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Erasmus Mundus Joint Doctorate Program
EUROPHOTONICS
Doctorate Program in Photonics Engineering, Nanophotonics and Biophotonics
Edition 2012-2015

Project n°	Project Title	Main advisor	Second advisor
1	Nanometric surface probing with ultra-cold atoms	LENS : F. S. Cataliotti	KIT : W. Pernice
2	Light transport and interaction with matter in strongly heterogeneous media	LENS : D. S. Wiersma	UPC: K. Staliunas
3	Entanglement-enhanced atomic instruments	ICFO : M. W. Mitchell	LENS : G. Modugno, M. Fattori
4	Effect of hydrodynamic forces in integrin mediated leukocyte arrest and migration	ICFO: M. Garcia-Parajo	LENS : F. Pavone
5	Monitoring cells mechanical and structural properties at sub-micrometric scales in 3D	KIT: M. Bastmeyer	Inst. FRESNEL : H. Rigneault/S.Brasselet
6	Three-dimensional quantitative microscopy of crystalline nanostructures	Inst. FRESNEL : V. Chamard	KIT (ISS): A.A. Minkevich/T. Baumbach
7	Retinal imaging with MEMS scanning mirror for biometric purposes	KIT : W.Stork	UPC : J. Pujol, S. Royo
8	Control of high-order harmonic generation	UPC : C. Serrat	LENS : M. Bellini
9	Novel approaches to self-mixing interferometry	UPC : S. Royo	KIT : C. Stiller
10	Integrated single photon emitters in CVD diamond nano-photonics structures	KIT: W. Pernice	ICFO; F. Koppens
11	Nanophotonic systems for reconfigurable ultra-fast signal processing	KIT: C. Koos	ICFO : V. Pruneri



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Doctorate Program in Photonics Engineering, Nanophotonics and Biophotonics Edition 2012-2015

Project details :

1. Nanometric surface probing with ultra-cold atoms:

Main supervisor: Prof. Francesco S. Cataliotti
LENS, Italy
Co-supervisor: Prof. Wolfgang Pernice
Karlsruhe Institute of Technology, KIT, Germany
www.kit.edu

We intend explore the possibilities offered by ultracold atoms as nanometric surface probes. The interaction between a neutral atom and the surface of a dielectric or a conductor is a subject of research around which are concentrated many experimental and theoretical efforts in recent years. The reasons are varied. On the one hand it is a fundamental problem of QED, which has open conceptual and experimental aspects, such as e.g. the role of thermal fluctuations of the electromagnetic field produced by the surface. On the other hand, the interest is also motivated by the possibility of technological applications for advanced sensors. Finally, the systematic study of these forces is a crucial step for the derivation of new limits on hypothetical forces in non-Newtonian short distance.

The experimental project at LENS is concerned with the realization of an apparatus for laser cooling of atoms and their manipulation at sub-micrometric distances from a nano-structured surface that allows for rapid replacement of the test surfaces.

2. Light transport and interaction with matter in strongly heterogeneous media

Main supervisor: Prof. Diederik S. Wiersma
LENS, Italy
Co-supervisor: Prof. Kestutis Staliunas
Universitat Politecnica de Catalunya, UPC, Spain

Disordered optical materials are known to be excellent testbeds for the investigation of complex classical and quantum mesoscopic phenomena. Light transport in such systems is generally described by a multiple scattering process on a spatially random potential. Interferences between multiply-scattered waves lead to the formation of complex optical modes as well as to a spatially fluctuating local density of optical states. The most common model for disorder assumes that the scatterers are homogeneously distributed in space. It is expected, however, that large-scale inhomogeneities would affect transport significantly as well as the resulting interference effects. For example, it is known that random walkers in a medium containing obstacles with sizes distributed algebraically can propagate subdiffusively, i.e. their mean square displacement evolves slower than linear with time. In such cases, one may expect interferences to be stronger, thereby favoring localization effects and leading to an enhanced interaction with matter. Studying wave transport in such systems could therefore have a strong impact on the fundamental level (possibly new interference phenomena) as well as for applied sciences (similarity of these materials with human tissues, porous media, foams, etc...).

This PhD project therefore proposes to investigate theoretically and numerically the optical properties of strongly heterogeneous media, with a particular attention to interference effects and nonlinear effects in

subdiffusive media. Approaches such as the multiple scattering theory, Monte Carlo simulations and the numerical solution of Maxwell's equations will be considered to describe light transport in such systems. The two research teams are complementary with respect to the proposed project. On one hand, the research group of the leading institution is internationally recognized as an expert in the field of light transport in disordered materials and interference effects (Anderson localization, random lasing). More recent works have been concerned with the theoretical study of superdiffusive optical materials introduced by the group itself a few years ago. On the other hand, the research group of the partner institution has an expertise in the field of wave diffraction, beam manipulations in modulated systems (photonic crystals) and generally on nonlinear wave dynamics of optical systems.

The larger part of the PhD project will be performed at the leading institution and will concentrate on establishing a first theoretical description and numerical study of subdiffusive transport for waves, including interference effects. The second part of the project will be conducted at the partner institution and will focus on light-matter interaction and the resulting nonlinear phenomena.

3. Entanglement-enhanced atomic instruments

Main supervisor: Prof. Morgan W. Mitchell
Institute of Photonic Sciences (ICFO), Barcelona, Spain
Co-supervisor: Prof. Giovanni Modugno, Dr. Marco Fattori Institution
LENS, Italy

We are developing atom interferometers, instruments that use interference of atomic states to make sensitive measurements of magnetic fields, accelerations, and other effects [1]. Atom interferometers are the most sensitive instruments for measuring time (atomic clocks), magnetic fields (optical magnetometers), and gravitational acceleration (atomic gravimeters). Quantum entanglement is one of the most surprising features of the microscopic world, enabling ultra-rapid computation and non-local effects such as teleportation. Entanglement allows quantum particles to coordinate their behaviour better than classical objects can. We are working to use this exotic quantum behaviour in atom interferometers, to overcome classical sensitivity limits, and eventually to detect signals that are otherwise undetectable.

For this work, we use the best-behaved material and photonic systems: ultra-cold trapped atoms [2] and atom-resonant quantum light sources [3]. Using these, we have recently demonstrated a magnetometer working at the shot-noise limit [4], used optical squeezing (entanglement of photons) to improve the sensitivity of an optical magnetometer [5], and used interactions between quantum systems to beat the so-called 'Heisenberg limit' of interferometer sensitivity [6].

The student will work on two state-of-the-art cold-atom experiments, a cold atom magnetometer at ICFO (75 % of the time) and a Bose-condensate atom interferometer at LENS (25 %). The student will join a team working with the latest technologies for atomic manipulation, including fiber and diode lasers, acousto-optic and electro-optic modulators, ultra-low-noise photo-detection, and ultra-high vacuum.

Website:

<http://mitchellgroup.icfo.es> LENS atomic physics

References:

- [1] "Atom interferometry with a weakly interacting Bose-Einstein condensate," M. Fattori, C. D'Errico, G. Roati, M. Zaccanti, M. Jona-Lasinio, M. Modugno, M. Inguscio and G. Modugno, *Phys. Rev. Lett.* 100, 080405 (2008)
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- [3] "Atom-resonant heralded single photons by interaction-free measurement," F. Wolfgramm, Y. A. de Icaza Astiz, F. A. Beduini, A. Cerè, M. W. Mitchell, *Phys. Rev. Lett.* 106, 053602 (2011)
- [4] "Sub-projection-noise sensitivity in broadband atomic magnetometry," M. Koschorreck, M. Napolitano, B. Dubost, M. W. Mitchell, *Phys. Rev. Lett.* 104, 093602 (2010)
- [5] "Squeezed-light optical magnetometry," F. Wolfgramm, A. Cerè, F. A. Beduini, A. Predojević, M. Koschorreck, M. W. Mitchell, *Phys. Rev. Lett.* 105, 053601 (2010)
- [6] "Interaction-based quantum metrology showing scaling beyond the Heisenberg limit," M. Napolitano, M. Koschorreck, B. Dubost, N. Behbood, R. J. Sewell, M. W. Mitchell, *Nature* 471, 486 (2011).

4. Effect of hydrodynamic forces in integrin mediated leukocyte arrest and migration

Main supervisor: Prof. Maria Garcia-Parajo
Institute of Photonic Sciences (ICFO), Barcelona, Spain
Co-supervisor: Prof. Francesco Pavone
LENS, Italy

Motivation: A broad range of phenomena in health and disease are governed by cell adhesion and migration. When properly regulated, adhesion/migration enables morphogenesis, host defence and tissue healing. However, when regulation fails, adhesion and/or migration mediate devastating pathologies such as cancer, autoimmune diseases and chronic inflammation. For instance, the firm arrest of circulating leukocytes to sites of inflammation and lymphoid tissues is crucial for correct regulation of the immune response. Indeed, a key checkpoint in leukocyte recruitment to inflammatory targets is their ability to firmly arrest on vascular endothelial cells and maintain resistance to detachment by disruptive shear-forces while crawling on the surface of the endothelium. This lateral migration allows leukocytes to search out sites permissive for endothelial crossing with variable distances for their original arrest site. The integrin LFA-1 is the main leukocyte adhesion receptor regulating the processes of crawling, firm adhesion and migration¹. Still, very little is known about how LFA-1 contributes to these processes in the presence of disruptive shear-forces. Although integrins are thought to undergo rapid conformational changes both prior to, and shortly after, binding to their major endothelial ligands, it is unclear when and where high-affinity integrin subsets are generated and how they cooperate with intermediate-affinity integrin subsets to support rapid shear-stress-resistant leukocyte crawling over endothelial cells. The major challenge in these studies is given by the large heterogeneity on the different conformational states exhibited by LFA-1 on the surface of leukocytes, their different lateral mobility and their spatial distribution on the cell membrane^{2,3}. Single molecule fluorescence techniques are ideal to reveal heterogeneities that are commonly hidden in ensemble measurements. Moreover, latest technological advancements allow the recording of single molecule data in the presence of external stimuli such as mechanical forces.

Project description: The goal of this project is to dissect the role of hydrodynamic forces in integrin-mediated leukocyte adhesion and migration. For this we will apply single molecule fluorescence techniques combined with an in-vitro flow chamber to emulate physiological shear-stress conditions. Using this combined approach we will be able to record real time adhesion and migration of immune cells at the single molecule, single cell level under a variety of geometric and external force settings simulating physiological in-vivo conditions.

In the first part of the project we will determine the mobility and conformational states of LFA-1 on monocytes in the presence of external forces. The spatial-temporal organization of LFA-1 and of their different extracellular interactors forming supramolecular adhesion sites will be studied using single dye tracking microscopy and superresolution near-field nanoscopy⁴ at different external stimuli. For this we will use a flow chamber to allow shear-flows in the physiological range while simultaneously collecting single molecule fluorescence data. Specific reporters of LFA-1 conformational states will be used to assess the accumulation and (potentially different) spatial distribution of LFA-1 on monocytes during the processes of firm arrest, polarization and migration on ligand-bearing substrates. In addition, mutants expressing fluorescence proteins attached to the cytoplasmic tails of LFA-1 (available at Garcia-Parajo Lab) will be transfected on monocytes to directly visualize conformational changes of the integrin under the influence of shear-forces.

In the second part of the project we will focus on cytoskeleton rearrangement and dynamics as well as altered recruitment of intracellular signalling molecules to the sites of LFA-1 accumulation. In the presence of shear flow we will expect that cells become more compliant and thus cytoskeleton re-arrangement will have to occur, affecting in turn LFA-1 activation and mobility. An approach based on three-dimensional single particle tracking will be required to follow the intracellular dynamics of specific cytoplasmic molecules interacting with LFA-1. In this case, the molecules of interest (talin, actin, vinculin etc) will be produced and fluorescently labelled in vitro, and subsequently introduced in living cells by means of electroporation, microinjection or microporation.

Finally, we will study the process of leukocyte migration and extravasation through endothelial cells. For this part, monolayers of endothelial cells will be grown on glass and monocytes will be seeded on the endothelial

beds. It has been observed that leukocyte trans-endothelial migration is dramatically facilitated in the presence of shear-flow⁵. This might be due to two effects: change of the cell compliance due to cytoskeleton re-arrangements, as well as changes on the conformational states of LFA-1 leading to inactive or intermediate integrins that poorly engage (or dynamically switch on-off) to their ligands facilitating migration. I would be absolutely novel to observe these processes at the single molecule level and as they dynamically occur in living cells. By the end of the project we expect to generate a dynamic picture of the role of mechanical forces on in integrin-mediated leukocyte adhesion and migration.

References:

1. Luo, et al (2007) Structural basis of integrin regulation and signaling. *Annu. Rev. Immunol.* 25: 619-647.
2. Diez-Ahedo, et al. (2009) Dynamic re-organization of individual adhesion nanoclusters in living cells by ligand-patterned surfaces. *Small* 5: 1258-1263.
3. Bakker et al, Lateral mobility of individual integrin nanoclusters orchestrates the onset for leukocyte adhesion, in revision 2011.
4. van Zanten, et al. (2009) Hotspots of GPI-anchored proteins and integrin nanoclusters function as nucleation sites for cell adhesion. *Proc. Natl. Acad. Sci USA.* 106: 18557-18562.
5. Cinamon et al. (2001) Shear forces promote lymphocyte migration across vascular endothelium bearing apical chemokines, *Nature Immunol.* 2: 515-522.

Preliminary schedule:

T0 – T0 + 12 months: Mobility vs conformational states of LFA-1 under mechanical stimuli FCS development on lipid membranes over planar photonic antennas, Barcelona

T0 + 12 months – T0 + 22 months: Cytoskeleton & intracellular dynamics using 3D single particle tracking, Florence

T0 + 22 months – T0 + 30 months: Integrin and cytoskeleton remodelling during migration and extravasation, Barcelona & Florence

T0 + 30 months – T0 + 36 months: Writing PhD dissertation, preparing PhD defence

5. Monitoring cells mechanical and structural properties at sub-micrometric scales in 3D

Main supervisor: Prof. Martin Bastmeyer
Karlsruhe Institute of Technology, KIT, Germany

Co-supervisor: Dr. Hervé Rigneault and Dr. Sophie Brasselet
Institut Fresnel, Marseille, France
<http://www.fresnel.fr/mosaic/>

The cell membrane exhibits a complex architecture and morphology, which plays a determining role in key biological processes such as migration, differentiation, and proliferation. There is nowadays a large amount of research on the understanding of cell-extracellular matrix interactions, focusing in particular on the mechanical properties of cells. Cell forces can be measured on scaffolds micro-structures which are deformed under cell traction [1]. Researchers at Karlsruhe Institute of Technology (KIT, Zoologisches Institut Zell- und Neurobiologie), have recently developed a way to fabricate micrometer-scale composite-polymer scaffolds with distinct protein-binding properties which can be used as model substrates mimicking specific properties of their environment in 3D [2].

While mechanical properties of cells can be quantified, there is still no direct relation known with their microscopic scale membrane morphology. The goal of this project is to develop a non-invasive method based on fluorescence imaging microscopy, able to measure local forces and membrane sub-micrometric scale structure information in 3D. This information is contained in the read-out of lipid probes orientational order, measured using the polarization-resolved fluorescence. Such an instrument, recently developed at Institut Fresnel (mosaic team), consists in varying the polarization of the excitation light to measure the orientation of fluorescent molecules in biological samples, such as cell membranes [3,4]. It is possible to retrieve in a specific location the information on how the molecules are oriented (if they are highly ordered such as in a crystal or highly disordered such as in a liquid), and relate this information to cell membrane morphology within the typical optical resolution of about 300nm. So far, only 2D information is obtained on cells adhering on a surface. This project will consist in developing a scheme to measure 3D information, which involves specific polarization control schemes adapted to a 3D geometry.

The PhD schedule will be divided in periods of developments of adequate scaffolds able to report on 3D cell traction forces (KIT), and developments of the polarization resolved fluorescence microscopy imaging in 3D in the prepared scaffolds. Regular exchanges will therefore be performed between the two laboratories.

References:

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- [3] A. Kress, Patrick Ferrand, H. Rigneault, Hai-Tao He, Didier Marguet, S. Brasselet, “Probing MHC Class I Protein and Lipid Order in Cell Membranes by Fluorescence Polarisation-resolved Imaging”, *Biophys. J.* 101, pp. 468–476 (2011)
- [4] A. Gasecka, T.-J. Han, C. Favard, B.R. Cho, S. Brasselet, “Quantitative imaging of molecular order in lipid membranes using two-photon fuorescence polarimetry”, *BioPhys J.* 97 (10) 2854-2862 (2009)

6. Three-dimensional quantitative microscopy of crystalline nanostructures

Main supervisor: Dr. Virginie Chamard
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Co-supervisor: A.A. Minkevich and Prof. T. Baumbach
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Hard x-ray lens-less microscopy raises the hopes for a non-invasive quantitative imaging, capable of achieving the extreme resolving power demands of nanoscience [1]. However, a limit imposed by the partial coherence of third generation synchrotron sources restricts the sample size to the micrometer range. Recently, x-ray ptychography has been demonstrated as a solution for arbitrarily extending the field of view without degrading the resolution [2]. Researchers of the Fresnel Institute have recently shown that ptychography, applied in the Bragg geometry, opens new perspectives for crystalline imaging [3]. The spatial dependence of the three-dimensional Bragg peak intensity is mapped and the entire data subsequently inverted with a Bragg-adapted phase retrieval ptychographical algorithm. As a demonstration, the image obtained from an extended crystalline sample, nano-structured from a silicon-on-insulator substrate was reported.

The Erasmus Mundus program offers the possibility to establish a fruitful collaboration between the ISS-KIT in Karlsruhe and the Fresnel Institute in Marseille. The group of Prof. Baumbach has an international recognition in the x-ray scattering field and the activity developed by A. A. Minkevich in lens-less microscopy methods has a strong overlap with the research perspectives foreseen at the Fresnel Institute.

This PhD thesis project is based on the complementary expertise of the two institutes. Its aim is to exploit the sensitivity of x-rays in regard to the chemical composition inside the nanocrystals and combine it with the ptychographical approach. The measurement will be performed near the chemical specie absorption edge. The final aim of the PhD thesis is the 3D imaging of the strain and chemical composition fields inside a nano-crystal within a 10 nm range resolution. The possibility to retrieve, without transverse size restriction, the highly-resolved three-dimensional density and displacement field is expected to allow for the unprecedented investigation of a wide variety of crystalline materials, ranging from life science to micro-electronics.

The student should develop both experimental and computing skills. He/she will share equally his/her time between the Fresnel Institute, Marseille (main proposer) and the Institute for Synchrotron Radiation, Karlsruhe.

References:

- [1] A. A. Minkevich *et al.*, *Phys. Rev. B* **78** (2008), 174110. A. A. Minkevich *et al.* *Eur. Phys. Lett.* **94** (2011), 66001. V. Chamard *et al.*, *Phys. Rev. Lett.* **104** (2010), 165501.
- [2] J. M. Rodenburg *et al.*, *Phys. Rev. Lett.* **98** (2007), 034801. M. Dierolf *et al.*, *Nature* **467**, (2010) 436.
- [3] P. Godard *et al.*, *Nature Comm.* (2011). P. Godard *et al.*, *Phys. Rev. B* **84** (2011), 144109.

7. Retinal imaging with MEMS scanning mirror for biometric purposes

Main supervisor: Prof. W. Stork
Karlsruhe Institute of Technology, KIT, Germany
Co-supervisor: Prof. Jaume Pujol and Prof. Santiago Royo
Universitat Politecnica de Catalunya, UPC, Spain

Secure personal identification is of growing importance in the modern world. Biometric control at the airport and at each internet based payment procedure will be established in the future. Current systems use fingerprint, iris or face identification methods. All these methods can be rather easily counterfeited. Therefore currently systems with combined methods are under investigation. Such combined systems are more complex, more expensive and less convenient and at least not secure.

The only biometric feature, which is immutable the whole life and can be accessed contactless with optical imaging methods is the pattern of the retinal vessels. Retinal imaging for biometric purposes was investigated in the 1980 years. The developed systems were used for high level security systems in defense applications. These systems are similar to fundus cameras in ophthalmology, where the eye has to be positioned very accurately due to a small depth of focus and therefore the procedure is not applicable for simple home terminals or high throughput devices. For this reasons currently there are no products available anymore.

Scanning Laser ophthalmoscopes use collimated Laser beams with an extended depth of focus, but the existing scanning mirrors are too slow for a fast image aquisition, so the eye hast to be fixed for a while which prevents the addressed application.

The overall goal of this PhD project is therefore the development of retina imager using low cost MEMS micro mirrors which were originally developed for miniature Laser projection purposes (handy beamer). With these devices fast scanning of fields in the order of $50^\circ \times 25^\circ$ with VGA resolution are possible. We want to measure the backscattered light synchronously with the scanning frequency. The acquired images are then used for the biometric identification of persons with their unique vessel pattern.

Advantages of the new micro mirrors are the fast scanning speed and the low cost. A future Integration into mobile phones makes them to an ideal biometric device.

Work Program: Starting the work in Karlsruhe with MEMS Evaluation Kit and continuing the work with experimental retinal image capture at the Centre for Sensor, Instrument and Systems Development at UPC.

References :

[Wi84] Wilson, T. and Sheppard, C.: "Theory and Practice of Scanning Optical Microscopy". Academic Press. 1984.

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[Si35] C. Simon and I. Goldstein, "A New Scientific Method of Identification," New York State, Journal of Medicine, Vol. 35, No. 18, pp. 901-906, September, 1935.

8. Control of high-order harmonic generation

Main supervisor: Prof. Carles Serrat
Universitat Politecnica de Catalunya, UPC, Spain
<http://www.cd6.upc.edu>
Co-supervisor: Prof. Marco Bellini,
LENS - INO, Italy

Generation of coherent light in the short wavelength region of the electromagnetic spectrum by high harmonic generation (HHG) has been extensively studied during the last years. In this process high-order harmonic pulses are generated at frequencies that are multiples of the optical frequency of an intense laser pulse interacting with atoms or molecules, producing coherent radiation up to the extreme ultraviolet (XUV) and soft X-rays. The low yield of HHG especially for high photon energies, combined with a lack in shape control and tunability, however, prevents many exciting applications such as optimal attosecond pulse

generation, the visualization and manipulation of atoms, molecules and nano-materials, or recording the dynamic behavior of chemical reactions at the electronic level.

In this context, different schemes have been proposed in order to control the HHG yield. In particular, HHG enhancement by periodic modulation of the gas density using an array of gas jets has been demonstrated in the INO---LENS group [1], and control and tunability of the harmonics yield by adding a static---electric---field pattern along the high---order harmonics propagation direction has recently been predicted in the group at UPC [2].

In the present PhD project we propose to investigate theoretically and experimentally optimal control of the HHG process. The goal is to achieve a better characterization of the harmonic generation process under the influence of spatial patterns along the propagation direction, such as gas density variation and static-electric-field patterns, to eventually find optimal conditions for applications of these sources in attosecond pulse generation and spectroscopy.

References :

[1] A. Pirri, C. Corsi, and M. Bellini, Enhancing the yield of high--order harmonics with an array of gas jets, Phys. Rev. A 78, 011801 R (2008).

[2] C. Serrat and J. Biegert, All--Regions Tunable High Harmonic Enhancement by a Periodic Static Electric Field, Phys. Rev. Lett. 104, 073901 (2010); C. Serrat, Control of high--order harmonics for attoscience using a static--electric--field pattern (submitted).

Preliminary schedule of the research program.- The successful candidate will undertake the most part of the PhD work at UPC, and will spend a minimum of six months -distributed during the PhD period-, at INO-LENS. Further details on the research program and schedule are to be defined.

9. Novel approaches to self-mixing interferometry

Main supervisor: Prof. Santiago Royo
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Co-supervisor: Prof. Christoph Stiller
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In self-mixing interferometry (SMI) a laser diode gets part of the emitted radiation back-reflected on a target and fed into the laser cavity, so signal intensity beats in the emission of the laser appear, which may be monitored using an embedded photodiode. The technique is able to measure distances, velocities, and displacements of the target with typical resolutions of some tenths of nanometers, with setups which are extremely compact, robust and self-aligned. This makes this sensors suitable for non-contact nanometric metrology applications in hostile environments or in very reduced spaces.

This PhD candidate will explore unconventional approaches which extend the capabilities of classical SMI sensors and allows its use in a number of novel applications, or the improvement of the already existent ones. The main idea is getting out of the conventional working regime of the sensor to pursue and develop concepts in SMI for high-resolution detection of electromagnetic fields, and characterization of macro, micro and nanostructures.

The obtained sensor will be applied to develop solutions in three fields within the scope of the expertise of CD6, which are health-related instrumentation, non-destructive testing and non-contact metrology. A very relevant problem which will be tackled using the sensor will be real-time monitoring of different physiological quantities, which may open the door at a large number of health-related applications. In non-destructive testing, applications to preventive inspection of structures, and of automotive applications will be analyzed. In non-contact metrology, its use as a optical profiler of different quantities at the nanoscopic scale will be analyzed.

10. Integrated single photon emitters in CVD diamond nano-photonic structures

Main supervisor: Dr. Wolfram Pernice
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Co-supervisor: Karlsruhe Institute of Technology, KIT, Germany
Dr. Frank Koppens
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Institute of Photonic Sciences (ICFO), Barcelona, Spain

The development of robust and practical quantum information processing systems is an important problem at the interface between materials science, photonics and atomic physics. Light-emitting defects (color centers) in single-crystal diamond are increasingly attractive for their implementation in a solid-state platform. While single crystal diamond substrates are limited in size, polycrystalline diamond thin films can be deposited on a wafer scale on suitable substrates. Because of the high refractive index of diamond and its large transparency window, diamond is also a superior candidate for the fabrication of optical components.

In this project, color centers in polycrystalline diamond grown by chemical vapour deposition (CVD) will be explored for the realization of integrated single photon emitters. The experimental project will be carried out jointly between the KIT (Karlsruhe, Germany) and the ICFO (Barcelona, Spain). Goal of the project is the development of an integrated photonic platform for linear quantum optics. The work will be concerned with the implementation and fabrication of suitable nano-photonic components that provide efficient coupling to CVD diamond color centers. These include nano-photonic waveguides and optical cavities in the form of ring resonators or photonic crystals, as well as optical input ports for efficient fiber coupling. Possibilities of integrating single photon detectors on photonic circuits may also be explored at a later stage of the research. State-of-the art facilities will be available in a modern laboratory setting. Extensive experience in nano-photonics and quantum optics in the collaborating groups will provide a stimulating environment for cutting-edge research.

11. Nanophotonic systems for reconfigurable ultra-fast signal processing

Main supervisor: Prof. Christian Koos
Institute of Photonics and Quantum Electronics and Institute of Microstructure
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Karlsruhe Institute of Technology, KIT, Germany
Co-supervisor: Prof. Valerio Pruneri
Institute of Photonic Sciences (ICFO), Barcelona, Spain

World-wide data traffic is doubling every 18 months. Scaling today's device and network technologies will soon be insufficient to sustain this development, particularly when regarding power consumption. Already today, information and communication technology (ICT) accounts for more than 10 % of the total electric power consumption in most industrialized countries. Energy efficiency in data communications must hence be significantly improved within the next years.

This project aims at novel nanophotonic systems that enable low-power optical signal processing of Terabit/s data streams. We have recently demonstrated demultiplexing of a 26 Tbit/s signal by an all-optical implementation of a fast Fourier transform (FFT) [1]. This experiment, however, was based on discrete optical elements such as delay interferometers, and functionality was limited to the FFT. In the current project, we will investigate novel concepts for fully integrated optical signal processors which can be electronically reconfigured to perform various different signal processing tasks. Such systems can be built from a cascaded array of tunable, but structurally identical 'unit cells' [2], [3]. To decrease foot print and power consumption, we will use silicon-organic hybrid (SOH) integration to realize the systems. In this approach, nanophotonic silicon-on-insulator waveguides are combined with functional organic cladding materials such as electro-optic polymers or liquid crystals, Figure 1(b) [4]. The SOH technique has previously been used to realize broadband electro-optic modulators with more than 60 GHz of bandwidth and ultra-fast all-optical demultiplexers operating at data rates of 170 Gbit/s [4], [5].

We are looking for ambitious candidates holding a Master degree in electrical engineering or physics. Applicants should have both a strong theoretical background and experimental skills, and should be able to work within an international team.

Work plan:

The work program comprises several steps:

- Theoretical investigation and evaluation of different photonic signal processing concepts (KIT)

- Definition and design of a silicon-organic hybrid demonstrator system (KIT)
- Fabrication and Characterization of silicon chip (KIT/ICFO)
- Hybridization of silicon structures with functional organic materials (ICFO)
- Characterization of fabricated SOH structures and functional testing (ICFO/KIT)

References:

- [1] Hillerkuss, D. *et al.*: 26 Tbit s⁻¹ line-rate super-channel transmission utilizing all-optical fast Fourier transform processing. *Nature Photonics* 5, 364-371,(2011).
- [2] Ibrahim, S.-E *et al.* 'Fully Reconfigurable Silicon Photonic Lattice Filters with Four Cascaded Unit Cells, in 'Optical Fiber Communication Conference (OFC)', paper OWJ5, (2010).
- [3] Dowling, E. *et al.*, 'Lightwave lattice filters for optically multiplexed communication systems', *Lightwave Technology, Journal of* 12(3), 471 -486 (1994).
- [4] Alloatti, L. *et al.*, '42.7 Gbit/s electro-optic modulator in silicon technology', *Opt. Express* 19(12), 11841—11851, (2011).
- [5] Koos, C. *et al.*, 'All-optical high-speed signal processing with silicon-organic hybrid slot waveguides', *Nature Photonics* 3(4), 216-219, (2009).