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Spiking excitable semiconductor laser as optical neurons: dynamics, clustering and global emerging behaviors

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14. ABSTRACT

Within the framework of this two-year project, detailed experimental and numerical studies have been performed, focusing on the interplay of noise and nonlinear dynamics. Specifically, we used a method of time-series analysis, referred to as symbolic ordinal analysis, to demonstrate that serial correlations present in the output intensity of a semiconductor laser with optical feedback operating in the low-frequency fluctuations regime share common features with serial correlations present in the inter-spike-intervals (ISIs) of biological neuronal systems. The symbolic dynamics underlying the sequence of inter-dropout-intervals in the laser intensity has the same statistical features, in terms of distribution of symbolic patterns, as in ISI sequences of biological neurons. Therefore, semiconductor laser-based optical neurons could provide a novel, inexpensive and controllable experimental set up that could allow for improving our understanding of neuronal activity. By establishing a direct connection between these different dynamical systems our research offers new perspectives, both, in photonics and in neuroscience. For example, the optical setup could be used to analyze the role of external forcing in neuronal spike sequences. On the hand, optical neurons constructed from inexpensive semiconductor lasers could lead to the development of novel neuro-inspired optical computing devices (threshold detectors, logic gates, signal recognition, etc.).

15. SUBJECT TERMS

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Spiking excitable semiconductor laser as optical neurons: dynamics, clustering and global emerging behaviors
Reported period: August 2012 – July 2014

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(Dated: June 28, 2014)

1. SUMMARY

This Final Report summarizes the main achievements of the research funded by this project. Our work was aimed at advancing our understanding of the interplay of noise and nonlinearity in semiconductor lasers and to exploit stochastic and/or nonlinear phenomena for novel applications.

Semiconductor lasers are key elements in optical technologies, being coherent light sources in fiber optics communications, optical data storage, life sciences applications, material processing and sensing. They have a huge economic impact and are crucial for the photonics technologies that improve our everyday life style. For developing novel devices and applications, it is crucial to have a good understanding of nonlinear light-matter interactions and their nontrivial interplay with the various noise sources (such as spontaneous emission, thermal and electrical noise).

Within the framework of this two-year project, detailed experimental and numerical studies have been performed, focusing on the interplay of noise and nonlinear dynamics. Specifically, we used a method of time-series analysis, referred to as symbolic ordinal analysis, to demonstrate that serial correlations present in the output intensity of a semiconductor laser with optical feedback operating in the low-frequency fluctuations regime share common features with serial correlations present in the inter-spike-intervals (ISIs) of biological neuronal systems. The symbolic dynamics underlying the sequence of inter-dropout-intervals in the laser intensity has the same statistical features, in terms of distribution of symbolic patterns, as in ISI sequences of biological neurons. Therefore, semiconductor laser-based optical neurons could provide a novel, inexpensive and controllable experimental set up that could allow for improving our understanding of neuronal activity. By establishing a direct connection between these different dynamical systems our research offers new perspectives, both, in photonics and in neuroscience. For example, the optical setup could be used to analyze the role of external forcing in neuronal spike sequences. On the hand, optical neurons constructed from inexpensive semiconductor lasers could lead to the development of novel neuro-inspired optical computing devices (threshold detectors, logic gates, signal recognition, etc.).

Other topics of research included the analysis of extreme events in the form of ultra-high pulses in the output intensity of semiconductor lasers with continuous-wave (cw) external optical injection or optical feedback. Extreme events is nowadays a highly active field of research. Rogue waves, earthquakes of high magnitude and financial crises are all rare and extreme events corresponding to significant and abrupt changes of environmental or socio-economic conditions with potentially catastrophic consequences. They may lead to tremendous social and economic losses and therefore they present a huge challenge for public policy and scientific research, in particular for their prediction and control. Semiconductor lasers under external perturbations can display a dynamical regime where extreme pulses occasionally occur and thus, they are optimal devices for investigating novel methods for predicting extreme events (revealing early warning signals) and novel methods for controlling these events.

Regarding novel applications, we proposed the implementation of an all-optical stochastic logic gate based in the interplay of polarization bistability and noise in optically injected vertical-cavity surface emitting lasers (VCSELs). We also demonstrated a novel method of sub-wavelength position sensing that exploits the regime of quasiperiodic dynamics of semiconductor lasers with optical feedback from two external cavities.

The results obtained in the framework of this two-year project were published in 12 high-impact journal papers, and were presented as Invited Talks and Oral/Poster contributions in several international conferences and workshops. The research involved the work of three PhD students that recently defended their PhD theses: Sandro Perrone at the Universitat Politecnica de Catalunya (UPC, February 2014), Jose Maria Aparicio Reinoso at the Universidad Nacional de Educacion a Distancia (UNED, March 2014) and Andres Aragoneses (UPC, June 2014).

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2. PUBLICATIONS

The results of our research were published in 12 papers in high-impact journals in the fields of photonics and nonlinear physics: two *Optics Express* (impact factor 3.587), one *Optics Letters* (impact factor 3.399), two *Scientific Reports* (impact factor 2.927), one *Philosophical Transactions of the Royal Society A* (impact factor 2.891), three *Physical Review A* (impact factor 2.878), two *Physical Review E* (impact factor 2.255) and one *IEEE J. Quantum Electronics* (impact factor 1.879).

1. M. Sciamanna, M. Virte, C. Masoller, and A. Gavrielides, *Hopf bifurcation to square-wave switching in mutually coupled semiconductor lasers*, Phys. Rev. E 86, 016218 (2012). Download
2. D. W. Sukow, T. Gilfillan, B. Pope, M. S. Torre, A. Gavrielides, and C. Masoller, Square-wave switching in vertical-cavity surface-emitting lasers with polarization-rotated optical feedback: experiments and simulations, Phys. Rev. A 86, 033818 (2012). Download
3. S. Perrone, R. Vilaseca, and C. Masoller, *Stochastic logic gate that exploits noise and polarization bistability in an optically injected VCSEL*, Optics Express 20, 22692 (2012). Download
4. J. Zamora-Munt, B. Garbin, S. Barland, M. Giudici, J. R. Rios Leite, C. Masoller, and J. R. Tredicce, *Rogue waves in optically injected lasers: origin, predictability, and suppression*, Phys. Rev. A 87, 035802 (2013). Download
5. A. Aragoneses, N. Rubido, J. Tiana-Alsina, M. C. Torrent, and C. Masoller, *Distinguishing signatures of determinism and stochasticity in spiking complex systems*, Sci. Rep. 3, 1778 (2013). Download
6. J. A. Reinoso, J. Zamora-Munt and C. Masoller, *Extreme intensity pulses in a semiconductor laser with a short external cavity*, Phys. Rev. E 87, 062913 (2013). Download
7. C. Masoller, M. Sciamanna and A. Gavrielides, *Two-parameter study of square-wave switching dynamics in orthogonally delay-coupled semiconductor lasers*, Phil. Trans. R. Soc. A 371, 20120471 (2013). Download
8. M. Salvide, C. Masoller and M. S. Torre, *All-optical stochastic logic gate based on a VCSEL with tunable optical injection*, IEEE J. Quantum Electron 49, 886 (2013). Download
9. S. D. Cohen, A. Aragoneses, D. Rontani, M. C. Torrent, C. Masoller and D. J. Gauthier, *Multidimensional subwavelength position sensing using a semiconductor laser with optical feedback*, Opt. Lett. 38, 4331 (2013). Download
10. A. Aragoneses, T. Sorrentino, S. Perrone, D. J. Gauthier, M. C. Torrent and C. Masoller, *Experimental and numerical study of the symbolic dynamics of a modulated external-cavity semiconductor laser*, Optics Express 22, 4705 (2014). Download
11. S. Perrone, R. Vilaseca, J. Zamora-Munt, and C. Masoller, *Controlling the likelihood of rogue waves in an optically injected semiconductor laser via direct current modulation*, Phys. Rev. A 89, 033804 (2014). Download
12. A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent and C. Masoller, *Unveiling the complex organization of recurrent patterns in spiking dynamical systems*, Sci. Rep. 4, 4696 (2014). Download

3. RESEARCH TOPICS

Our research continued the work done in the framework of our previous AFOSR three-year project (FA9550-07-1-0238, 2007-2009) and EOARD two-year project (FA8655-10-1-3075, 2010-2011) and focused on three main topics:

1. Polarization dynamics of edge-emitting lasers (EELs) and vertical-cavity surface emitting lasers (VCSELs)
2. Nonlinear dynamics of semiconductor lasers with optical injection
3. Nonlinear dynamics of semiconductor lasers with optical feedback

In the next subsections we present the main achievements in each topic and the related publications.

3.1. Polarization dynamics of EELs and VCSELs

Main achievements:

- Regular all-optical square-wave (SW) switching was demonstrated via orthogonal optical feedback or orthogonal optical coupling. The bifurcation scenario leading to SWs was analyzed in terms of various model parameters. Deterministic stable SWs were distinguished from noise-sustained transient SWs.
- An all-optical implementation of a VCSEL-based stochastic logic gate was proposed based on the interplay of i) polarization bistability, ii) external orthogonal optical injection and iii) spontaneous emission noise.
- The two logical inputs were encoded in a three-level signal modulating either the external injection strength or the wavelength of the injected light and a comparison between the encoding schemes was performed. It was shown that optical encoding significantly improves the operation rate: while in the opto-electronic scheme the minimum bit time that allows for robust and reliable operation is about 30-40 ns, in the optical scheme it is 5-7 ns.

Related publications:

- M. Sciamanna, M. Virte, C. Masoller, and A. Gavrielides, *Hopf bifurcation to square-wave switching in mutually coupled semiconductor lasers*, Phys. Rev. E 86, 016218 (2012).
- D. W. Sukow, T. Gilfillan, B. Pope, M. S. Torre, A. Gavrielides, and C. Masoller, Square-wave switching in vertical-cavity surface-emitting lasers with polarization-rotated optical feedback: experiments and simulations, Phys. Rev. A 86, 033818 (2012).
- C. Masoller, M. Sciamanna and A. Gavrielides, *Two-parameter study of square-wave switching dynamics in orthogonally delay-coupled semiconductor lasers*, Phil. Trans. R. Soc. A 371, 20120471 (2013).
- S. Perrone, R. Vilaseca, and C. Masoller, *Stochastic logic gate that exploits noise and polarization bistability in an optically injected VCSEL*, Optics Express 20, 22692 (2012).
- M. Salvide, C. Masoller and M. S. Torre, *All-optical stochastic logic gate based on a VCSEL with tunable optical injection*, IEEE J. Quantum Electron 49, 886 (2013).

3.2. Nonlinear dynamics of of semiconductor lasers with optical injection

Main achievement:

- Demonstration of the predictability and noise-suppression of deterministic rogue waves (ultra-high pulses) in the output intensity of a VCSEL with cw optical injection.
- Characterization of the role of direct current modulation in the likelihood of rogue waves. Demonstration that an optimal range of modulation frequencies, close to the solitary laser relaxation oscillation frequency, can lead to the complete suppression of rogue waves.

Related publications:

- J. Zamora-Munt, B. Garbin, S. Barland, M. Giudici, J. R. Rios Leite, C. Masoller, and J. R. Tredicce, *Rogue waves in optically injected lasers: origin, predictability, and suppression*, Phys. Rev. A 87, 035802 (2013).
- S. Perrone, R. Vilaseca, J. Zamora-Munt, and C. Masoller, *Controlling the likelihood of rogue waves in an optically injected semiconductor laser via direct current modulation*, Phys. Rev. A 89, 033804 (2014).

3.3. Nonlinear dynamics of semiconductor lasers with optical feedback

Main achievements:

- Experimental and numerical analysis of serial correlations in the sequence of intensity dropouts in the low-frequency fluctuations regime. Demonstration of similar symbolic dynamics as in sequences of inter-spike-interval in neuronal systems. We found a minimal model representing the symbolic dynamics and demonstrated that the model remains valid even under the influence of external forcing, implemented via direct modulation of the laser current.

- Numerical study of extreme intensity pulses in a semiconductor laser with a short external cavity. The mechanism generating extreme pulses was identified and it was contrasted with that leading to regular pulse packages.
- A setup capable of detecting nano-scale displacements of two independent objects at subwavelength resolution was experimentally demonstrated ($\lambda/160$). The setup was implemented via a semiconductor laser with dual feedback from two external cavities. In addition to the high resolution, this protocol offers the significant advantage of sensing two objects by just measuring one variable, the rf spectrum.

Related publications:

- A. Aragoneses, N. Rubido, J. Tiana-Alsina, M. C. Torrent, and C. Masoller, *Distinguishing signatures of determinism and stochasticity in spiking complex systems*, Sci. Rep. 3, 1778 (2013).
- J. A. Reinoso, J. Zamora-Munt and C. Masoller, *Extreme intensity pulses in a semiconductor laser with a short external cavity*, Phys. Rev. E 87, 062913 (2013).
- S. D. Cohen, A. Aragoneses, D. Rontani, M. C. Torrent, C. Masoller and D. J. Gauthier, *Multidimensional subwavelength position sensing using a semiconductor laser with optical feedback*, Opt. Lett. 38, 4331 (2013).
- A. Aragoneses, T. Sorrentino, S. Perrone, D. J. Gauthier, M. C. Torrent and C. Masoller, *Experimental and numerical study of the symbolic dynamics of a modulated external-cavity semiconductor laser*, Optics Express 22, 4705 (2014).
- A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent and C. Masoller, *Unveiling the complex organization of recurrent patterns in spiking dynamical systems*, Sci. Rep. 4, 4696 (2014).

4. PHD THESIS

1. TITLE: Exploiting nonlinearity and noise in optical tweezers and semiconductor lasers: from resonant damping to stochastic logic gates and extreme pulses.
   STUDENT: Sandro Perrone
   UNIVERSITY: Universitat Politecnica de Catalunya
   FACULTY/SCHOOL: Departament de Fsica i Enginyeria Nuclear
   YEAR: February 2014

2. TITLE: Experimental study of feedback-induced dynamics in semiconductor lasers: from symbolic analysis to subwavelength position sensing.
   STUDENT: Andres Aragoneses
   UNIVERSITY: Universitat Politecnica de Catalunya
   FACULTY/SCHOOL: Departament de Fsica i Enginyeria Nuclear
   YEAR: June 2014

Another PhD student involved in the research, Jose Maria Aparicio Reinoso, defended his PhD thesis at the Universidad Nacional de Educacion a Distancia (Madrid, March 2014).

5. SCIENCE COMMUNICATION

5.1. Invited talks

1. Workshop on Nonlinear dynamics in semiconductor lasers, Berlin, Germany, September 2012.
   Rogue waves in optically injected lasers: Origin, predictability and suppression.
   Presented by C. Masoller
2. International Symposium on Nonlinear Theory and its Applications (NOLTA), Palma de Mallorca, Spain, October 2012.
   Nonlinear time-series analysis of low-frequency fluctuations in semiconductor lasers with optical feedback.
   Presented by A. Aragoneses in the Symposium on Delayed Systems

3. SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, US, May 2013.
   Interplay of bistability, noise and delay in semiconductor lasers: complex dynamics and applications.
   Presented by C. Masoller in the Symposium on Delayed Systems

4. XXXIII Dynamics Days Europe Madrid, Spain, June 2013.
   Distinguishing Signatures of Determinism and Stochasticity in Spiking Complex Systems.
   Plenary Invited Talk presented by C. Masoller

5. 14th Workshop on Instabilities and Non-equilibrium Structures, Via del Mar, Chile, December 2013.
   Extreme optical pulses: origin, predictability and suppression.
   Presented by C. Masoller

6. Workshop on Abnormal Wave Events (W-AWE 2014), Nice, France, June 2014.
   Controlling the likelihood of rogue waves in an optically injected semiconductor laser via direct current modulation.
   Presented by C. Masoller

5.2. Oral contributions

1. European Optical Society Annual Meeting (EOSAM), Aberdeen, Scotland, September 2012.
   Stochastic logic gate that exploits noise and polarization bistability in an optically injected VCSEL.
   Presented by S. Perrone

2. Conference on Lasers and Electro-Optics - CLEO/Europe, Munich, Germany, May 2013
   Experimental and numerical study of the predictability of rogue waves in semiconductor lasers.
   Presented by J. Zamora-Munt

3. XXXIII Dynamics Days Europe, Madrid, Spain, June 2013.
   Transitions of determinism and stochasticity in time-delayed complex systems with modulation.
   Presented by A. Aragoneses

4. XXXIV Biannual meeting, Real Spanish Physical Society, Valencia, Spain, July, 2013.
   Distinguishing signatures of determinism and stochasticity in spiking complex Systems.
   Presented by A. Aragoneses

5. European Conference on Complex Systems (ECCS), Barcelona, Spain, September, 2013.
   Extreme Intensity Pulses in a Semiconductor Laser with a Short External Cavity.
   Presented by J. M. Aparicio Reinoso

6. European Conference on Complex Systems (ECCS), Barcelona, Spain, September, 2013.
   Extreme Events in a Periodically Forced Laser System.
   Presented by S. Perrone

7. XIII Latin American Workshop on Nonlinear Phenomena (LAWNP 2013), Villa Carlos Paz, Argentina, October 2013.
   Inferring signatures of determinism in stochastic complex systems.
   Presented by C. Masoller

8. International Symposium on Physics and Applications of Laser Dynamics (ISPALD), Paris, France, October 2013.
   Characterizing the Symbolic Dynamics Underlying the Intensity Dropouts of a Semiconductor Laser with Optical Feedback in the Regime of Low Frequency Fluctuations.
   Presented by A. Aragoneses

9. International Symposium on Physics and Applications of Laser Dynamics (ISPALD), Paris, France, October 2013.
   Laser-based dynamical sensor resolving two-dimensional translations at the nanoscale.
   Presented by D. Rontani

10. Workshop on Extreme Nonlinear Optics & Solitons, Weierstrass Institute for Applied Analysis and Stochastics, Berlin,Germany, October 2013.
    Predictability, control, and mechanisms responsible for the appearance of extreme intensity pulses in semiconductor lasers.
    Presented by J. Zamora-Munt

11. 6th Rio de la Plata Workshop on Laser Dynamics and Nonlinear Photonics, Montevideo, Uruguay, December 2013.
    Symbolic analysis of low-frequency fluctuations in semiconductor lasers with optical feedback.
    Presented by C. Masoller

12. Congreso de Fisica Estadistica (FISES), Ourense, Spain, April, 2014.
    Characterizing the complex dynamics of a semiconductor laser with optical feedback and modulation.
    Presented by A. Aragoneses

13. SPIE Photonics Europe 2014, Brussels, Belgium, April 2014.
    Experimental study of the complex dynamics of semiconductor lasers with feedback via symbolic time-series analysis.
    Presented by T. Sorrentino

14. IX Congreso NoLineal 2014, Badajoz, Spain, June 2014.
    Symbolic dynamics of directly modulated semiconductor lasers with optical feedback.
    Presented by T. Sorrentino

15. Advanced Photonics Congress, Nonlinear Photonics, Barcelona, Spain, July 2014.
    Experimental and numerical study of the predictability of rogue waves in semiconductor lasers.
    To be presented by J. Zamora Munt

5.3. Poster presentations

1. Congreso de Fisica Estadistica (FISES), Palma de Mallorca, Spain, October 2012.
   Ordinal time-series analysis of low-frequency fluctuations in semiconductor lasers with optical feedback.
   Presented by A. Aragoneses

2. XXXIII Dynamics Days Europe Madrid, Spain, June 2013.
   Extreme intensity pulses in a semiconductor laser with a short external cavity.
   Presented by J. M. Aparicio Reinoso

3. XIII Latin American Workshop on Nonlinear Phenomena (LAWNP 2013), Villa Carlos Paz, Argentina, October 2013.
   Ultrahigh intensity pulses in the nonlinear dynamics of semiconductor lasers.
   Presented by C. Masoller

4. 6th Rio de la Plata Workshop on Laser Dynamics and Nonlinear Photonics, Montevideo, Uruguay, December 2013.
   Numerical implementation of a stochastic logic gate based on a VCSEL with tunable optical injection.
   Presented by M. S. Torre

5. Congreso de Fisica Estadistica (FISES), Ourense, Spain, April, 2014.
   Unveiling the complex organization of recurrent patterns in spiking dynamical systems.
   Presented by A. Aragoneses

6. Advanced Photonics Congress, Nonlinear Photonics, Barcelona, Spain, July 2014.
   Suppression of Optical Rogue Waves in a CW Injected Semiconductor Laser With Current Modulation and Noise.
   To be presented by J. Zamora Munt

5.4. Dissemination of research results in media

Our article in Scientific Reports (May 2013) was featured in the printed edition of Terrassa newspaper and in the digital edition of the national newspaper El Periodico. The first author, Mr. Andres Aragoneses, was interviewed by radio and TV of Terrassa.

6. COLLABORATORS AND PEOPLE INVOLVED

The work carried out during this two-year project was done in collaboration with several researchers working in the field of semiconductor laser nonlinear dynamics. The study of square-wave regular switching was done in collaboration with Dr. A. Gavrielides (EOARD), Dr. David Sukow (Washington and Lee University, US) and Dr. Marc Sciamanna (Supelec, Metz, France); progress on all-optical stochastic logic gates was done in collaboration with Prof. Ramon Vilaseca (UPC, co-supervisor of the thesis of S. Perrone) and Dra. Maria Susana Torre (Universidad Nacional del Centro de la Provincia de Buenos Aires, Tandil, Argentina); work on optical rogue waves was done in collaboration with Dr. Jordi Zamora Munt (Institute for Cross-Disciplinary Physics and Complex Systems, Palma de Mallorca, Spain), Dr. Stephane Barland, Dr. Massimo Giudici and Prof. Jorge Tredicce (Institut Non-Lineaire de Nice, France, where the experiments were carried out) and Prof. Ramon Vilaseca (UPC); the implementation of a nano-scale sub-wavelength position sensor was done through a three-month visit of a PhD student (A. Aragoneses) to Prof. Daniel Gauthier lab (Duke University, US, where the experiments were carried out; Aragoneses' visit was partially funded by this project).