



ERASMUS MUNDUS



## **Euromicrophotonics EMJD Doctorate Program phD projects 2011 – 2014**

The underlined name corresponds to the main advisor professor.

### **1. Super-resolution fluorescence microscopy using nanostructured substrates**

Involved institutions : Institut Fresnel (Hugues Giovannini) and ICFO (Pablo Loza-Alvares)

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Improving the spatial resolution of far-field fluorescence microscopes below 100 nm has become a major challenge in the last ten years and has spurred the emergence of many innovative techniques [1]. Amongst them, structured illumination (SI) and Stimulated Emission Depletion (STED) microscopy have shown its potential for ameliorating resolution. In SI microscopy, the improvement of resolution is achieved on both the transverse and axial directions while keeping a wide-field configuration. In this approach, the sample is illuminated by a light grid stemming from the interferences of two of three coherent beams. Various images of the sample are recorded for different positions of the grid. The fluorescence density is then retrieved numerically with an inversion algorithm.

This technique has been extended to Total Internal Reflection Fluorescence Microscopy (TIRFM) in which the excitation field is an evanescent wave obtained through the total internal reflection of the beam at the interface of a high and low index semi-infinite media [2]. This configuration is adapted to surface-imaging inasmuch as only the fluorescent markers close to the interface are strongly illuminated. TIRFM is widely used in biological studies, especially for the observation of plasma membranes of cells or single biomolecular dynamics. Recently, this method has been shown to achieve a lateral resolution of approximately 100 nm [2] for an illumination wavelength of 500 nm, while keeping the 100 nm axial resolution of conventional TIRFM.

To improve further the transverse resolution of structured illumination fluorescence microscopy, it has been suggested to use a periodically nanostructured glass slide as sample support. The objective is to generate a light grid with a period much smaller than that possibly obtained with an interference pattern (the period of which being, at best, equal to half of the wavelength) [3-5]. The main difficulty for designing the pattern of the glass slide is that the light intensity above it should exhibit high frequencies but it should also be homogeneous in average (when varying the polarization or incident angle) to avoid any blind region. The second issue is to develop efficient inversion algorithms to retrieve the fluorophore density from the various images [6]. The first theoretical results show that a resolution about 50 nm can be expected using grating-substrates that feasible with the present nanotechnology techniques [6]. In STED microscopy [7], super resolution is achieved by depleting electronic excited states, via stimulated emission, in the peripheral region of a focused fluorescent spot while leaving a small fluorescent region in the centre intact. This produces an effective smaller fluorescent spot that has to be scanned together with the excitation beam to produce an image. Although this smaller spot results in an improvement of the resolution only in the transversal direction, STED directly produces a 2D super resolution image [8]. In a similar way as in SI, STED can improve the transversal resolution of TIRF.

The objective of this thesis is to develop a grating-TIRFM imager and a STED-TIRF microscope. The work includes both an experimental and a theoretical part. During his/her stay in the Institut Fresnel, the student will acquire images on an existing home-built TIRF

Microscope and will participate to the making of the grating-substrates in collaboration with an institute that is specialized in nanotechnology. He/she will also develop inversion algorithms to process the data and retrieve the fluorescence maps. In addition, during the stay at ICFO, the student will have the opportunity to work with a state of the art STED CW microscope (the first commercially available in Europe). The student will modify this microscope to combine it with the TIRF technique. The student will work in a multidisciplinary environment in close contact with biomedical researchers.

[1] S. Hell, "Far-field optical nanoscopy," *Science* 25, 1153–1158 (2007)

[2] E. Chung, D. Kim, and P. So, "Extended resolution widefield optical imaging objective-launched standing-wave total internal reflection fluorescence microscopy," *Opt. Lett.* 31, 945–947 (2006)

[3] Sentenac et al, "Subdiffraction resolution in total internal reflection fluorescence microscopy with a grating substrate," *Opt. Lett.* 33, 255–257 (2008)

[4] Sentenac et al, "Beyond the Rayleigh criterion: grating assisted far-field optical diffraction tomography," *Phys. Rev. Lett.* 97, 243901–4 (2006)

[5] Sentenac et al, "Sub-diffraction light focusing on a grating substrate," *Phys. Rev. Lett.* 101, 203901, (2008)

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[8] Hein, B., K. I. Willig, and S. W. Hell, Stimulated emission depletion (STED) nanoscopy of a fluorescent protein-labeled organelle inside a living cell, *Proc. Natl. Acad. Sci. USA*. 105, 14271–14276 (2008)

## **2. Biomolecular mechanics using single molecule manipulation and detection**

Involved institutions : LENS ([Francesco Pavone](#)), Institut Fresnel (Sophie Brasselet)

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Physical properties of biomolecules (proteins and DNA) and cells interacting with their environment during a biological process are strongly governed by intermolecular interactions at large scale. These interactions are key factors that build up cell mechanical properties. The use of manipulation tools (such as optical or magnetic tweezers) provides information not accessible with conventional methods. This allows original investigations on fundamental biochemical and cell biological processes, such as regulation of gene expression, transcription, muscle contraction, protein synthesis, virus infection, cell interaction, etc. The use of magneto-optical tweezers also allows a novel approach to the characterization of the physical properties of biopolymers. Our scientific research is focused both on single biomolecules and more complex systems (i.e. cells, vesicles, viruses, etc).

This project will combine the expertise present in LENS and Institut Fresnel to tackle the problem of proteins interaction in vitro or in vivo, using fluorescent labels that permit to measure both the conformation changes and the orientational dynamics of biomolecular complexes. The scale of investigation can go from a single molecule to clusters of molecules. This information, combining single molecule tracking and optical / magnetic forces, can reveal new information on biomolecular mechanics. The instrument proposed in this project will combine single molecule fluorescent detection [1] and manipulation [2], high spatial resolution and polarization-resolved fluorescence imaging [3]. These tools, which are powerful for molecular investigation, can strongly benefit from a combination of their advantages to get a new insight into biomolecular mechanics.

The candidate to this PhD project will be involved in the development of advanced microscopy tools combining single molecule tracking, forces and polarization detection. This work will be mostly experimental with some models developments, and requires either a background in physics, biophysics-biotechnologies, or engineering.

[1] F. Vanzi, L. Sacconi, and F. S. Pavone, Analysis of kinetics in noisy systems: application to single molecule tethered particle motion, *Biophys J.* vol. 93 pp 21-36 (2007). (LENS)

[2] D. Normanno, F. Vanzi, F.S. Pavone. Single-molecule manipulation reveals supercoiling-dependent modulation of lac repressor-mediated DNA looping. *Nucleic Acids Res.* 36(8):2505-13 (2008) (LENS)

[3] A. Gasecka, L-Q. Dieu, D. Bruehvilier, S. Brasselet, "Probing molecular order in zeolite L inclusion compounds using two-photon fluorescence polarimetric microscopy", *J. Phys. Chem. B* 114 (12), pp 4192–4198 (2010) (Institut Fresnel)

Websites : <http://www.lens.unifi.it/bio/>,

<http://www.fresnel.fr/spip/spip.php?rubrique28&lang=en>

### 3. Plasmon-soliton coupling

Involved institutions : Institut Fresnel (Gilles Renversez, André Nicolet), ICFO (Yaroslav Kartashov)

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During the last few years, the fabrication and study of nanoscale metal structures leads to the development of plasmonics as a part of photonics [1]. The main advantage of the involved waves (Surface Plasmon Polariton SPP) in these structures is their tight spatial confinement near the metal/dielectrics interface. Several applications have already been proposed or realized [2]. To extend the capabilities of these structures, one way is to consider the coupling between the plasmons and optical solitons. This way is not studied yet except in one article which mentions their coupling but focusing only on the soliton properties [3]. The solution we propose would allow us to control optically the plasmon-based nanodevice using the field intensity in the nonlinear region. These hybrid devices would also allow to eliminate or to reduce the limitations of conventional SPP-based structures, generated by the high losses due to the metals.

References

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[2] E. Ozbay. Plasmonics: Merging photonics and electronics at nanoscale dimensions. *Science*, 311:189–193, 2006.

[3] E. Feigenbaum and M. Orenstein. Plasmon-soliton. *Optics Lett.*, 32:674, 2007.

Website : <http://www.fresnel.fr/spip/spip.php?rubrique9>

### 4. Manipulation of Degenerate Quantum Gases with photonic structures

Involved institutions : LENS (Francesco Saverio Cataliotti), ICFO (Maciej Lewenstein)

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We intend to fabricate light potentials on degenerate quantum gases using photonic structures. This will allow to guide laser light to the atoms for manipulation of internal and external degrees of freedom and for atomic detection. The use of nano-structured optical materials with a wide variety of optical mechanical and electrical properties (wide band optical transmission, optical gain, nonlinearity ferroelectricity, pyroelectricity, photorefractivity, etc.) will open up a wealth of new possibilities. Cooling atoms of different statistics to quantum degeneracy and bringing them in the light potential will offer the opportunity of having a

precise knowledge of the model Hamiltonian, of manipulating its coupling constants or working with controllable disorder thus offering a unique opportunity of studying matter wave transport and open quantum problems. This could allow the possible realization of new devices such as quantum switches, quantum gates and quantum states sources.

Website : <http://www.lens.unifi.it/index.php?nl=descript>

## **5. Photonic Crystal Micro-Resonators.**

Involved institutions : UPC (Kestutis Staliunas), LENS (Diederik Wiersma)

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By "photonic crystal resonators" we mean the micro-resonators which are filled inside by linear or/and nonlinear material spatially modulated on the wavelength scale - the photonic crystals. It is not to confuse with the defects inside the bulk photonic crystals, sometimes acting as the small cavities, which are in literature also sometimes called by "photonic crystal resonators". As it is known, the light propagation even in bulk photonic crystals (no resonator mirrors) shows fascinating properties such as complicated band structure, self-collimation, spatial filtering effects and others. The photonic crystal placed inside the resonator makes the processes more interesting and complicated: the effective propagation distance of the photon through the photonic crystal effectively increases due to multiple reflections (it is technologically very difficult to obtain long photonic structures). Also the mode structure of the resonator introduces new properties in addition to the properties of the bulk photonic crystals.

We plan to study both experimentally and theoretically these photonic crystal resonators in different levels of complexity. In the simplest case we will study linear resonators containing only one longitudinal period of intracavity photonic crystal, but we will continue with several period structure. Next - we plan to fill such resonators by amplifying media (most likely dye solution) and to study the fluorescence or even laser in such a system (photonic crystal laser). And finally, we plan to consider not purely periodic modulation of the index, but more complicated (and interesting) situations: we think about the fractal character of the modulation of index; also about the weakly random index modulation in both cases of linear and nonlinear photonic crystal resonators.

The possible tasks of the PhD student range from conceptual-theoretical work (writing a theory of the light propagation in such materials), to numerical investigations (calculating the light propagation, the band diagrams, the Bloch-like modes in concrete materials and concrete architectures), and to experimental studies. The concrete participation in each task will depend on whether the candidate is more attracted by theoretical, numerical or experimental work.

Website : <http://dfen.upc.edu/>, <http://www.complexphotonics.org/>

## **6. Physics of atoms in orbital lattices**

Involved institutions: Maciej Lewenstein (ICFO), Massimo Inguscio (LENS)

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The project will deal with a novel type of ultracold atoms physics: physics of atoms in orbital lattices. We mean to study strongly and weakly correlated state of atoms in higher orbital states in optical lattices. Such systems are hardly realizable in condensed matter due to many factors. Phonons frequently lift orbital degeneracy, condensed matter is restricted to electrons i.e. spin  $\frac{1}{2}$  fermions, etc. In atomic physics it became possible to realize such systems, and several leading groups have made the first steps (W. Phillips, I. Bloch). Very recently A. Hemmerich realized first hybrid orbital lattice and exotic bosonic superfluid in such lattice.

Several groups are planning to study orbital physics with fermionic atoms where the orbital states may be stable due to the Pauli principle. Particularly interesting are planned experiment with ytterbium planned at LENS. Recent theoretical work of Ivan Deutsch group predict very useful p-wave Feshbach resonance in such atoms, that allows to control and change inter actions in such systems.

The thesis project deals with theory of such systems, The starting point is the Hubbard model describing fermions in 3 internal p-orbital states. We plan to use various theoretical methods to study this model: a) reduction to an effective spin model at strong coupling b) simulation of the spin model c) mean field theory of the spin model d) theories beyond the spin model based on slave boson type of approach. We expect appearance of novel type of quantum phases including exotic spin liquids, Fermi superfluids etc. We plan to consider square and hexagonal optical lattices. We plan to work in close collaboration with the experimental groups of LENS and Hamburg.

Website : <http://www.icfo.es/index.php?section=home0&lang=english>

## 7. Coupled high-Q micro-cavities

Involved institutions: KIT ([Heinz Kalt](#)), LENS (Diederik Wiersma)

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Cavity quantum electro dynamics (CQED) involving (visible) light has attracted quite some attention since the fabrication of optical cavities with ultra-high quality factors (Q-factors) enabled the strong coupling between cavity photons and single optical emitters. The latter are typically established in form of optical transitions in cold atoms or excitonic transitions in molecules or quantum dots. The resulting mixed state of optical excitation and photon (polariton) leads e.g. to correlation effects between emitted photons (non-classical light).

A wide field of new types of photon states opens up, when a coupling of various cavities in chains or arrays is achieved. First results have e.g. been demonstrated for micro-wave photons coupled to superconducting qubits. A most interesting task would be to demonstrate similar CQED effect in the visible or near-IR spectral range.

A prerequisite for such experiments are high-Q optical resonators. A high Q leads to long dwelling times of the photons in the cavity and in combination with a small modal volume one can achieve strong coupling to attached or incorporated quantum dots or dye molecules. This has been shown e.g. for single quantum dots in Bragg-type semiconductor micro-cavities.

The highest Q-factors have been demonstrated for whispering-gallery-mode (WGM) micro-resonators like glass spheres and glass toroids. Just recently the groups of H.Kalt (Institute of Applied Physics at KIT) and T.Mappes (Institute of Microstructure Technology at KIT) have introduced a novel type of WGM resonator based on polymers. These goblet resonators achieve Q-factors of ten millions and are thus most promising for applications like micro-lasers and bio-molecule sensors integrated into lab-on-chip devices.

Currently we are developing processing techniques that should allow to position polymer cavities within respective distances of about 100nm. We further test the attachment of quantum dots and dye molecules to the cavities using e.g. dip-pen nanolithography to achieve strong light-matter coupling.

The task of a PhD candidate will be to investigate strong coupling between quantum dots and the cavities as well as the coupling between different cavities. The latter can be achieved either via optical (glass or polymer) wave guides or direct coupling of adjacent cavities in chains or arrays. If successful, one will be able to address phenomena like polariton tunnelling between cavities or slowing down and localization of light in cavity arrays.

The work is embedded at Karlsruhe Institute of Technology (KIT) in a cooperation of the Institute of Applied Physics, the Institute of Microstructure Technology, the Light Technology Institute and the Institute of Theoretical Solid State Physics. This collaboration provides a solid background in nano- and microstructure technologies, advanced spectroscopy and photonics theory.

The second European partner in this project is the European Laboratory for Non-Linear Spectroscopy (LENS) in Florence. The LENS team has excellent facilities for imaging the near and far field contribution of the electro magnetic field, using SNOM and confocal microscopy. This allows resolving the spectral and spatial distribution of the modes, as well as their polarization. In addition, at LENS a unique combination of techniques has been developed to tune the modes of photonic structures by locally addressing them with fluids (local micro-infiltration) and by thermal oxidation via illumination by the SNOM tip. This will allow to bring individual resonators in and out of resonances with their neighbours and allows to study, for instance, the avoided crossing that you obtain when two resonators couple. The technique can also be used to bring a high Q resonator in exact resonance with a local emitter, thereby allowing to study the weak, and possibly strong, coupling regime between source and cavity.

Website : <http://www.aph.kit.edu/kalt/english/288.php>

### **8. Multimodal eye's optical quality**

Involved institutions: UPC ([Jaume Pujol](#)), KIT (W.Stork)

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The monitorization optical image formed by the eye on the retina has a great interest in order to improve the diagnosis of ocular diseases, to assess the outcomes of ocular treatments, such as refractive surgical procedures, and to improve their quality. Several instruments that provide partial information about eye's optical quality have been developed. One of the aims of this project is developing new systems that permits a complete evaluation in real time of retinal image quality integrating different techniques. The project is proposed by two laboratories with great experience and expertise in research and development projects in biomedical sensors, optical design and optical instrumentation applied to the ophthalmology field.

Work Program: Starting the work at the Centre for Sensor, Instrument and Systems Development at UPC, developing experimental platform, continuing in Karlsruhe developing sensors and finalizing in at the CD6 and Karlsruhe with measurements and application at the ophthalmology field.

Website : [www.itiv.kit.edu](http://www.itiv.kit.edu), [www.cd6.upc.edu](http://www.cd6.upc.edu)

### **9. 3D Deflectometric measurement techniques for highly reflecting surfaces**

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Many surfaces dealt with in industrial production are reflecting. Some examples are windshields, car body panels, various press tools and polished, glazed, varnished or chrome coated objects. To ensure the quality of such surfaces, technical processes are needed to detect defects, control the contour accuracy and measure the three dimensional shape. Since the direct acquisition of a reflecting surface with optical imaging devices is not possible, an indirect approach must be taken. One possible approach is offered by deflectometry, which already occupies a broad field in quality assurance in industrial applications: A computer controlled screen displays a pattern; a camera acquires the image reflected by the surface of

interest. The image is distorted by the shape of the reflecting surface - very much like the image of a human is shrunk or elongated by a magic mirror.

While 2D techniques for quality assurance are already well understood[1] and applied in industry, there is only very basic results available for 3 dimensional metrology using deflectometry. The knowledge is only applicable for very specific and limited use cases [2]. This research will deepen the understanding of the challenges for the 3D case and will investigate and advance possible solutions.

References

[1] S. Kammel and F. P. Leon. Deflectometric measurement of specular surfaces. IEEE Transactions on Instrumentation and Measurement, 57(4):763–769, Apr. 2008.

[2] M. C. Knauer, J. Kaminski, and G. Häusler. Measurement of eye glasses with phase measuring deflectometry, OSMIN Annual Report 2003.

Website : <http://www.mrt.uni-karlsruhe.de/stiller.php>

## **10. Light management in printed solar cells**

Involved institutions : KIT ([Uli Lemmer](#)), ICFO (Jordi Martorell)

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Solar cells on the basis of organic semiconductors and printable inorganic nanostructures are attracting much interest as potential future low-cost energy conversion devices. In order to maintain reasonable efficiencies, multistack solar cells minimizing energy relaxation losses can be realized. Due to the resulting relatively complex multilayer thin film structures, a careful investigation and optimization of the propagation of light in the device is mandatory. The interplay of thin film interference effects and the possible use of lateral periodic structures (photonic crystals) and nonperiodic scattering dielectric and metallic nanostructures give degrees of freedom for the optimization of the absorption profile and the resulting exciton [1] and carrier dynamics [2]. In this thesis work, both experimental and theoretical approaches for the optical design of efficient printed solar cells shall be explored.

[1] Luat T. Vuong, Gregory Kozyreff, Rafael Betancur, and Jordi Martorell, Cavity-controlled radiative recombination of excitons in thin-film solar cells, Appl. Phys. Lett. 95, 233106 (2009).

[2] Nico Christ, Siegfried Kettlitz, Sebastian Valouch, Simon Züfle, Christian Gärtner, Martin Punke, Uli Lemmer, Nanosecond response of organic solar cells and photodetectors, J. Appl. Phys. 105, 104513 (2009).

Website : [http://www.liti.kit.edu/mitarbeiter\\_lemmer.php?year=2010](http://www.liti.kit.edu/mitarbeiter_lemmer.php?year=2010)