THIRD 'RIO DE LA PLATA' WORKSHOP ON NOISE, CHAOS, AND COMPLEXITY IN LASERS AND NONLINEAR OPTICS

Organizers:

Cristina Masoller (Universitat Politecnica de Catalunya, Spain)
Alejandro Hnilo (Centro de Investigaciones en Láseres y Aplicaciones, Argentina)

Acknowledgements:

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Held at Club del Lago Hotel, Maldonado, Uruguay
December 3 - December 7, 2007

PROGRAM

Monday, December 3

18:00 – 19:00 Registration

19:00 – 20:30 Get together welcome drink

20:30 – 21:30 Dinner

Tuesday, December 4

8:30 – 9:00 Registration

Chair: Cristina Masoller

9:00 – 9:45 Jason Gallas (Porto Alegre, Brazil)
Chaotic phases of optically injected lasers and related models

9:45 – 10:30 Marcel Clerc (Santiago, Chile)
Pattern collapse as a mechanism for the formation of solitary states

10:30 – 11:00 Coffee break

Chair: Marcel Clerc

11:00 – 11:45 Igal Brener (Albuquerque, USA)
Terahertz semiconductor lasers, receivers and metamaterials

11:45– 12:30 Ramon Vilaseca (Terrassa, Spain)
Broadband second harmonic parametric scattering in ferroelectric crystals with random domains structure

12:30 - 13:30 Lunch

Chair: Alan Shore

14:30 – 15:15 Luis Pesquera (Santander, Spain)
Nonlinear dynamics reconstruction of chaotic cryptosystems based on a laser diode subject to optoelectronic feedback with fixed and variable delay

15:15 – 16:00 Laurent Larger (Besançon, France)
The integro-differential delay electro-optic oscillator: new dynamical features and robust generalized synchronization capabilities with a delay shared feedback coupling

16:00 – 16:30 Yanne Chembo (Besançon, France)
Stability properties of a pure microwave oscillation in a narrow band electro-optic delay oscillator

16:30 – 17:00 Coffee break

Chair: Miguel Hoyuelos

17:00 – 17:45 Delphine Wolfersberger (Metz, France)
Control of visible or near infrared light in bulk photorefractive materials: from waveguides to cavities

17:45 – 18:15 Adrian Jacobo (Palma de Mallorca, Spain)
Cavity Solitons in Kerr media: control, interaction and noise effects

18:15 – 18:45 Maxime Jacquot (Besançon, France)
Recent results on optical phase dynamics in electro-optic phase modulation combined with nonlinear differential phase demodulation: experiments and modeling

20:30 – 21:30 Dinner

Wednesday, December 5

8:30 – 9:00 Registration

Chair: Delphine Wolfersberger

9:00 – 9:45 Jose R. Rios Leite (Recife, Brazil)
Low frequency synchronization between chaotic semiconductor lasers

9:45 – 10:30 Fritz Henneberger (Berlin, Germany)
Noninvasive optical control of semiconductor lasers

Free time for optional Boat Excursion to Isla de Lobos

12:30 - 13:30 Lunch

Chair: Maria Susana Torre

16:00 – 16:45 Alan Shore (Bangor, Wales)
Dynamics of VCSELs subject to optical feedback and optical injection

16:45 – 17:30 Wolfgang Elsäßer (Darmstadt,Germany)
Quantum noise of optoelectronic emitters: an excursion from squeezed states of light emitted by VCSELs via the intensity noise of Quantum Cascade lasers to Quantum Dot super-luminescent diodes

17:30 – 18:00 Coffee break

Chair: Arturo Lezama

18:00 – 18:30 Christophe Szwaj (Villeneuve d'Ascq, France)
Control of optical turbulence

18:30 – 19:00 Uwe Bandelow (Berlin, Germany)
Enhanced modulation bandwidth by integrated feedback

19:00 – 19:30 Otti D'Huys (Brussels, Belgium)
Analysis of networks of delay-coupled Kuramoto-oscillators with different topologies

20:30 – 21:30 Dinner

21:30 – 23:00 **Poster session with wine**

Thursday, December 6

Chair: Laurent Larger

9:00 – 9:45 Marc Sciamanna **(**Metz, France)
Dynamical diversity in VCSELs with optical injection

9:45 – 10:30 Krassimir Panajotov (Brussels, Belgium)
Feedback from an extremely-short external-cavity in VCSELs and experimental observation of coherence resonance

10:30 – 11:00 Coffee break

Chair: Stephen Hegarty

11:00 – 11:45 Tom Gavrielides (Air Force Research Laboratory, USA)
Semiconductor lasers subject to delayed polarization rotated feedback

11:45 – 12:30 Cristina Masoller (Terrassa, Spain)
Dynamics of semiconductor lasers with incoherent feedback

12:30 - 13:30 Lunch

Chair: Laurent Larger

14:30 – 15:15 Arturo Lezama (Montevideo, Uruguay)
Single-pass quantum fluctuation spectroscopy in atomic samples

15:15 – 16:00 Marcelo Martinelli (San Paulo, Brazil)
My fair light: bright multicolor entanglement

16:00 – 16:30 Coffee break

Chair: Wolfgang Elsäßer

16:30 – 17:15 Stephen Hegarty (Cork, Ireland)
Quantum-dot lasers subject to external optical perturbation

17:15 – 18:00 Jorge Tredicce (Nice, France)
Mapping local defects of extended media using cavity solitons

18:00 – 18:20 James Fillerup (Virginia, USA)
Doing business with AFOSR

18:20 – 18:30 C. Masoller, concluding remarks

20:30 – 21:30 Dinner

TALKS

Uwe Bandelow

Weierstrass Institute for Applied Analysis and Stochastics, Berlin, Germany

Enhanced modulation bandwidth by integrated feedback

Directly modulated semiconductor lasers are of great interest for low cost transmitter applications in short reach optical data transmission systems. However, until now, the application of these lasers for data rates beyond 10 Gbit/s per channel is limited by the modulation bandwidth. In this paper the 40 Gb/s direct current modulation of DFB lasers with integrated feedback sections will be analyzed and demonstrated by exploiting an additional photon-photon (PP) resonance peak at frequencies which potentially exceed the usual relaxation-oscillation frequency a few times. We take advantage of this PP resonance, first to increase the bandwidth of small signal modulation, and second to demonstrate the potential of this approach for direct large-signal current modulation at 40 Gbit/s.

Igal Brener

Sandia National Laboratories & Center for Integrated Nanotechnologies, Albuquerque, USA

Terahertz semiconductor lasers, receivers and metamaterials

The invention of the quantum cascade laser (QCL) in general and QCLs operating at terahertz frequencies (THz) in particular have been fueling the development of solid-state devices at a wavelength range where bulky and power hungry sources and detectors still dominate. In this talk I will review recent developments in THz quantum cascade lasers and their use in integrated-solid state heterodyne receivers. Also, the implementation of metamaterials operating at these frequencies is starting to enable new devices that were not possible just a few years ago, such as modulators, filters and non-reciprocal devices. I will discuss the physics and applications of these THz metamaterial-based devices, and new directions such as sensors and novel fabrication of metamaterials.

Yanne Chembo[1], Laurent Larger[1], Pere Colet[2]

[1]*UMR CNRS FEMTO-ST 6174, Département d'Optique P. M. Duffieux, Université de Franche-Comté, Besançon, France*

[2] *Institute for Cross-Disciplinary Physics and Complex Systems, Palma de Mallorca, Spain*

Stability properties of a pure microwave oscillation in a narrow band electro-optic delay oscillator

High spectral purity optoelectronic oscillators have been demonstrated already 10 years ago. This novel kind of ultra-stable microwave oscillator involves a telecom electro-optic Mach-Zehnder modulator, a very long fiber delay line (up to several kilometers), and a very narrow-band electronic feedback (a few MHz around 10GHz, to select a single delay mode). Whereas much attention was paid to the spectral purity features of the microwave oscillation arising after a standard Hopf bifurcation, no particular theoretical and experimental investigations have been surprisingly conducted concerning the nonlinear stability of the microwave limit cycle. We propose an envelop stability analysis considering the very specific time scales of concern, leading to a surprisingly secondary Neimark-Sacker bifurcation of the microwave oscillation. This bifurcation gives rise to a slow amplitude modulation of the microwave oscillation. The theoretical analysis is supported by numerical and experimental observations.

Marcel Clerc

Universidad de Chile, Santiago, Chile

Pattern collapse as a mechanism for the formation of solitary states

We report a new mechanism for the formation of localized states, which takes place without front propagation and coexistence of modulation instability. Correspondingly, localized structures appear as solitary states, displaying a behavior of single independent cells. The phenomenon is observed in the liquid crystal light-valve experiment and is described by a one-dimensional normal form model. We show that such solitary structures exist when a pattern solution collapses and its ghost remains to influence the phase portrait.

Otti D'Huys[1], R. Vicente[2], C. Mirasso[3], T. Erneux[4], J. Danckaert[1], and I. Fischer[5]

[1] *Dept. of Applied Physics and Photonics (TONA) and Dept. of Physics (DNTK), Vrije Universiteit Brussel, Brussel, Belgium*

[2] *Max-Planck-Institut für Hirnforschung, Frankfurt, Germany*

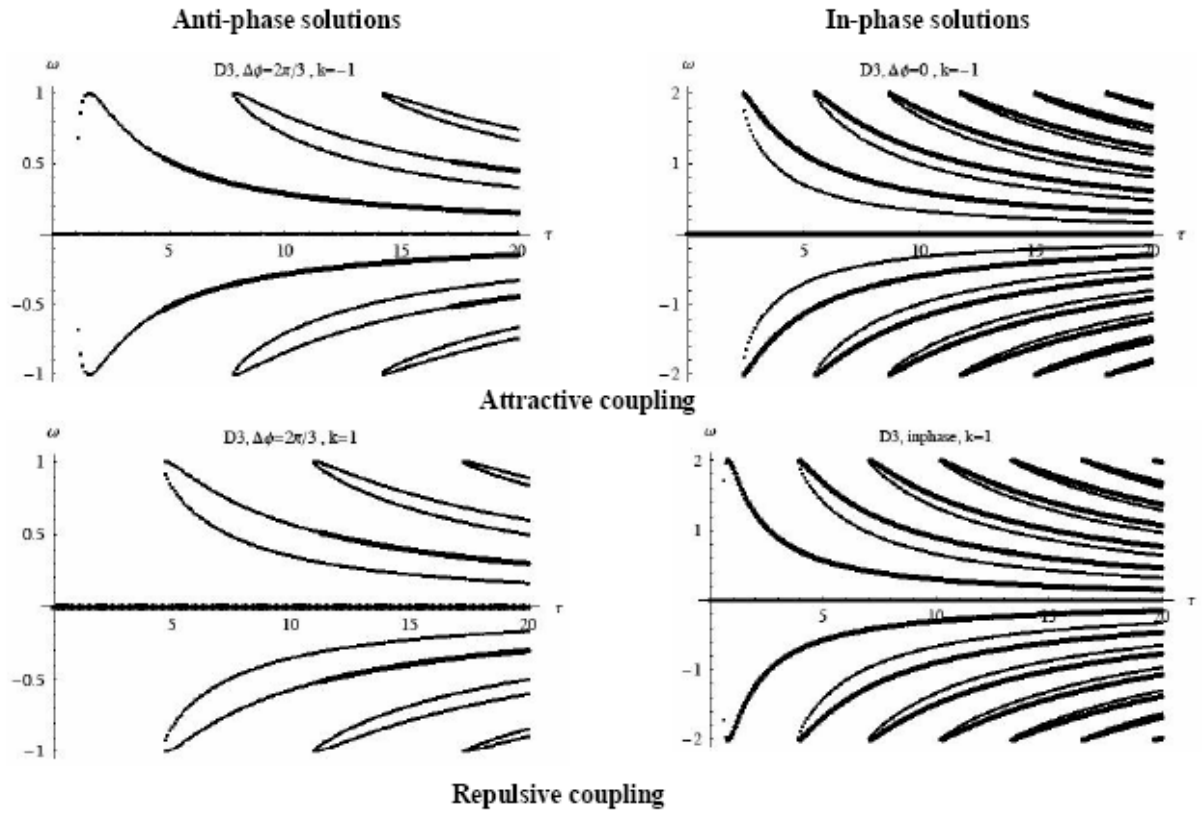
[3] *Instituto de Fisica Interdisciplinar y Sistemas Complejos , Universitat de les Illes Balears, Palma de Mallorca, Spain*

[4] *Optique Nonlinéaire Théorique , Université Libre de Bruxelles , Bruxelles, Belgium*

[5] *School of Engineering and Physical Sciences , Heriot-Watt University, Edinburgh, U.K.*

Analysis of networks of delay-coupled Kuramoto-oscillators with different topologies

In order to investigate the synchronization patterns observed in different topologies of networks of semiconductor lasers that are optically or opto-electronically coupled with delay, a good starting point is to study the influence of coupling delays in different network topologies of Kuramoto-oscillators. Kuramoto equations can be considered as a phase reduction of weakly-coupled oscillators, such as interacting semiconductor lasers. We concentrate on symmetric conditions: the natural frequencies, delay times and coupling strengths are chosen equal for all oscillators in the network. Our analysis includes analytic and semi-analytic results, complemented by numerical modeling. In particular, we study unidirectionally coupled rings, bidirectionally coupled rings and globally coupled oscillators, where we look for the existence and stability of both the in-phase and the anti-phase solutions. An analytical stability criterion is also derived for the anti-phase solutions. In the unidirectional ring the delay mainly acts as inducer of multiple but similar branches of solutions (in-phase and anti-phase). In the dynamics of bidirectionally coupled rings the most symmetric solution is found to be more probable than other solutions thanks to the introduction of the coupling delay. An example is shown in the picture below. Finally, we compare our results on rings of oscillators with those obtained for linear chains of oscillators. Comparing with the linear chain similar branches of solutions are obtained, but due to boundary conditions middle and outer elements are no longer exactly in- or out-of-phase with each other.



Frequency of the system as a function of the coupling delay, for three bidirectionally coupled Kuramoto oscillators. Thick lines stand for stable solutions. There exist more in-phase solutions than anti-phase solutions, and the former are stable over a larger range of delays and frequencies.

Wolfgang Elsäßer

Institute of Applied Physics, Darmstadt University of Technology, Darmstadt Germany

Quantum noise of optoelectronic emitters: an excursion from squeezed states of light emitted by VCSELs via the intensity noise of Quantum Cascade lasers to Quantum Dot super-luminescent diodes

Since the advent of laser, there has been always a perpetual and accompanying research on the quantum fluctuations of light. In this contribution I shall give an overview on the intensity noise properties of recent optoelectronic semiconductor-based light emitters. Since the pioneering work of Y. Yamamoto in the 80ies on the possibility of sub-shot noise emission characteristics or Sub-Poissonian statistics of edge-emitting semiconductor lasers there has been always a continuous search for improvements and the optimum emitter structure, both in

theory and experiment. In this talk, I would like to concentrate on three examples of emitters to illustrate the idea and the physics behind. Starting with sub-shot noise emission of Vertical-Cavity Surface-Emitting Lasers (VCSELs), the basic concept will be illustrated before moving further on towards quantum cascade lasers emitting in the mid-infrared around 5 to 10 micrometers. Here, emphasis on the newly observed scaling behavior of the intensity noise will be made, which is due to the particular level-scheme and the cascaded structure, thus requiring a different rate equation description in comparison to edge emitters. Finally, the intensity noise behavior of near-infrared emitting quantum-dot gain medium super luminescent diodes (SLDs) will be studied. It exhibits the typical excess noise behavior due to the amplified spontaneous emission process. Finally, a comparison and a conclusion will be drawn, both, under the aspect of quantum optics and applications of these optoelectronic emitters, as e.g. in high-resolution spectroscopy or optical coherence tomography.

[1] F. T. Arecchi, "Laser Handbook" (North-Holland, Amsterdam, 1972)

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[3] J. Kitching, A. Yariv, and Y. Shevy, "Room temperature generation of amplitude squeezed light from a semiconductor laser with weak optical feedback", Phys. Rev. Lett. **74**, 3372 (1995)

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[5] C. Degen, J. L. Vey, W. Elsässer, P. Schnitzer, and K. Ebeling, "Amplitude noise squeezed light from polarization single-mode VCSEL", Electron. Lett. **34**, 353 (1998)

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James Fillerup
Air Force Office of Scientific Research, Southern Office of Aerospace Research and Development, USA

Doing with Business with AFOSR

The Air Force Office of Scientific Research (AFOSR) is the funding arm of the U.S. Air Force. We invest in basic research throughout the world in hopes of pushing the boundaries of the cutting edge. In this talk I will discuss the various options for working with my organization. These options include being sponsored to visit our scientists in the U.S., supporting conferences of interest to the Air Force and funding small seed grants.

Jason A. C. Gallas
Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

Chaotic phases of optically injected lasers and related models

A crucial ingredient for secure communications using lasers is that messages can only be recovered if the parameters of the transmitter and the receiver lasers are well matched and stable. From a theoretical point of view, parameters are also key elements which properly tuned allow one to reach operating regimes providing new insight in dynamical systems. Recently, we described the intricacies of chaotic phases of lasers and related models when ruled by sets of ordinary differential equations. Such diagrams contain many features which are not found in phase diagrams presently available in the literature. Of particular interest for applications is the structuring of the chaotic phases, phases which are still poorly understood. Wide regions supporting "smooth and continuous chaos" are of interest for efficient secure communication with lasers. Here, we report qualitative and metric properties of the evolution of periodic and chaotic oscillations when more than one parameter are tuned simultaneously. In particular, we show how to sweep large parameter ranges while keeping invariant desired properties of the solutions. (We thank support by CNPq and AFOSR).

Tom Gavrielides
Air Force Research Laboratory, USA

Semiconductor lasers subject to delayed polarization rotated feedback

We examine several system configurations in which one or more semiconductor lasers are coupled through polarization rotated delayed feedback. We summarize our experimental and theoretical results for a single diode laser, steady, periodic and chaotic states under the influence of the polarization feedback. The unstable TM steady state without feedback now becomes an injection driven state as theoretical results agree quite well with the experiments. Additionally, we show that the two chaotic lasing polarizations are in a driven synchronization state. Further, we summarize the results for unidirectional coupled with rotated polarization of two diode lasers and show that synchronous time, perfect synchronization and inverse synchronization are obtained. We also examine the steady states, and periodic states with a particular emphasis in square wave pulsations. Experiments and numerical computations are offered for stripe lasers as well as for VCSELs. Additional configurations of the two coupled face to face system with delayed rotated polarization are examined and new results, experimental and theoretical, are outlined. Finally, we show that square wave pulsations are robust, span a large feedback region and coexist with the steady states of the system.

Stephen Hegarty, David Goulding, Bryan Kelleher, Sergey Melnik and Guillaume Huyet
Tyndall National Institute, Cork, Ireland

Quantum-dot lasers subject to external optical perturbation

Semiconductor quantum-dot lasers have long been proposed as sources resistant to destabilisation under the influence of external optical feedback, and in the case of InAs quantum-dots grown on GaAs substrates, this has indeed been shown to be true, at least when operating at the 1.3 micron telecommunications window. In this talk I will discuss two extensions to this experiment, where the perturbing external mirror is replaced firstly by an isolated master laser, and then by a non-isolated quantum-dot laser, giving a mutually coupled configuration. Both configurations give wide regions of stability in parameter space, as well

as a variety of dynamical states such as excitable pulsing and multi-stability. I will present finally current attempts to understand these phenomena through rate-equation modelling.

Fritz Henneberger, Sylvia Schikora and Hans-Jürgen Wünsche
Humboldt University of Berlin, Department of Physics, Berlin, Germany

Noninvasive optical control of Semiconductor Lasers

We investigate ultra-fast all-optical and noninvasive control of semiconductor lasers under various conditions of operation. The setup [1] implemented experimentally uses feedback from a Fabry-Perot cavity and represents a generalization of the well-known extended time-delayed feedback control to the optical domain [2]. Unlike in electronics, the optical phase makes the control gain a complex quantity which qualitatively changes the scenario and enables control in cases where it is impossible otherwise. We demonstrate noninvasive stabilization of unstable continuous and periodic emission at Hopf- and period-doubling bifurcations as well as in the chaotic regime.

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[2] J. E. S. Socolar, D.W. Sukow, and D. J. Gauthier, "Stabilizing unstable periodic orbits in fast dynamical systems", Phys. Rev. E 50, 3245 (1994).

Adrian Jacobo, Damià Gomila, Pere Colet and Manuél Matías
Institute for Cross-Disciplinary Physics and Complex Systems, Palma de Mallorca, Spain

Cavity Solitons in Kerr media: control, interaction and noise effects

Cavity solitons, appearing in the transverse plane of nonlinear optical cavities, have been advocated for use in fast and compact optical information storage. Localized structures may develop a number of instabilities like start moving, breathing, or oscillating. In the latter case, they would oscillate in time while remaining stationary in space. The Lugiato-Lefever Kerr model shows a route in which autonomous oscillating cavity solitons are destroyed, leading to

an excitability regime [1,2]. Excitability is a concept arising originally from biology (e.g., neuroscience), and it has been found in a variety of systems, including optical systems. Typically a system is said to be excitable if while it sits at a stable fixed point, perturbations beyond a certain threshold induce a large response before coming back to the rest state. Here we introduce an addressing beam which allow us to control the properties of this excitability. The presence of this addressing beam introduces a new route to excitability with a tunable threshold. We also study the interaction of two cavity solitons, both in the oscillatory and in the excitable regimes. Finally we study the effect of noise in the system and the possibility of coherence resonance.

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[2] D.Gomila, A. Jacobo, M.A. Matías, P. Colet Phys. Rev. E 75, 026217 (2007)

Maxime Jacquot, M. Peil and L. Larger

UMR CNRS FEMTO-ST 6174, Département d'Optique P. M. Duffieux, Université de Franche-Comté, Besançon, France

Recent results on optical phase dynamics in electro-optic phase modulation combined with nonlinear differential phase demodulation: experiments and modeling

To remediate to practical complexity issued from security reason in intensity chaos optical communication systems, we developed a new phase chaos generator. A novel nonlinear phase difference delay differential equation is ruling the dynamics of the setup, which exhibits specific dynamical regimes, among which flat and broadband multi-GHz chaos is obtained. Experimental and numerical results will be reported, as well as a complete emitter-receiver architecture intended for phase chaos synchronization and communication.

Laurent Larger[1], M. Peil[1], I. Fischer[2], M. Jacquot[1]

[1]*UMR CNRS FEMTO-ST 6174, Département d'Optique P. M. Duffieux, Université de Franche-Comté, Besançon, France*

[2] *Heriot-Watt University, Edinburgh, Scotland, U.K.*

The integro-differential delay electro-optic oscillator: new dynamical features and robust generalized synchronization capabilities with a delay shared feedback coupling

We will report on various, and recent, experimental results obtained with optoelectronic delay feedback oscillators, involving high speed integrated electro-optic LiNbO3 modulators. Initially developed for investigating the rich and numerous dynamical features of scalar nonlinear delay dynamics (Ikeda-like dynamics), they have been then used for applications to chaos based communication systems. Versatility and robustness of the setup lead, during parallel more fundamental investigations, to the development of new dynamical configurations. The latter are concerned on one hand by a modified dynamical process (from a first order differential one, to a second order integro-differential process), and on another hand by a particular bidirectional coupling configuration between two identical such oscillators. We will thus report both on new dynamical phenomena originating from three widespread (6 orders of magnitude) characteristic time scales of the system, as well as on the recently demonstrated robust generalized synchronization properties of two such electro-optic oscillators, that are subjected to a delay shared feedback coupling.

Arturo Lezama[1], P. Valente[2], H. Failache[1], M. Martinelli[2] and P. Nussenzveig[2]

[1]*Instituto de Física, Facultad de Ingeniería, Montevideo, Uruguay*

[2]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*

Single-pass quantum fluctuation spectroscopy in atomic samples

Nonlinear interaction between light and atoms is a well known test bench for quantum optics. Purely quantum states of light such as light squeezing or photon anti bunching, were initially predicted to occur via interaction of laser beams with simple atomic systems. Although most recent experiments use atomic samples contained in optical cavities to enhance the nonlinear interaction, single pass experiments still deserve interest due to the inherent simplicity and possible technological applications. In this talk we discuss the statistical properties of light fluctuations (noise) corresponding to quantized optical fields traversing an optically thick atomic medium taking into account the complete Zeeman structure of the involved atomic transition. We examine the generation of vacuum squeezing. The connection between squeezing ant two mode (continuous variable) polarization entanglement is illustrated.

Marcelo Martinelli and P. Nussenzveig
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

My fair light: bright multicolor entanglement

Entanglement between bright optical beams can be generated quite simply from initially squeezed beams combined on beamsplitters. Yet, this approach is limited to single-frequency entangled light. Direct generation of entanglement, on the other hand, by means of nonlinear processes, can produce fields of different frequencies (or colors). This opens up the possibility of changing the color of quantum information and connecting pieces of quantum hardware which interact with light at different frequencies. The system we study is the above-threshold optical parametric oscillator. Entanglement between the twin beams it produces was predicted in 1988, but was only experimentally verified in 2005, owing to the difficulty in measuring phase noise. Shortly after, we predicted that this simple and very well-known system should directly produce tripartite entanglement, between the bright pump, signal, and idler beams. In this talk, I will present our measurements of twin beam entanglement and also of bright three-color optical quantum correlations, a first step towards tripartite entanglement.

Cristina Masoller[1], C. Serrat[1], R. Vilaseca[1], T. Sorrentino[2], M. Chevrollier[2], and M. Oria[2]
[1]*Departament de Fisica e Ingenieria Nuclear, Universitat Politecnica de Catalunya, Terrassa, Barcelona, Spain*
[2]*Lab. de Física Atômica e Lasers, Universidade Federal da Paraíba, João Pessoa, Brazil*

Dynamics of semiconductor lasers with incoherent feedback

I will present numerical results on the dynamics of semiconductor lasers with polarization-rotated optical feedback. I consider models for single and multi-mode lasers. In both cases, the carrier equation is modified to include a time-delayed term that takes into account the polarization-rotated incoherent feedback. It is assumed that the light fed back into the laser does not interfere coherently with the lasing field but only depletes the carrier reservoir. The model for the single-mode laser includes frequency-dependent feedback, thermal and gain saturation effects [1], and it is aimed at explained frequency bistability observed by Oria and co-workers [2]. In [2] a frequency-sensitive filter (Cs-vapor cell) was placed in the way of the

feedback beam to spectrally modulate the feedback power. Two different emission frequencies with the same output power were observed. The model allows understanding this observation and also predicts dynamical hysteresis in the absence of feedback, due to slow thermal relaxation. This prediction was found to be in agreement with the observations [1]. The model for a multimode laser consists of traveling wave equations for two contra-propagating fields, and includes a parabolic frequency-dependent gain [3]. Results of simulations are confronted with experimental observations by Houlihan et al. [4] and are found to be consistent with several features observed in [4]; however, some discrepancies will also be discussed.

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Krassimir Panajotov[1], Mikel Arizaleta Arteaga[1,2], Miguel Valencia[1], Marc Sciamanna[3], Manuel Lopez-Amo[2], Hugo Thienpont[1]

[1]*Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Brussels, Belgium*

[2]*Department of Electrical and Electronic Engineering, Public University of Navarra, Pamplona, Spain*

[3]*Supelec, LMOPS CNRS, Metz, France*

Feedback from an extremely-short external-cavity in VCSELs and experimental observation of coherence resonance

We first discuss the effect of isotropic optical feedback from an extremely short external cavity (ESEC) on the emission properties of Vertical-Cavity Surface-Emitting Lasers (VCSELs). When changing the external cavity length a modulation of the total power and the wavelength emitted by the VCSEL is observed with a period of half the emission wavelength. By making use of a two modes rate equation VCSEL model we develop a map of bistability to investigate the parametric dependence of polarization properties of VCSELs in such configuration, finding out a periodic dependence of the polarization switching currents on the ESEC length. By increasing the external mirror reflectivity we can make this periodic dependence stronger and strongly asymmetric providing the possibility to prevent PS for any

injection current and thus, achieving polarization stabilization in VCSELs. Further numerical simulations with isotropic and non isotropic feedback show how parameters as gain compression coefficients, frequency splitting between the linearly polarized modes, differential gain and the mirror reflectivity, affect the map of bistability. The theoretical results are supported by extensive experimental mapping. The switching currents and the hysteresis width can be widely tuned by varying the external cavity length. The amplitude of modulation of the polarization switching current with the external cavity length is experimentally confirmed to be proportional to the external mirror reflectivity, proving its key role in achieving polarization control of such lasers using optical feedback. Moreover, by a proper choice of the optical feedback parameters, the emission can be stabilized in any of the two linearly polarized modes. Finally, by making use of the fine-polarization tuning provided by the ESEC feedback we report on the experimental observation of coherence resonance in a bistable system with delay. Our system consists of a VCSEL subject to time-delayed optical feedback simultaneously from a long and from extremely short external cavity. Coherence resonance is experimentally proven by analysis of the residence time distribution of the polarization mode-hopping regime and of the signal to noise ratio in the power spectrum.

Luis Pesquera[1], S. Ortín[1], M. Jacquot[2], M. Peil[2],L. Larger[2]

[1]Instituto de Física de Cantabria (CSIC-UC), Santander, Spain.

[2]UMR CNRS FEMTO-ST 6174/Optics Dpt, Université de Franche-Comté, Besançon, France

Nonlinear dynamics reconstruction of chaotic cryptosystems based on a laser diode subject to optoelectronic feedback with fixed and variable delay

Chaotic communication is a promising technique to complement quantum or software cryptography. However, security of these systems remains the key issue to be addressed. In this talk we consider a chaotic communication system with a transmitter based on a DBR laser subject to optoelectronic feedback with fixed and variable delay. The signal is encrypted within the high dimensional chaotic fluctuations of the wavelength of the tunable laser diode. It is shown that the nonlinear dynamics of the chaotic carrier can be reconstructed from experimental time series when the time delay is fixed. The transmitter nonlinear dynamics is reconstructed by using a modular neural network. It is found that the required number of neurons to achieve similar training errors does not increase with the delay time, even though

the system is high dimensional. However, the training error increases with the feedback strength. The nonlinear model is used as the receiver to extract the message. Therefore these systems are vulnerable when the time delay is fixed. It has been proposed to use a variable time delay to enhance the security. A first step to break the system is the extraction of the time delay. It is shown that the periodic time delay can be extracted from experimental data. Different periodic functions are considered for the time delay. The period of the time delay is obtained from the mutual information. Applying a modified filling factor method the periodic time delay function is recovered for different periods and modulation depths.

Jose R. Rios Leite and Jhon F. Martinez Avila
Departamento de Fisica, Universidade Federal de Pernambuco, Recife, Brazil

Low frequency synchronization between chaotic semiconductor lasers

Semiconductor lasers with optical feedback and chaotic low frequency fluctuation are well known to synchronize. We will present new experimental results on the synchronization of such lasers when optical bi-directional coupling create competition between isochronous and lead-lagging behavior.

Marc Sciamanna
Supélec, LMOPS CNRS UMR-7132, Metz, France

Dynamical diversity in VCSELs with optical injection

We report on the dynamics of the polarization modes and high order transverse modes that occur when VCSELs are subject to optical injection. Several dynamical scenarios shall be discussed and compared to those typically encountered in conventional laser problems using edge-emitting lasers. In particular the two polarization mode competition that typically underlies VCSEL light emission induces new injection-locking steady states and modifies the bifurcation that delimits the injection locking boundaries. Depending on the injection strength and master-slave frequency detuning, polarization switching and transverse mode switching can be observed and accompanied by dynamical instabilities (period doubling, chaos etc.).

Theoretical analysis based on continuation of VCSEL models will be compared with experimental observations. Finally we shall report on the influence of polarization mode competition on the synchronization of unidirectionally coupled VCSELs and its use for chaos secure communication systems.

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Dynamics of VCSELs subject to optical feedback and optical injection

This presentation seeks to offer an overview of experimental work directed at the exploration of dynamical properties of VCSELs subject to optical injection and optical feedback. The work was mainly undertaken at Bangor University but has included an experimental collaboration with Inha University as well as theoretical interactions with colleagues in Tandil, Argentina and Terrassa, Spain. Experimental work in collaboration with Inha University was facilitated by an interaction with Raycan Co. Inc.

In general the dynamics of VCSELs – including when subject to optical feedback and optical injection exhibit strong similarities to that of standard edge-emitting laser diodes. Two specific features serve to enhance the richness of VCSEL dynamics: the excitation of transverse modes and polarization switching – in some cases these being coexistent phenomena. Recent experimental work at Bangor has examined a range of behaviors which arise when VCSELs are subject to polarization-preserved and polarization-switched optical feedback. Theoretical analysis has elucidated a variety of dynamical scenarios which may arise when a modulated VCSEL is subject to optical feedback. Good qualitative agreement has been achieved between experimental and theoretical work in this respect. Work undertaken in collaboration with Inha University includes the first report of experimental

observations of the polarization switching dynamics of a modulated 1.5-μm wavelength single-mode vertical cavity surface emitting laser (VCSEL) under optical injection control. An injected optical beam with polarization orthogonal to that of the stand-alone VCSEL caused a dynamical instability of the laser polarization state near threshold. Successful switching of the polarization state of the output of the VCSEL modulated at 5 MHz was achieved.

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Control of optical turbulence

We consider the suppression of the so-called ``turbulent regimes'' in optical system with advection. It is well known that spatiotemporal systems submitted to advection can undergoes a convective instability above a critical value of the drift parameter. The result is a hypersensivity to noise leading to spatiotemporal erratic regimes called noise sustained structures [1] or “optical turbulence“ [2]. This phenomenom appears with slight difference either in system with local saturation (e.g. liquid crystal with optical feedback [3]) or with global saturation (e.g. actively mode-locked laser [2,4,5]). We demonstrate that it is possible to suppress this kind of instability with a rather simple method. To do this, we revisit the “coherent photon seeding'' method applied empirically in the nineties to stabilized actively mode-locked laser [6]. We study numerically and experimentally the process of stabilization on a elementary advection-diffusion equation (Ginzburg-Landau equation with advection). In addition to determine the adequate parameters, this study allows to interpret the stabilization process: the feedback creates a new deterministic solution toward which the system evolves, the convective threshold has been shifted. This new solution is no more sensitive to noise. Although this process is very different from “Ott-Grebogy-Yorke“ method, it requires extremely small perturbation to be achieve (just above noise level).

Finally, we check experimentally this method on a Free Electron Laser (UVSOR, Japan). We suppress the ``turbulent'' regimes occurring in this laser with a simple optical feedback. The

ratio of the re-injected power is in the order of 10^{-8}. This control scheme should be applicable in other system (optical or not).

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Mapping local defects of extended media using Cavity Solitons

We propose here a method to disclose and visualize local defects of an spatially extended system using properties of cavity solitons (CS) or localized structures. The stable positions of CS depend on spatial gradients in the parameters and on local defects of the hosting medium. By accurate control of parameter gradients in an optically injected VCSEL, we are able to put in evidence the defects in the structure of the device. The system acts as a force microscope with low resolution but extremely high sensitivity.

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Broadband second harmonic parametric scattering in ferroelectric crystals with random domains structure

Optical second-harmonic generation (SHG) in material structures with some class of disorder is a subject of present interest. We report the results of an experimental study on broadband second-harmonic parametric scattering in an un-poled Strontium Barium Niobate (SBN) crystal with random ferroelectric domains. We consider different geometries of the interacting waves. The observed spatial distribution of the SHG is due to the larger facility to achieve phase matching conditions in the presence of disorder, and the polarization of the SH light can be both ordinary and extraordinary. The nonlinear coefficients of the crystal may be determined from the measurement of the SHG as a function of the fundamental beams polarization. The experimental results are in very good agreement with the predictions of our theoretical model.

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Control of visible or near infrared light in bulk photorefractive materials: from waveguides to cavities

The development of all-optical devices operating entirely with light promises significant advances in communication technologies. Control of light by light can be realized in nonlinear materials with optical properties dependent on light intensity. For example, the self-action of beams can result in suppression of diffraction spreading and formation of spatial solitons. Interacting solitons co or counter-propagating can enable passive or active optical components such as optical routers, reconfigurable interconnects and perform all-optical computations. The dynamic creation of waveguides in photorefractive semiconductors (InP:Fe, $Sn_2P_2S_6$) is investigated in the case of a longitudinal soliton-like propagation of a self-focused near-infrared wave. The corresponding response time of the self-focused waveguide is of the order of tens of microseconds at telecommunications intensities. Systematic measurements of the fast photorefractive self focusing as a function of the beam intensity, the electric field applied and the temperature show two different characteristic time

scales : one around the tens of μs related to the transient regime and one of the order of several ms related to the steady state regime. A theoretical model simulating the temporal dynamic of the self focusing is developed and checked against experimental results. In the case of an exact balance between the diffraction and the nonlinear optical effect, the beam propagates as a spatial soliton and by interactions, simple or more complex optical functions as X or Y couplers can be realized. Another interesting application concerns the self-alignment between a laser diode and an optical fiber by using counter-propagating solitons interactions. In such a case or for a photorefractive material in a laser cavity, the control of spatio-temporal instabilities is of practical interest.

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Appearance of solitonic effects by spectral broadening in the normal dispersion regime

Compression of optical pulses in the normal dispersion regime in highly nonlinear optical fibers is limited by several effects. In this contribution a new effect of pulse splitting is presented which has been experimentally verified after it has been numerical calculated. The splitting can be explained by the nonlinear Schrödinger equation without using higher order nonlinearities as Raman scattering. The analysis reveals a mixture of normal and solitonic effects after this splitting occurs.

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Phase diagrams and structure of chaotic phases in optically injected semiconductor lasers and other nonlinear systems

We report high-resolution phase diagrams for a single-mode semiconductor laser with optical injection. Phase diagrams display a highly complicated structure of regions containing stable periodic oscillations embedded in the chaotic phases. We analyze very regular regions displaying sequences of self-similar structures accumulating in certain boundaries in the parameter space. We show that this organization occurs in several familiar dynamical systems ruled by sets of nonlinear ordinary differential equations. In contrast, we study a very regular organization formed by infinite spirals containing stable periodic oscillations embedded in the chaotic phases in a simple resistive electronic circuit.

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Numerical validation of the complex Swift Hohenberg equation for laser

The complex Swift Hohenberg equation (CSH) is a generic order parameter equation that applies to many physical systems. In the case of class C lasers, it can be obtained from the Maxwell Bloch (MB) equations using the assumption that the amplitudes of the physical fields depend slowly on time and transversal spatial scales, and the detuning is small. The resulting CSH equation contains terms of different asymptotic order, associated to the effects of dispersion and diffusion. The precision degree of the CSH equation, as order parameter equation that describes the laser dynamics given by the MB equations, was numerically checked. The difference between the solutions of the CSH and MB equations grows as the distance to the emission threshold, as theoretically predicted. The pump percentage over threshold for a relative error of 10% takes values between 0.003% and 0.4% depending on the kind of solution.

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Hysteresis in planar liquid cristal cells illuminated by polarized light

Hysteresis has been reported experimentally in Liquid Crystal tunable Bragg Gratings for certain tuning ranges [1]. To study this effect, a model cell with a simpler but similar geometry is proposed. Results obtained with this cell show that when illuminated with polarized light, a disclination line appears in the liquid crystal that, for larger values of the applied voltage, retracts showing hysteresis. This effect seems to be the origin of the hysteresis in the Tunable Gratings. In this work we perform a numerical study of the model

cell, showing the appearance of the hysteresis cycle, and study the energy of the liquid crystal director field and its relation with the hysteresis.

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The influence of current sweep rate on the polarization switching in VCSELs with external cavity

Despite Vertical-cavity surface-emitting lasers (VCSELs) have cylindrical symmetry structure; cavity anisotropy means that the output of a VCSEL is linearly polarized along one of two orthogonal directions. Near the lasing threshold, VCSELs normally support one linear polarization, when the bias current is increased; the polarization often switches to the orthogonal linear polarization. Such polarization switching (PS) adds the richness of the dynamics of VCSELs and has drawn a lot of attention. In the present paper, we experimentally study the influence of current sweep rate on the PS of VCSELs subject to optical feedback.

In the experiment, a commercial VCSEL was driven by an ultra-low noise current source and was temperature controlled within 0.01°C. A triangle modulation signal was added to the VCSEL through the current source. For the free-running VCSEL, no polarization switching was observed within current operating range. The VCSEL show polarization switching when it is subjected to optical feedback. Fig. 1 shows the polarization properties of the VCSEL with -36.2 dB feedback ratio. The upper row is time evolution of the X-polarization (thick black curve) and Y-polarization (thick grey curve) during one cycle of the modulating signal (thin grey curve). The lower row is polarization-resolved light-current (L-I) curve (more than 10 cycles of the modulating signal are shown). The results show that the PS currents for increasing and decreasing current in the VCSEL with optical feedback are dependent on the bias current sweep rate. In the free-running VCSEL, there is a power-law relationship between the time delay of PS and modulation frequency [1-2]. To test whether a similar relationship exists in the VCSEL with external cavity, PS currents and PS time delay as a function of modulation frequency are plotted in Fig. 2. PS currents for increasing and

decreasing current are denoted as J_1 and J_2, respectively. t_1 is the time delay from the minimum of the ramp to the PS for upward scans, t_2 is the time delay from the maximum of the ramp to the PS for downward scans. Fig. 2(a) shows that J_1 increases with increasing modulation frequency f, for f > 100 Hz, which is similar to the case in free-running VCSEL [2], however, for lower frequencies (f < 100 Hz), J_1 first increases with the frequency, then drops to the lower value for f = 100 Hz, which is different from the case of the free-running VCSEL [1-2]. The combination of optical feedback and current modulation is thought to cause this difference. In Fig. 2(b), J2 decreases with the modulation frequency. In Fig. 2(c) and 2(d), the solid lines are linear fitting, they clearly show a scaling law between $\log(t_1)$, $\log(t_2)$ and log(f): $\log(t_1)$=-0.98log(f)+0.175; $\log(t_2)$ = -0.92log(f)-0.359.

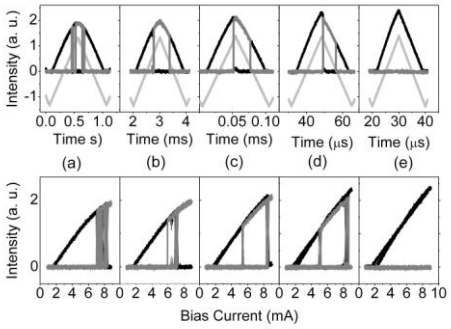

Fig. 1 The polarization properties of the VCSEL with -36.2 dB feedback ratio. Modulating frequencies are (a) 1 Hz, (b) 500 Hz, (c) 5 kHz, (d) 30 kHz and (e) 50 kHz.

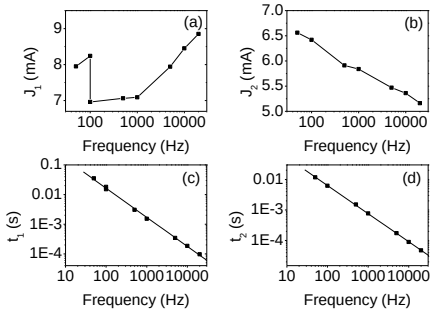

Fig. 2 Log-linear plot of the PS current for (a) increasing and (b) decreasing current versus the modulation frequency. Log-log plot of the time delay of PS for (c) increasing and (d) decreasing current versus the modulation frequency. The solid lines in (c) and (d) is the linear fit log(t1, t2)=a log(f) +b.

In summary, the PS currents for increasing and decreasing current in the VCSEL with optical feedback are dependent on the bias current sweep rate. The results show that the time delay of the PS follows a power law relationship with the current sweep rate.

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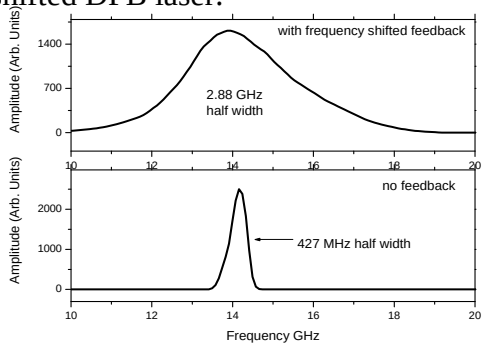
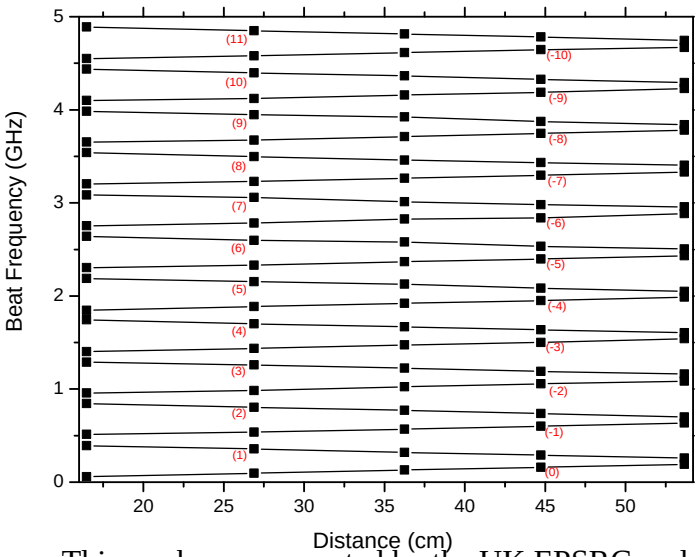
Optical frequency domain ranging using an off-the-shelf DFB laser

Optical frequency domain ranging (OFDR) has been studied and used in various fields for precise distance measurements over both short and long distances. In conventional optical frequency domain ranging a frequency chirped single mode laser is used to convert distance into a beat frequency. Light from a reference and target arms of a Michelson interferometer are mixed at a detection port generating a beat frequency proportional to the path difference in the interferometer. A direct approach at generating a frequency comb is to utilise a laser diode together with an acoustic-optical modulator (AOM) in an external cavity configuration. This approach offers simplicity of implementation together with the exceptional performance characteristics conferred by exploiting the gain bandwidth of laser diodes.

Here we demonstrate chirped-comb generation and distance measurements using a frequency shifted DFB laser.



Oscillation spectrum taken through a scanning Fabry-Perot interferomoter. The top plot shows the spectrum with frequency shifted feedback from an external cavity grating, the bottom spectrum is for the stand alone laser



The observed beat frequencies at the output of the Michelson interferometer. The observed beat frequency is plotted against the distance difference between the target and reference arm. The beat order number is shown in red on each line.

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Synchronous behavior in identical pulse coupled oscillators

We studied synchronization and clustering in three types of identical pulse coupled relaxation oscillators in a global coupling configuration. We considered a mean field approach as well as a distance dependence coupling. The groups of oscillators under study were real light-controlled oscillators (LCOs)[1], simplified LCOs and integrate-and-fire oscillators. In order to study the synchronous behavior, we have used two criteria (phase difference and period) introduced in [2]. We have compared the synchronous behavior of the three types of oscillators by means of the total synchronization probability. We found that LCOs' behavior is similar in most of cases. On the other hand, the integrate-and-fire oscillators exhibit expected results under the mean field approach but the results for the distance dependence coupling contrast with the intuition. In all cases, the duration of the transient has been computed and the results show under the mean field approach, the transient grows logarithmically with the number of oscillators.

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Synchronization in multiple time delay chaotic laser diodes subject to incoherent optical feedback and incoherent optical injection

We present the first report of the synchronization regimes in the unidirectionally-coupled multiple time delay chaotic laser diodes subject to incoherent optical feedbacks and incoherent optical injection. We derive the existence conditions for the synchronization regimes. Numerical modeling supports the analytical findings.

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Chaos synchronization regimes in multiple time delay optoelectronic lasers

This paper provides the first report of synchronization regimes in both unidirectionally and bidirectionally-coupled multiple time delay chaotic optoelectronic lasers. We find the existence conditions for complete, lag, and anticipating synchronization regimes and support the analytical findings with numerical simulations.

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Polarization-resolved modulation response of vertical-cavity surface-emitting lasers

The small-signal modulation response of VCSELs is studied numerically, based on the spin-flip model. A detailed characterization of the influence of various parameters, such as the spin-flip rate, the dichroism and the birefringence is done. In the regime of polarization out of phase self-sustained oscillations, a complex modulation response is found, that exhibits multiple resonance peaks with frequencies that depend on the spin-flip rate. In parameter regions of stable polarization emission, the modulation response is mainly that of a single-mode laser and rather independent of the spin-flip rate.

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