# Research activities of the Group on Nonlinear Dynamics, Nonlinear Optics and Lasers (DONLL) at the Universitat Politècnica de Catalunya (Campus de Terrassa)

# Investigación del Grupo de Dinámica No-lineal, Óptica No-lineal y Láseres (DONLL) de la Universitat Politècnica de Catalunya (Campus de Terrassa)

Jordi Tiana(1), Jordi Zamora(1), Cristian Nistor(1), Vito Roppo(1), Lina Maigyte(1), Andrés Aragoneses(1), Nikhil P. Khumar(1), Cristina Martínez(1), Juan José Fernández(2), Carles Serrat(3), Josep Lluís Font(3), Ramon Herrero(2), Crina Cojocaru(1), Jose F. Trull(2), Cristina Masoller(1), Kestutis Staliunas(4), M. Carme Torrent(2), Jordi García-Ojalvo(1), Ramon Vilaseca(1*,S)

1. Departamento de Física e Ing. Nuclear, Universitat Politècnica de Catalunya (UPC), Edificio Gaia, Rambla Sant Nebridi s/n, 08222 Terrassa, Spain.
2. Departamento de Física e Ing. Nuclear, Universitat Politècnica de Catalunya (UPC), Colom 1, 08222 Terrassa, Spain
3. Departamento de Física e Ing. Nuclear, Universitat Politècnica de Catalunya (UPC), Colom 11 08222 Terrassa, Spain
4. Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

(*) Email: ramon.vilaseca@upc.edu S: miembro de SEDOPTICA / SEDOPTICA member

Recibido / Received: 30/10/2010. Aceptado / Accepted: 15/12/2010

**ABSTRACT:**

The research Group on Nonlinear Dynamics, Nonlinear Optics and Lasers (DONLL) of the Universitat Politècnica de Catalunya, at the Campus de Terrassa, works on different subjects in the following fields: linear and nonlinear light propagation in micro- and nano-structured (spatially modulated) materials; nonlinear dynamics in lasers (in particular in semiconductor lasers) and other optical systems and structures; nonlinear dynamics and light effects in biological samples, and coherent control and Attoscience. Details about the main objectives and results in these areas are summarized below.

**Keywords:** Nonlinear Dynamics, Nonlinear Optics, Semiconductor Laser Dynamics, Nonlinear Oscillators, Synchronization Dynamics, Photonic Crystals, Nonlinear Photonic Crystals, Random Nonlinear Photonic Crystals, Nanophotonics, Spatial Solitons, BEC, Attoscience, Coherent Control, Ultrashort Pulses.

**RESUMEN:**

El Grupo de Investigación en Dinámica No Lineal, Óptica No Lineal y Láseres (DONLL) de la Universitat Politècnica de Catalunya en el Campus de Terrassa, trabaja en diferentes temas en los siguientes campos: propagación lineal y no lineal de la luz en materiales micro- y nano-estructurados; dinámica no lineal de láseres (en particular láseres de semiconductor) y otros sistemas y estructuras ópticas; dinámica no lineal y efectos de la luz en muestras biológicas, y control coherente y Attociencia. En este trabajo se resumen los principales objetivos y resultados de estas investigaciones.

**Palabras clave:** Dinámica No Lineal, Óptica No Lineal, Dinámica de Láseres de Semiconductor, Osciladores No Lineales, Dinámica de Sincronización, Cristales Fotónicos, Cristales Fotónicos No Lineales, Cristales Fotónicos No Lineales Aleatorios, Nanofotónica, Solitones Espaciales, BEC, Attociencia, Control Coherente, Pulsos Ultracortos.

 © Sociedad Española de Óptica

## REFERENCES AND LINKS


[1]. K.Staliunas, R. Herrero, "Nondiffractive propagation of light in photonic crystals", *Phys. Rev. E* **73**, 016601 (2006).

[2]. M. Peckus, R. Rogalskis, M. Andrulevicius, T. Tamulevicius, A. Guobiene, V. Jarutis, V. Sirutkaitis, K. Staliunas, "Resonators with manipulated diffraction due to two- and three-dimensional intracavity photonic crystals", *Phys. Rev. A*, **79**, 033806 (2009).

[3]. R. Iliew, C. Etrich, T. Pertsch, F. Lederer, K. Staliunas, "Subdiffractive all-photonic crystal Fabry-Perot resonators", *Opt. Lett.* **33**, 2695-2697 (2008).

[4]. K. Staliunas, R. Herrero, R. Vilaseca, "Subdiffraction and spatial filtering due to periodic spatial modulation of the gain-loss profile", *Phys. Rev. A* **80**, 013821 (2009).

[5]. M. Botey, R. Herrero, K. Staliunas, "Light in materials with periodic gain-loss modulation on a wavelength scale", *Phys. Rev. A* **80**, 013821 (2009).

[6]. K. Staliunas, Y. Loiko, R. Herrero, J. Trull, C. Cojocaru, "Efficient parametric amplification of narrow beams in photonic crystals", *Opt. Lett.* **32**, 1992-1994 (2007).

[7]. Y. Loiko, R. Herrero, K. Staliunas, "Ultrashort light pulses in photonic crystals in subdiffractive regimes", *J. Opt. Soc. Am. B* **24**, 1639-1645 (2007).

[8]. C. Nistor, C. Cojocaru, Yu. Loiko, J. Trull, R. Herrero, K. Staliunas, "Second-harmonic generation of narrow beams in subdiffractive photonic crystals", *Phys. Rev. A* **78**, 053818 (2008).

[9]. C. Nistor, C. Cojocaru, T. J. Karle, F. Raineri, J. Trull, R. Raj, K. Staliunas, "Lossless backward secondharmonic generation of extremely narrow subdiffractive beams in two-dimensional photonic crystals", *Phys. Rev. A* **82**, 033805 (2010).

[10]. A. M. Yacomotti, F. Raineri, C. Cojocaru, P. Monnier, J. A. Levenson, R. Raj, "Nonadiabatic dynamics of the electromagnetc field and charge carriers in high-Q photonic crystal resonators", *Phys. Rev. Lett.* **96**, 093901 (2006).

[11]. M. Centini, V. Roppo, E. Fazio, F. Pettazzi, C. Sibilia, J. W. Haus, J. V. Foreman, N. Akozbek, M. J. Bloemer, M. Scalora, "Inhibition of ñlinear absorption in opaque materials using phaselocked harmonic generation", *Phys. Rev. Lett.* **101**, 113905 (2008).

[12]. V. Roppo, D. Dumay, J. Trull, C. Cojocaru, S. M. Saltiel, K. Staliunas, R. Vilaseca, D. N. Neshev, W. Krolikowski, Yu. S. Kivshar, "Planar second harmonic generation with noncollinear pumps in disordered media", *Opt. Express* **16**, 14192-14199 (2008).

[13]. J. Trull, C. Cojocaru, R. Fischer, S. Saltiel, K. Staliunas, R. Herrero, R. Vilaseca, D. Neshev, W. Krolikowski, Y. Kivshar, "Second-harmonic parametric scattering in ferroelectric crystals with disordered nonlinear domain structures", *Opt. Express* **15**, 15868-15877 (2007).

[14]. C. M. González, M. C. Torrent, J. García-Ojalvo, "Controlling the leader-laggard dynamics in delay-synchronized lasers", *Chaos* **17**, 033122 (2007).

[15]. C. M. Gonzalez, C. Masoller, M. C. Torrent, J. Garcia-Ojalvo, "Synchronization via clustering in a small delay-coupled laser network", *EPL* **79**, 64003 (2007).

[16]. C. M. González, J. M. Buldú, M. C. Torrent, J. García-Ojalvo, "Processing distributed inputs in coupled excitable lasers", *Phys. Rev. A* **76**, 053824 (2007).

[17]. J. Tiana-Alsina, J. M. Buldú, M. C. Torrent, J. García Ojalvo, "Quantifying stochasticity in the dynamics of delay-coupled semiconductor lasers via forbidden patterns", *Philos. T. R. Soc. A* **368**, 367-377 (2010).

[18]. J. Tiana-Alsina, M. C. Torrent, O. A. Rosso, C. Masoller, J. García Ojalvo, "Quantifying the statistical complexity of low-frequency fluctuations in semiconductor lasers with optical feedback", *Phys. Rev. A* **82**, 013819 (2010).

[19]. C. Masoller, C. Serrat, R. Vilaseca, "Modeling multi-longitudinal-mode semiconductor lasers with incoherent feedback", *Phys. Rev. A* **76**, 043814 (2007).

[20] J. Zamora-Munt, C. Masoller, "Generation of optical pulses in VCSELs below the static threshold using asymmetric current modulation", *Opt. Express* **16**, 17848-17853 (2008).


 © Sociedad Española de Óptica

[21]. J. Zamora-Munt, C. Masoller, "Numerical implementation of a VCSEL-based stochastic logic gate via polarization bistability", *Opt. Express* **18**, 16418-16429 (2010).

[22]. Y. Hong, C. Masoller, M. S. Torre, S. Priyadarshi, A. A. Qader, P. S. Spencer, K. A. Shore, "Thermal effects and dynamical hysteresis in the turn-on and turn-off of vertical-cavity surface-emitting lasers", *Opt. Lett.* **35**, 3688-3690 (2010).

[23]. J. L. Font, R. Vilaseca, K. Staliunas, E. Roldan, G. J. de Valcarcel, "Transverse effects in a thin slab of material with local-field induced intrinsic optical bistability", *J. Opt. Soc. Am. B* **25**, 2036-2048 (2008).

[24]. K. Staliunas, O. Egorov, Yu. S. Kivshar, F. Lederer, "Bloch cavity solitons in nonlinear resonators with intracavity photonic crystals", *Phys. Rev. Lett.* **101**, 153903 (2008).

[25]. K. Staliunas, R. Herrero, G. J. de Valcárcel, "Arresting soliton collapse in two-dimensional nonlinear Schrödinger systems via spatiotemporal modulation of the external potential", *Phys. Rev. A* **75**, 011604(R) (2007).

[26]. K. Staliunas, R. Herrero, G. J. de Valcárcel, "Diffraction management and sub-diffractive solitons in periodically driven Bose-Einstein condensates", *Physica D* **238**, 1326-1337 (2009).

[27]. K. Staliunas, G. J. de Valcarcel, J. M. Buldu, J. Garcia-Ojalvo, "Noise-induced phase bistability via stochastic rocking", *Phys. Rev. Lett.* **102**, 010601 (2009).

[28]. I. Pérez-Arjona, V. Sánchez-Morcillo, J. Redondo, K. Staliunas, E. Roldán, "Diffusion stabilizes cavity solitons in bidirectional lasers", *Opt. Express* **17**, 4897-4902 (2009).

[29]. E. Soliveres, V. Espinosa, I. Perez-Arjona, V. Sanchez-Morcillo, K. Staliunas, "Self collimation of ultrasound in a three-dimensional sonic crystal", *Appl. Phys. Lett*. **94**, 164101 (2009).

[30]. Yu. Loiko, C. Serrat, R. Vilaseca, V. Ahufinger, J. Mompart, R. Corbalán, "Ultrashort pulse control of space-dependent excitations in a three-level system", *Phys. Rev. A* **75**, 023801 (2007).

[31] Yu. Loiko, C. Serrat, R. Vilaseca, V. Ahufinger, J. Mompart, R. Corbalán,"Doppler-free adiabatic self-induced transparency", *Phys. Rev. A* **79**, 053809 (2009).

[32]. A. A. Juarez, R. Vilaseca, Z. Zhu, D. J. Gauthier, "Room-temperature spectral hole burning in an engineered inhomogeneously-broadened resonance", *Opt. Lett.* **33**, 2374-2376 (2008).

[33]. D. Faccio, C. Serrat, J. M. Cela, A. Farrés, P. Di Trapani, J. Biegert, "Modulated phase matching and high order harmonic enhancement mediated by the carrier-envelope phase", *Phys. Rev. A* **81**, 011803(R) (2010).

[34]. C. Serrat, J. Biegert, "All-regions tunable high harmonic enhancement by a periodic static electric field", *Phys. Rev. Lett.* **104**, 073901 (2010). Highlighted in *Nat. Photonics* 4, May 2010.

[35]. E. Hijano, C. Serrat, G. N. Gibson, J. Biegert, "Orbital geometry determined by orthogonal high harmonic polarization components", *Phys. Rev. A* **81**, 041401(R) (2010).

## 1. Linear and nonlinear light propagation in spatially modulated materials

We study the linear and nonlinear propagation and dynamics of light beams in spatially modulated materials, such as photonic crystals and related structures. In particular, we study the modification of the properties of light beams which occur in the cases of:

Linear photonic crystals [1,2], for which the special profiles of the dispersion relation $\omega(\vec{k})$ can strongly modify the diffraction characteristics of waves propagating in certain directions, leading to phenomena such as subdiffractive propagation (Fig. 1a) and beam filtering, which we have shown and characterized in different conditions. In collaboration with the University of Vilnius, patterns in resonators filled by photonic crystals were demonstrated for the first time. In collaboration with Jena [3] all-photonic-crystal resonators were proposed and calculated.

Linear materials with uniform refractive index, but with periodic spatial modulation of the gain and losses [4,5]. We have initiated the investigation of these materials, and have shown that, instead of bandgaps, mode locked regions appear, which also modify the spatial dispersion relation leading to a variety of nontrivial spatial effects. The study of the temporal dispersion in one-dimensionally modulated materials predicts

 © Sociedad Española de Óptica

mode locked states and superluminal light propagation regimes in parameter domains close to the locking regions. The study of spatial dispersion for a two-dimensional gain/loss modulation predicts nontrivial beam propagation effects such as self-collimation and negative diffraction, as well as angle-sensitive gain. Maxwell equations with a modulated gain/loss function are analyzed with a full Plane Wave Expansion, which allows us to calculate band diagrams in both 1D and 2D cases to prove the predicted effects. Angle-sensitive gain leads to a non-diffractive but diffusive propagation of light (Fig. 1b) and to spatial frequency filtering of light beams.

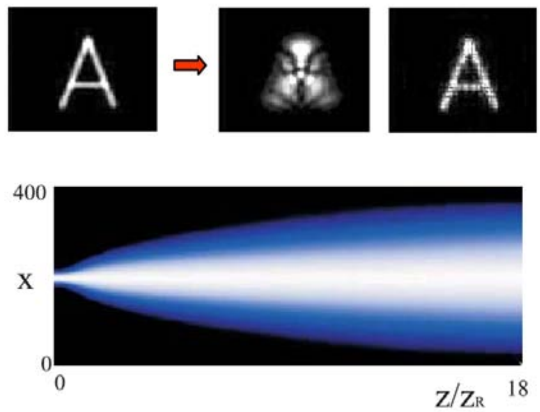


Fig. 1: (a) Letter "A" after propagation through a homogeneous medium and through a 3D photonic crystal under non-diffraction conditions. (b) Beam filtering by "superdiffusion" in a gain/loss spatially modulated crystal.

This diffraction and gain management is of technological importance and allows several applications. For instance, this is an advantage in applications, where one can not only amplify a highly directed beam and spatially filter it, but additionally one can have focusing of that beam behind the modulated material, when working in a slightly negative-diffraction regime.

Nonlinear photonic crystals, in particular with $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities [6-10]. In the $\chi^{(2)}$ case, we have studied effective sub- and harmonic generation of subdiffractive narrow beams, and in particular [8] we have explored whether simultaneous fulfilment of the phase-matching and nondiffraction conditions can be achieved in realistic material structures, i.e., taking into account all parameters such as material dispersion, geometry – photonic crystal – dispersion and, if existing, wave-guide dispersion. If possible, this could lead to a strong enhancement of nonlinear effects. We have found that if the photonic crystal is embedded within a waveguide, conditions can be found which are quite close to that goal.

Also in the $\chi^{(2)}$ case, and in collaboration with LPN-CNRS (Paris), we have studied the possibilities of ultrafast all-optical tuning of the photonic-crystal response [9]. We propose a new geometry of planar photonic crystal device that combined with the use of highly nonlinear semiconductor materials is able to considerably enhance the control of the structure's optical response via the nonlinear interaction. The effect relies on the nonlinear interaction between a signal (frequency $\omega$) and a control (frequency $2\omega$) beam. The temporal duration of these changes is only limited by the length of the pulse. This very fast effect can be used for the design of ultra-fast all-optical modulators or switching devices to be integrated in planar photonic circuits.

We are now investigating the extension of the phenomenon of phase-locked harmonic generation, recently described [11], to the case of spatially non-uniform materials. Finally, in the case of $\chi^{(3)}$ materials, after having studied nonadiabatic dynamics due to carrier excitation in collaboration with LPN-CNRS [10], we have next studied, among others, subdiffractive solitons in Kerr-nonlinear photonic crystals.

Materials with uniform refractive index but with random spatial distribution of quadratic nonlinearity. It has been shown recently that 2nd-order nonlinear processes can be simultaneously phase matched over a very large optical bandwidth in media with randomness in the size and distribution of anti-parallel nonlinear ferroelectric domains, and that can be done without careful crystal alignment. Unpoled crystals of Strontium Barium Niobate (SBN) are examples of such type of random nonlinear media. In collaboration with Canberra, we have studied transverse non-collinear second harmonic generation in such medium and have demonstrated that, on the one hand, it allows to characterize the spatial distribution of nonlinear

 © Sociedad Española de Óptica

domains [12], and on the other hand it provides a simple and robust method for characterizing femtosecond optical pulses (Fig. 2) [13].

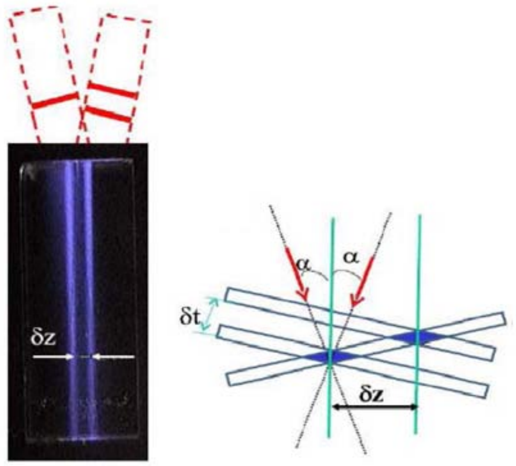


Fig. 2: Propagation of two beams with λ=810nm overlapping within a $\chi^{(2)}$ random nonlinear crystal. One of the beams is a unique short pulse, whereas the other beam is a sequence of two short sub-pulses. The two traces correspond to SHG light generated in the regions where pulse overlapping occurs. The trace width gives the pulse duration, whereas the trace separation gives the time separation between the two sub-pulses and thus can be used for absolute calibration of the measurement of the pulse width [13].

## 2. Nonlinear light dynamics in semiconductor lasers

As is well known, semiconductor lasers are among the most important devices for photonics science and technology. At the same time, they are nonlinear systems where important dynamic processes of interaction of light with matter can take place. Their fast response and compactness, and the possibility of coupling between two or more semiconductor lasers through free space or through an optical fiber, make them useful not only for applications in optical communications but also for studying coupling phenomena between nonlinear oscillators. From the point of view of the dynamics of semiconductor lasers we are studying, among others, the following problems:

Emergence of leader-laggard dynamics in bidirectionally coupled semiconductor lasers [14]. We have shown experimentally and theoretically, in collaboration with the group of Ingo Fischer at the Instituto de Física Interdisciplinar y Sistemas Complejos (CSIC-UIB), that this dynamics arises via a regime of quasiperiodicity, as the coupling goes from unidirectional to bidirectional.

Emergence of synchronization in a small network of delay-coupled lasers, which we have studied experimentally in terms of the increase of the coupling strength [15]. On the other hand we have studied experimentally and theoretically the effect of distributed input signals in two mutually injected semiconductor lasers with optical feedback [16].

Influence of noise in two coupled semiconductor lasers. We have showed experimentally that common noise applied to the injection current leads to zero-lag synchronization between the lasers.

In the same setup we have studied the regime in which the lasers synchronize their dynamics with a nonzero lag time, and the leader and laggard roles alternate irregularly between the lasers. The level of stochasticity of this behavior has been quantified in terms of the number of forbidden patterns of the time series of the switchings [17].

We are presently studying the synchronized dynamics of two semiconductor lasers coupled unidirectionally through two separate paths of different lengths. Our results show that for coupling strengths balanced between the two paths, the dynamics of the lasers show correlation at both coupling delay times, which prevents the system from being used for communication purposes in a narrow range of coupling strengths.

In the case of a semiconductor laser subject to moderate optical feedback, we have quantified the complexity of the underlying dynamics in the intensity experimental time series employing different tools from information theory [18].

Other two aspects of the dynamics of the semiconductor lasers subject to optical feedback in which we are working recently are: the appearance of correlations in the series of time intervals between dropouts, as a result of dichotomous noise being applied to the pump

© Sociedad Española de Óptica

current, and the consistency of the laser response to complex drive signals.

The richness of the dynamics of semiconductor lasers is even larger when the laser works in a multimode regime. We are studying such dynamics, in a single laser, in cases of both edge-emitting lasers (EELs) and vertical-cavity surface-emitting lasers (VCSELs). We consider various types of mode-mode interactions:

In EELs, we have performed simulations with a travelling-wave model with parabolic gain, adapted to a situation in which the laser is subject to incoherent polarization-rotated optical feedback [19]. We found square-wave modulation of the output power accompanied by multimode emission, where many longitudinal modes turn on and off synchronously.

In VCSELs, we have studied the competition of two modes with orthogonal linear polarizations and with different transverse optical profiles. In the case of edge-emitting lasers we have studied the competition between longitudinal modes. We have proposed a novel method for the generation of sub-nanosecond optical pulses in directly modulated VCSELs that operate, on average, below the cw threshold [20]. We have also proposed a way to exploit nonlinearity, polarization bistability and intrinsic spontaneous emission noise to implement a VCSEL-based stochastic logic gate [21].

We have studied an extension of the spin-flip model that takes into account thermal effects, and found that the inclusion of temperature gradients, Joule self-heating and carrier heating can result in significant changes in the shape of the polarization-resolved LI curve, which are in good agreement with experimental observations [22].

## 3. Nonlinear light dynamics, in other structures and systems

We have studied the propagation of narrow beams in thin layers of material exhibiting intrinsic optical bistability, and in particular the possibility of writing and erasing stable localized excitations (pixels) which might be useful for parallel information processing. We have considered in particular the effect of light and matter diffusion on the transverse stability of the excited pixels [23].

We have also studied light dynamics in resonators with embedded photonic crystals, in particular the formation of spatial solitons [24,25]. On the other hand we have extended our experience on nonlinear dynamics in spatially modulated optical systems to the case of Bose-Einstein condensates (BECs) and matter waves (for instance the idea of subdiffractive solitons has been exported to BECs [26]).

In collaboration with Valencia, we have contributed to the study of the modification of the phase symmetries of a laser (or any parametric nonlinear system) brought about by an appropriate temporal modulation of one of the parameters (“rocking”) [27]. This results in significant changes in the dynamic properties of the system, in particular in the number of degenerate solutions with the same intensity and different phase, which can be useful for information processing. This has been applied to optical and electronic systems. On the other hand we have also contributed to the study of hyperbolic patterns, and to the study of cavity solitons in bidirectional lasers [28].

In collaboration with Gandia and Valencia, we have contributed to the extension of the present knowledge on nonlinear dynamics of optical waves to the case of sound waves in acoustically nonlinear materials, where we have identified the similarities and differences with the optical case [29].

In collaboration with the Universitat Autònoma de Barcelona, we have contributed to the study of propagation of ultra-short pulses in atomic media and information storing [30], and on the other hand we have proposed a new method for optical transparency of an absorbing atomic medium, based on STIRAP and on the use of chirped pulses[31].

Finally, in collaboration with Duke university we have studied applications of slow light in optical fibers (brought about by Brillouin effect) to information recording in the fiber [32], as well

 © Sociedad Española de Óptica

as multi-photon adiabatic passage (STIRAP) in atomic media.

Other research activities of our Group about dynamics in biological systems, leadered by J. García-Ojalvo, are out of the scope of Optics and thus will not be reported here.

## 4. Coherent control and Attoscience

The area of this research is Attoscience, one of the fastest growing new interdisciplinary fields with profound impact in physics, chemistry, biology, as well as in medicine. We aim at studying the coherent motion of electron wavepackets inside atoms and molecules on attosecond ($10^{-18}$ seconds) timescales, considering the generation and propagation of high-order harmonics driven by high-energy laser pulses with different geometries.

On the one hand, we study different wavelength regimes considering various shapes of the input pulses, such as few-cycle Gaussian and Gauss-Bessel pulses [33], and the addition of periodic dc-electric and magnetic fields [34], as well as modulation of the gas density along the propagation direction.

On the other hand, we are at present extending our SFA-theory to take into account Coulomb corrections in the propagation of the electron wave-packets in the continuum, in collaboration with Prof. Carla Faria from University College London and Profs. Maciej Lewenstein and Jens Biegert (ICFO).

We are also considering excited states from where the generation process is enhanced, which is combined with coherent control techniques to investigate HHG from selectively populated excited states in alkali atoms.

Finally, we investigate the possibilities for orbital reconstruction using quantum tomography techniques [35].

Our studies are a basis for the physical interpretation of the experimental data obtained in ICFO's Attoscience and Ultrafast Optics (AUO) group, providing essential theoretical support ranging from microscopic single-atom response to full harmonic propagation as well as initial state preparation using coherent control techniques. Concerning computational resources, we have currently a project (FI-2010-3-0009: Scaled Attosecond Physics) running at the Barcelona Supercomputing Center (BSC) – MareNostrum led by Carles Serrat, in the frame of the Red Española de Supercomputación (RES).

**Acknowledgments**

Support from the Spanish Ministry of Education and Science under contracts FIS2008-06024-C03-02/FIS, FIS2008-06368-C02-02/FIS and Consolider Program Science SAUUL - CSD 2007-00013, from the Generalitat de Catalunya under contract 2005SGR 00457, from the European Union through COST MP0702 action, and from Barcelona Supercomputing Center (BSC) are acknowledged.

 © Sociedad Española de Óptica