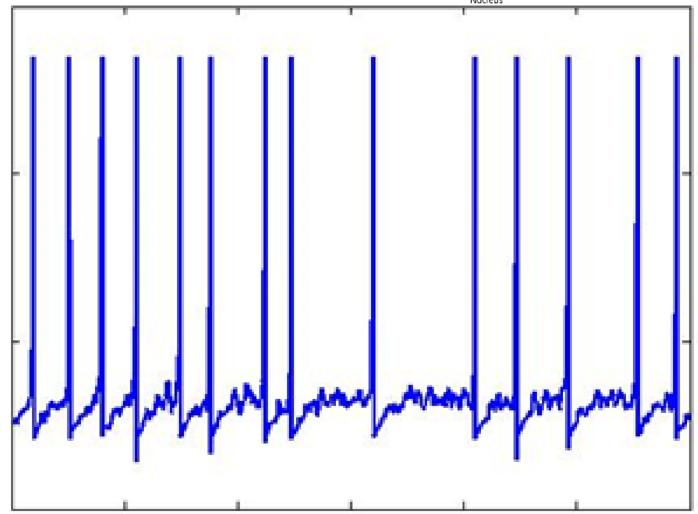





cristina.masoller@upc.edu @cristinamasoll1

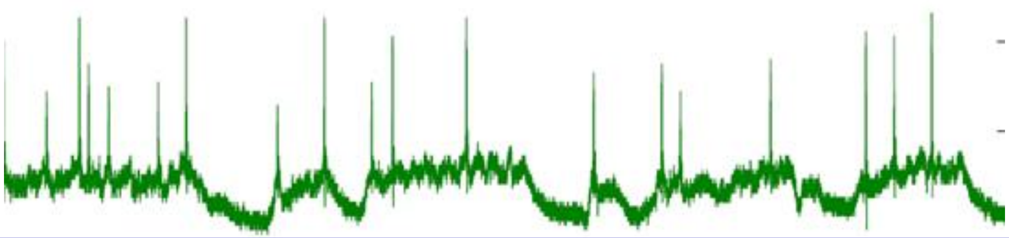
# Intensity emitted by a diode laser and simulated spikes

Time $10^{-9}$ s

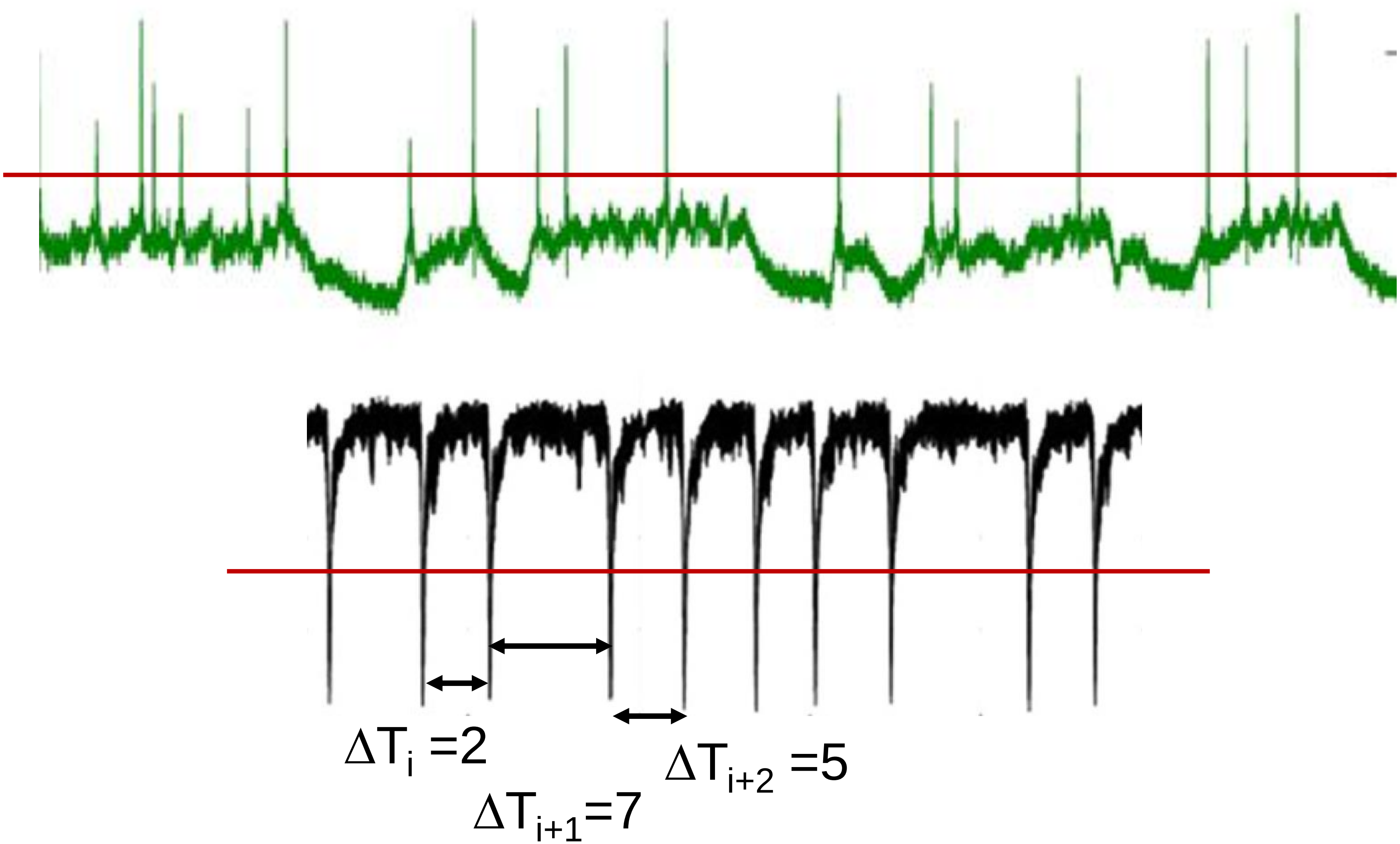
Time $10^{-3}$ s



**How neurons encode information?**

cristina.masoller@upc.edu @cristinamasoll1

# Thresholding detects the spike times ⇒ Point Process ⇒ analyze sequence of inter-spike-intervals (ISIs)

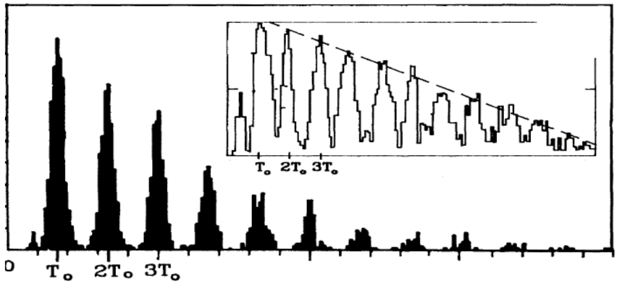



cristina.masoller@upc.edu @cristinamasoll1

# Neuron inter-spike-intervals (ISI) distribution

(spikes in the auditory nerve when a monkey hears a pure tone sound)

$P(\Delta T_i)$

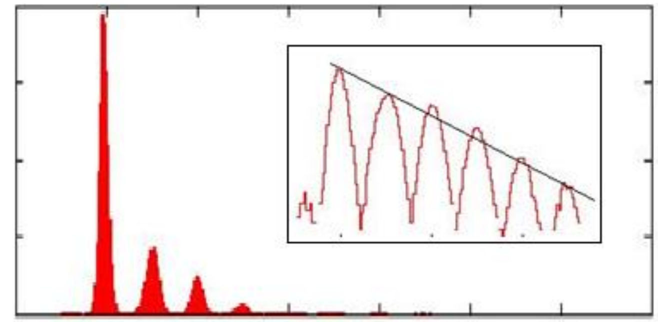



Inter-spike-interval, $\Delta T_i$

# Diode laser ISI distribution

(when the laser is sinusoidally modulated)

$P(\Delta T_i)$

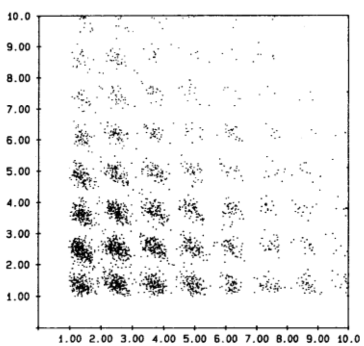


$2T_0$ $4T_0$

Inter-spike-interval, $\Delta T_i$

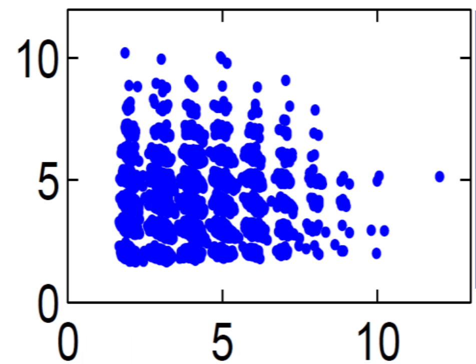
Auditory nerve when a cat hears a pure tone sound:

$\Delta T_{i+1}$




$\Delta T_i$

$\Delta T_{i+1}$




$\Delta T_i$

**How to detect similar temporal order in the ISI sequences?**

A. Longtin et al. PRL (1991), IJBC (1993).

A. Aragoneses et al. Opt Express (2014).



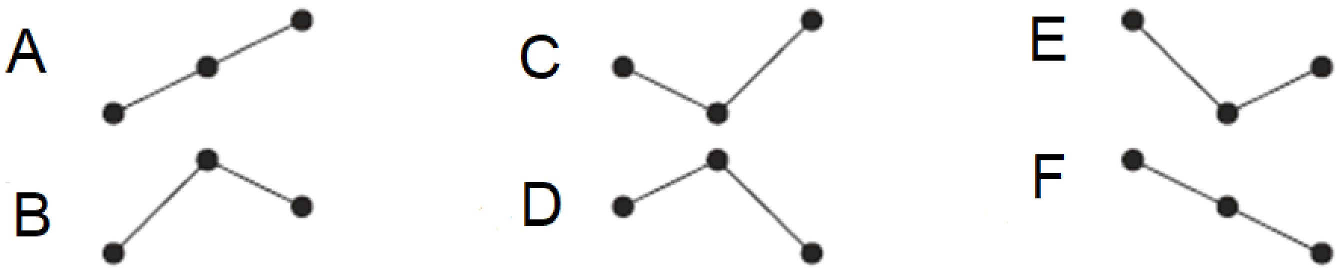
cristina.masoller@upc.edu @cristinamasoll1

# Analysis method: ordinal analysis

$\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

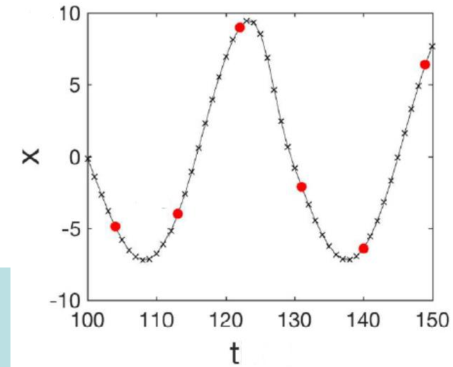
Possible order relations among three numbers (e.g., 2, 5, 7)

{…2, 5, 7…} {…5, 2, 7…} {…7, 2, 5 …}




{…2, 7, 5…} {…5, 7, 2…} {…7, 5, 2…}

**Which is the code?**



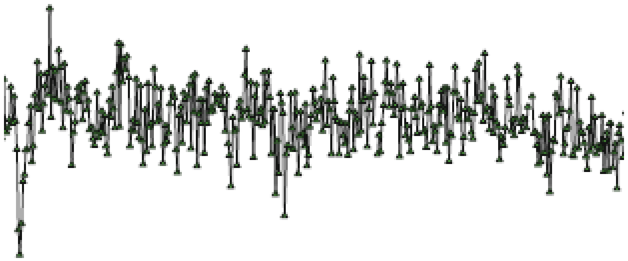

A B F C

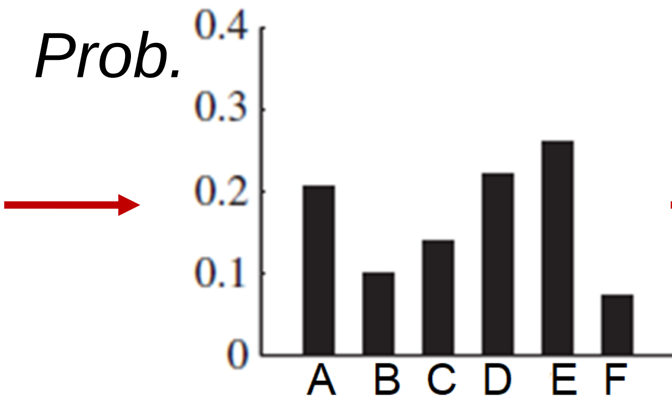
C. Bandt and B. Pompe, Phys. Rev. Lett. 88, 174102 (2002).



cristina.masoller@upc.edu @cristinamasoll1

## From a sequence of data points, by counting the different patterns we can estimate the "ordinal probabilities"






?

**What to do next?**

1. Permutation Entropy:

$p_i = p_j$ for all $i, j \Rightarrow H=1$
$p_i = 1, p_j = 0$ for all $j \neq i \Rightarrow H=0$

$$H = -\frac{1}{\ln N!} \sum_{i=1}^{N} p_i \ln p_i$$

(Nonlinear dimensionality reduction)

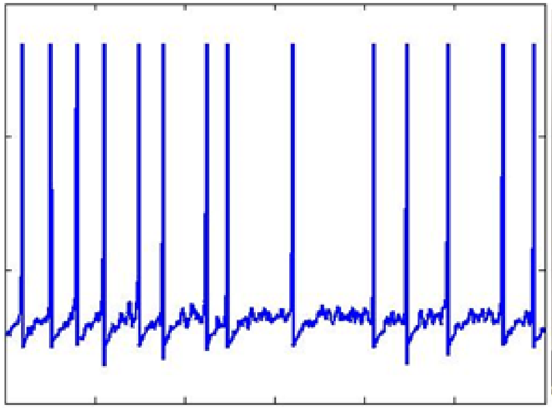
2. Analyze all the probabilities (features for machine learning algorithms)



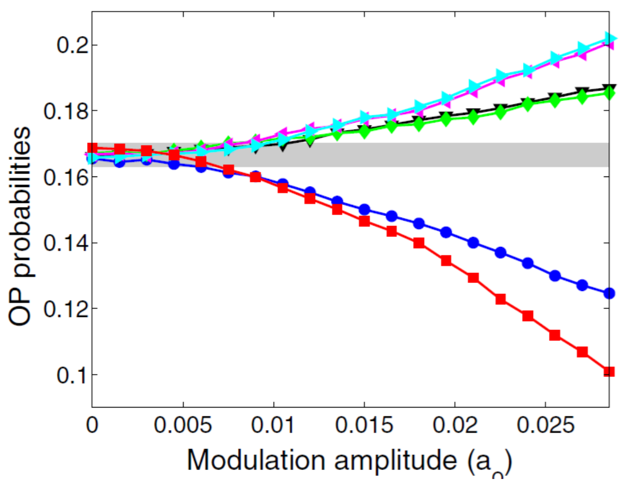
cristina.masoller@upc.edu @cristinamasoll1

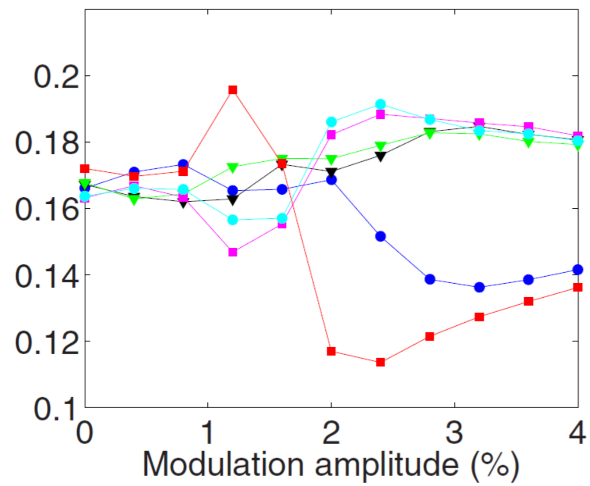
# Comparing the spike timing of a neuron and a laser when they are modulated with a *subthreshold* sinusoidal signal

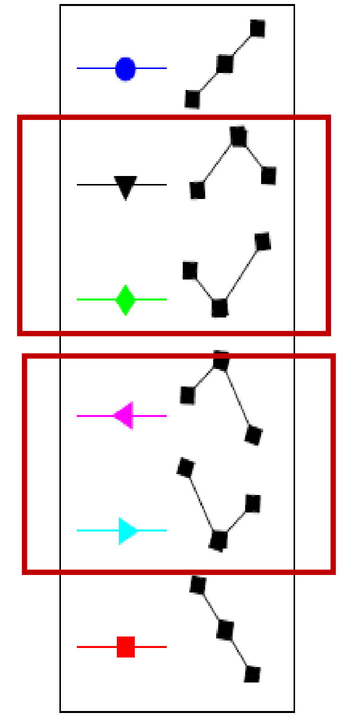
## Neuron model



## Diode laser with feedback



J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016)  A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)



cristina.masoller@upc.edu @cristinamasoll1

# Characterizing signal encoding and transmission in class I and class II neurons via ordinal time-series analysis

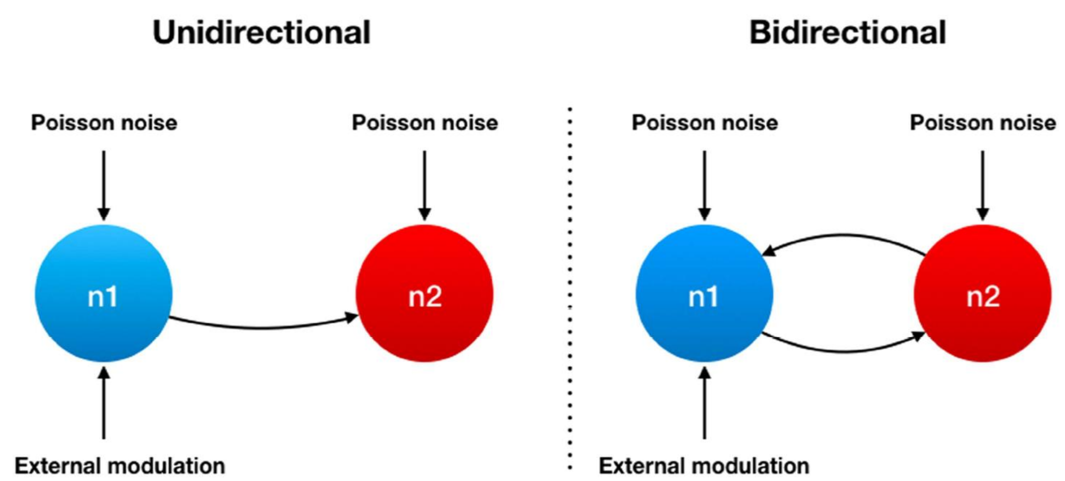
Cite as: Chaos **30**, 013123 (2020); doi: 10.1063/1.5121257
Submitted: 24 July 2019 · Accepted: 30 December 2019 ·
Published Online: 16 January 2020

View Online Export Citation CrossMark

C. Estarellas,[1,a)] M. Masoliver,[2,a)] C. Masoller,[2] and Claudio R. Mirasso[1]

**AFFILIATIONS**

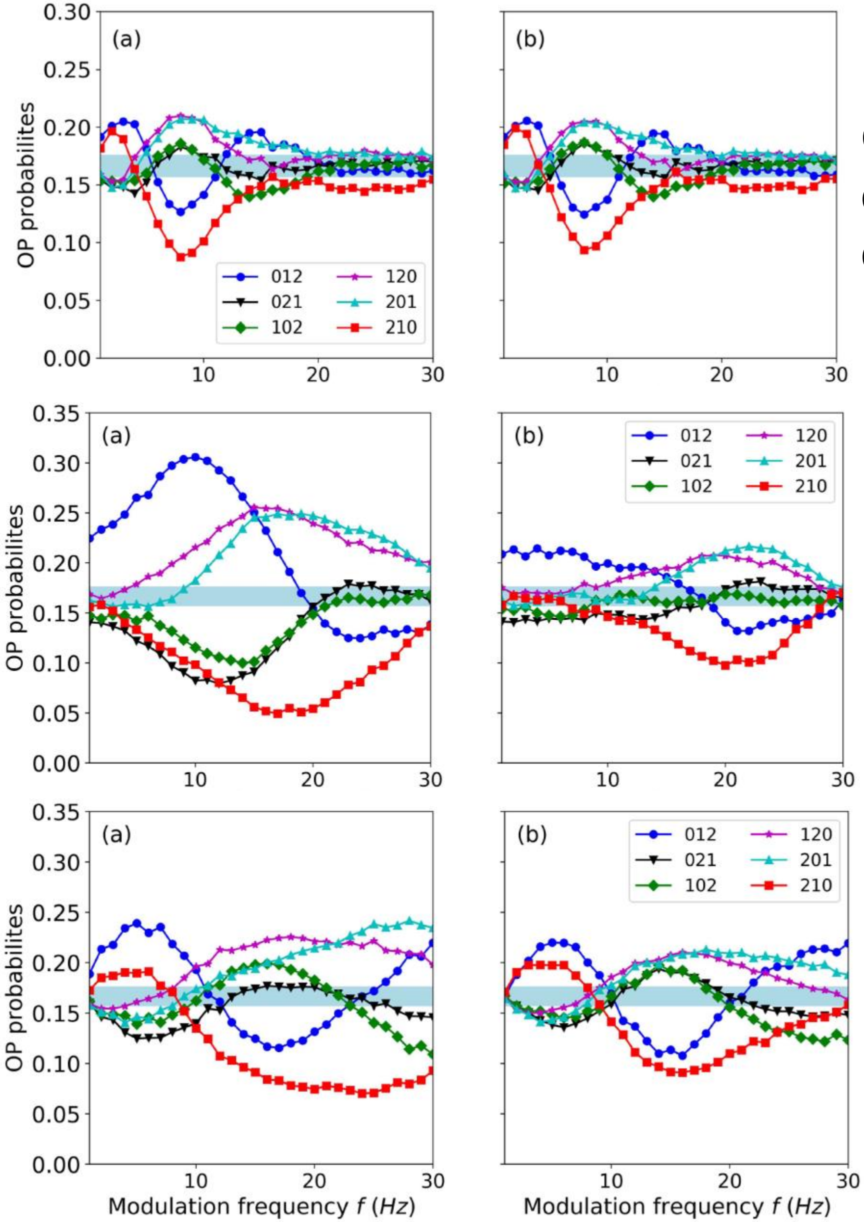
[1]Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC, UIB-CSIC), Campus Universitat de les Illes Balears E-07122, Palma de Mallorca, Spain
[2]Departament de Física, Universitat Politècnica de Catalunya, Terrassa 08222, Spain






cristina.masoller@upc.edu @cristinamasoll1

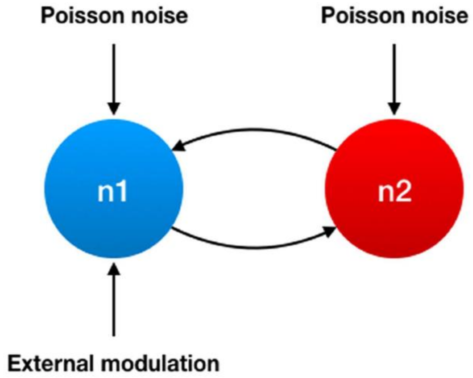
**Neuron 1** **Neuron 2**




Class I electrical coupling.

Class I chemical coupling.

Class II chemical coupling.




⇒ Depending on the signal frequency, specific combinations of neuron-class and coupling-type allow better encoding or better transmission of the signal.



cristina.masoller@upc.edu @cristinamasoll1

# Ongoing work in our lab

1. "Self pulsating lasers" (studied by Claudio and co-workers more than 25 years ago).

764 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 35, NO. 5, MAY 1999

## Self-Pulsating Semiconductor Lasers: Theory and Experiment

Claudio R. Mirasso, Guido H. M. van Tartwijk, E. Hernández-García, Daan Lenstra, S. Lynch, P. Landais, P. Phelan, J. O'Gorman, M. San Miguel, and W. Elsäßer

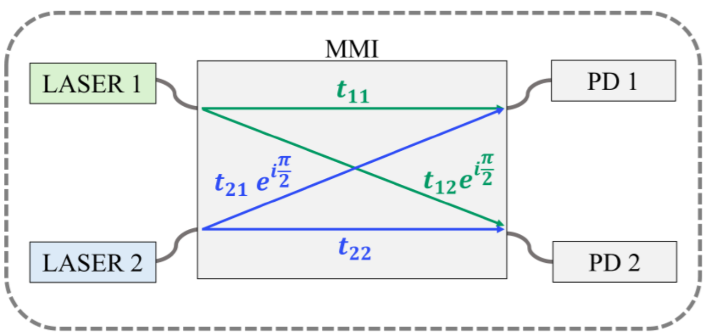
***Abstract*— We report detailed measurements of the pump-current dependency of the self-pulsating frequency of semiconductor CD lasers. A distinct kink in this dependence is found and explained using a rate-equation model. The kink denotes a transition between a region where the self-pulsations are weakly sustained relaxation oscillations and a region where $Q$-switching takes place. Simulations show that spontaneous emission noise plays a crucial role in the cross-over.**

***Index Terms*—CD lasers, laser noise, self-pulsations, semiconductor lasers.**

In the case of self-pulsations caused by saturable-absorbing effects, the self-pulsation frequency (SPF) dependence on the pump current was investigated in [2]. In later works, the self-pulsations were attributed to undamped relaxation oscillations (RO's) [3], [4]. The precise values of the RO frequency (ROF), as calculated from a small-signal analysis, and the actual SPF, highly nonlinear, are, however, different, as the SPF is always smaller than the ROF [5].

Saturable absorption effects, causing self-pulsations in

2. Synchronization of mutually coupled lasers




InP PIC with two DFB lasers and a multimode interferometer (MMI) for quantum random number generation.

$$I_{PD1}(t) = |t_{11}E_1(t) + t_{21}e^{i\frac{\pi}{2}}E_2(t)|^2$$



cristina.masoller@upc.edu @cristinamasoll1

# Happy birthday Claudio!!!!



cristina.masoller@upc.edu @cristinamasoll1